Hybrid Resonant Wave Energy Harvesting Buoy for Sensor Applications

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***Abstract*— An overview of a hybrid wave/solar energy harvesting buoy currently being developed by Electro Standards Laboratories (ESL) is presented here. Through previous work with the University of Rhode Island, a resonant-drive buoy system was designed, constructed and tested at sea. ESL has continued to improve upon the original resonant buoy design by incorporating a larger, more powerful linear electric generator with adaptive load control as well as the addition of flexible solar panels to capture a second source of renewable energy using a maximum power point tracking algorithm. Laboratory testing of the modified elements of the hybrid energy harvesting buoy have shown promising results. At sea field testing of the buoy is planned during the second half of 2013.**

Keywords*— *wave energy harvesting; hybrid buoy; linear electric generator; solar MPPT; ocean energy

I. Introduction

Over the past decade, a significant amount of work has been performed on the design, numerical modeling and field testing of ocean wave energy converter (WEC) devices [1-3]. A majority of these devices target large amounts of power for grid connection applications. Alternatively, Electro Standards Laboratories (ESL), in collaboration with the Department of Ocean Engineering at the University of Rhode Island (URI), has focused on the development of smaller scale point absorber buoy systems, capable of providing power to on-board sensors and instrumentation [4-7]. This technology is anticipated to have applications ranging from ocean observation systems and aids to navigation to providing renewable power for unmanned underwater vehicle (UUV) recharging stations. Targeted power levels for these applications generally are in the range of 1-10 W, but can require as much as 250 W for more complex applications. ESL and URI have developed two buoy design concepts: 1) a *direct-drive* system, which utilizes the differential motion between a surface float and a submerged resistance plate to drive a linear electric generator (LEG) and 2) a *resonant-drive* system, which relies on the coupled resonance of the buoy's heave motion and an inertial mass/spring system to drive the LEG [5]. This paper focuses on the current work at ESL, which aims to expand upon the original resonant buoy concept and incorporate solar energy harvesting to create a hybrid resonant energy harvesting buoy system.

II. Background

The original *resonant-drive* buoy is a multiple-spar buoy (starspar), consisting of a long central spar with four shorter satellite spars located radially every 90 degrees (Figure 1). The satellite spars provide both roll stability and a reduction in overall draft of the system. This design came out of the motivation for development of an independent point absorber wave energy harvesting buoy, which responds to omni-directional wave forcing and directly converts mechanical energy of the buoy motion to electrical energy [8]. This type of system eliminates the need for turbines and gears and has no external moving parts, resulting in a simplified system requiring little maintenance. The main mode of wave energy harvesting is from buoy heave motion, and thus, attempting to tune the system to the frequency of the waves will result in increased amplitude of heave motion (through resonance) and a greater amount of energy to be harvested. The direct conversion of mechanical buoy heave motion to electrical energy implies the use of a linear electric generator for power take off. The LEG, mounted within the central spar, consists of a permanent magnet rod (armature) suspended by a spring, which is allowed to oscillate through a copper coil stator. LEG oscillations are forced through the coupled resonant response of the mass of the armature attached to the spring system and the entire buoy's resonant heave motion. Equation (1) is used to determine the coupled system natural resonant frequency (ω_{sys}) , where ω_a and ω_b are the natural resonant frequencies of the armature mass/spring system and buoy, respectively, K_a is the spring constant of the armature spring and M_t the sum of the buoy mass (not including the armature mass) and the buoy's heave added mass.

$$\omega_{sys} = \frac{\sqrt{(\omega_b + \omega_a)^2 + \frac{K_s}{M_t}} - \sqrt{(\omega_b - \omega_a)^2 + \frac{K_s}{M_t}}}{2} \tag{1}$$

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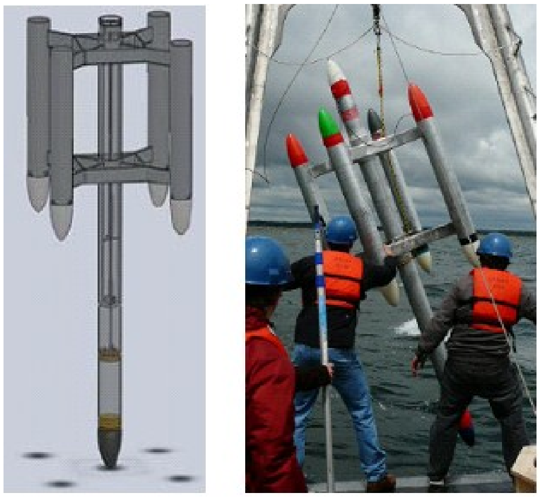

Fig. 1. Starspar conceptual drawing (*left*) and 1:4 scale prototype during field testing on 6/5/2012 (*right*)

To maximize this response, both the buoy's equivalent draft and the LEG spring stiffness must be tuned to the peak spectral period of the typical sea state in the targeted deployment location. For this work, the targeted full scale sea state was based on the 20 year average for Rhode Island shelf waters, resulting in a design significant wave height of $H_s = 1.2$ m and peak spectral period $T_p = 4.5$ s. According to linear wave theory [9], the energy per unit length of wave crest for this sea state is $J = 3.2$ KW/m. This comes from (2), where ρ is the density of sea water (assumed to be 1,025 kg/m^3) and g is the gravitational acceleration.

$$J = \frac{\rho g^2 H_s^2 T_p}{64\pi} \tag{2}$$

A *wave-to-wire* numerical model was developed to prove feasibility and aid in the design prior to construction and testing of scale prototypes and has been described in detail by [4,7]. The model considers three major, linked subsystems of the buoy design: 1) floating buoy dynamics, 2) LEG mechanical dynamics and 3) LEG electrical dynamics. For the model to correctly simulate and predict the amount of electrical energy that will be harvested by the buoy in a given sea state, it is necessary to take into account feedback between the subsystems. For example, motion of the armature changes the weight distribution of the buoy, which affects buoy motion. Additionally, electromagnetic forces induced in the LEG will alter the mechanical response of the generator armature. The buoy hydrodynamics and LEG dynamics can both be characterized by 2nd-order ordinary differential equations (ODE). Using (3), the buoy heave dynamics can be calculated,

$$\left(M_b + a_{33}(\infty)\right)\ddot{\xi}_3 + \int_0^t \kappa_{b3}(t-\tau)\dot{\xi}_3(\tau)d\tau + b_{f,33}\left|\dot{\xi}'_3\right|\dot{\xi}'_3 + F_{bs} = F_3 + F_g + F_{35} \tag{3}$$

where M_b is the buoy mass, $a_{33}(\infty)$ the instantaneous added mass (for very large frequency), $\kappa_{b3}(t)$ the heave memory term, $\xi_3(t)$ the buoy heave motion, $b_{f,33}$ the buoy heave viscous damping coefficient, $\dot{\xi}'_3 = \dot{\xi}_3 - \tilde{\omega}$ (where $\tilde{\omega}$ is the wave vertical particle velocity at the buoy equivalent draft), F_{bs} the heave buoyancy restoring force, F_3 the wave heave excitation force, F_g the LEG reaction force on the buoy, which is a function of armature motion, and F_{35} a change in the heave excitation and/or viscous damping due to the buoy roll/pitch motion. Similarly, (4) describes the LEG dynamics, where M_a is the armature mass (including half of the spring mass and inertial driving mass), μ the LEG damping coefficient, which combines electromagnetic resistance and friction, and z_a and z_b are the armature and buoy axial displacements, respectively, with upper dots representing time derivatives.

$$M_a \ddot{z}_a + \mu \dot{z}_a + K_s z_a = -M_a \ddot{z}_b \tag{4}$$

For laboratory testing, a 1:10 scale model prototype was built and tested in the wavetank at URI and results of these tests were used for model calibration. Tests were performed for both regular periodic (sinusoidal) and irregular waves. The 1:10 scale model prototype contained a small LEG with a simple two-phase resistive circuits [5]. Concurrently, testing of an LEG to be used in 1:4 scale buoy prototype was performed on the dry test bench located at ESL. Like the wavetank tests, the generator could be tested with sinusoidal and irregular wave profiles. For the case of irregular waves, the model was used to create a time-series of armature displacement under wave forcing from a JONSWAP spectrum, which then was used as the input profile for the controller on the test bench. Results from bench testing of the generator compared favorably with model simulations [4]. The 1:4 scale prototype starspar buoy was designed for a sea state with $H_s = 0.3$ m and $T_p = 2.25$ s, providing kinematic similarity with the full scale design based on Froude scaling principles. The central spar, which houses the LEG, consists of a 0.15 m diameter aluminum tube with an overall length of 3.5 m, including nose cones. The four satellite spars are each 1.6 m long (including nose cones) and equally spaced from the central spar. The nose cones were fabricated to obtain a highly streamlined form. The total mass of the is 105 kg, which is set by the necessary equivalent buoy draft to match the design system natural frequency. The maximum stroke length for the armature is ±0.32 m.

A field test of the 1:4 scale starspar prototype was performed in June 2012 in Narragansett Bay (Rhode Island) [6]. Wave conditions during the test were measured with a commercially available waverider buoy manufactured by Datawell BV. The significant wave height during the test was $H_s = 0.31$ m and the peak spectral period was $T_p = 2.52$ s, which were very close to the design wave conditions mentioned above. The buoy performed as designed, with heave motion of approximately ±0.55 m, clearly showing a resonant-type response to the wave forcing. Root mean square armature displacement and velocity were 0.14 m and 0.40 m/s, respectively. The RMS displacement of the armature was almost double that of the sea surface elevation, $\eta_{RMS} = H_s/4 = 0.0775$ m, showing that armature motion was also displaying a resonant response. The average electrical power harvested during the test was 0.41 W with peaks of 7-8 W (Figure 2). A numerical model simulation of the field test was performed for model validation purposes [7]. RMS armature displacement and velocity, as well as average power for the simulation were within 10% of the experimental data, as shown in Table I.

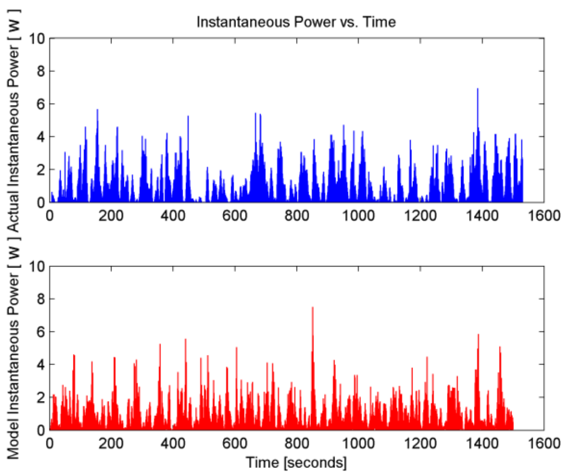

Fig. 2. Power harvested during field test on 6/5/2012 (*top*) and model simulation results (*bottom*)

TABLE I. COMPARISON OF EXPERIMENTAL AND MODEL RESULTS

Test				
	Data Set	$z_{a\,RMS}$	$\dot{z}_{a\,RMS}$	P_{mean}
June '12 (Starspar)	Experiment	0.14 m	0.40 m/s	0.41 W
	Simulation	0.14 m	0.39 m/s	0.44 W

III. HYBRID STARSPAR BUOY MODIFICATIONS

Given the results from the field testing of the starspar buoy in June 2012, it was clear that the power generation capabilities of the buoy could be improved. Since the buoy's heave response (±0.55 m) to the relatively small sea state (H_s = 0.31 m, T_p = 2.52 s) was excellent, work focused on modifications to the linear electric generator and the internal spring/mass system. Also, in an effort to diversify the energy sources available, the addition of solar energy harvesting capability to supplement wave energy harvesting was desired. The motivation for this lies in the fact that calm wave conditions generally correlate to fair weather and greater solar irradiance, while stormy conditions have larger waves and less sun. Implementing solar energy harvesting allows the buoy to, theoretically, generate power in most weather conditions. The following sections will briefly describe the modifications made to the original starspar buoy design as well as the motivations behind them.

A. Linear Electric Generator

The LEG in the original starspar buoy design was relatively small, limiting the amount of electrical power that could be produced. The size of the LEG was restricted by the configuration of the internal mass/spring system, which was based primarily on the properties of readily available stock springs and a desire to keep the driving mass low to increase roll stability by having more ballast mass in the bottom of the central spar. During the field tests, the buoy exhibited very little roll motion, giving us confidence that a portion of the ballast mass could be transferred to the LEG and mass/spring system without sacrificing too much in terms of stability. A new LEG stator was fabricated with an increased number of copper windings and was made significantly longer (by approximately 500%). In addition, a larger permanent magnet armature was chosen to compensate for the increased diameter and length of the stator. Given identical armature motion through each LEG, more voltage will be produced in the new LEG due to the greater number of windings and increased strength of the magnetic field, allowing for more power to be harvested under the application of an electrical load. Frictional damping within the LEG for the original starspar was determined to be approximately half of the LEG electromagnetic damping [6], which consumed a significant portion of the mechanical energy from the armature motion, further limiting electrical power. To minimize friction, the new LEG stator was fabricated using low wear-low friction materials.

B. Driving Mass/Spring System

In order for the new LEG to be used within the existing starspar buoy, it was necessary to modify the internal mass/spring system. The original starspar buoy design had a driving mass of 7 kg, which was due to the spring constant of the chosen springs. The permanent magnet armature used in the new LEG has a mass of 7.3 kg by itself, requiring that different springs be used to maintain the designed natural frequency of the system. To provide a greater driving force through the generator, it was decided to increase the driving mass to 25 kg, which is roughly 25% of the total buoy mass. The larger driving mass, in combination with the increased length of the LEG stator required that custom springs be ordered which provided the correct spring constant and initial tension to match the design frequency and have the static position of the armature in the center of its stroke.

C. Solar Energy Harvesting

For the purpose of solar energy harvesting, commercially available flexible solar panels were mounted on each of the four satellite spars to cover the area above the static water line. Each solar panel is rated at 7 W, however it is unlikely that this much power can actually be harvested by the buoy. In an ideal situation, each panel would be laid flat and oriented in the direction of the sun. On the hybrid starspar buoy, each panel is wrapped around a satellite spar in a vertical orientation and at least one panel will always be facing in the opposite direction of the sun. Since solar energy harvesting is meant only to be supplemental to wave energy harvesting, the efficiency lost by using this setup is acceptable. To compensate for a portion of the lost efficiency due to the orientation of the panels, a maximum power point tracking (MPPT) control algorithm will be used. The result is an automatic tuning of the current to produce the greatest amount of power from the solar cells in variable sunlight conditions.

D. Circuit Board

The circuit board in the original starspar buoy design was used as a central processing unit for system monitoring and charging control. The former utilized numerous ADC channels to collect and store information from a number of on-board sensors, including accelerometers and gyroscopes to track buoy motion and Hall Effect sensors for armature motion. The latter would first convert AC output voltage from the LEG to DC through a full-wave bridge rectifier and then using a DC/DC converter with an emulated resistance, power could be extracted and stored on batteries. In addition, wireless communications were powered and processed using the circuit board. While the circuit board performed well, numerous improvements were necessary to make it useful in the modified hybrid starspar. The hybrid starspar has two energy sources (wave and solar), with each source requiring its own circuit and separate controls to harvest usable power. For wave energy harvesting, the circuit has been upgraded to accept higher voltages and currents, which was necessary due to the use of the larger LEG. The charging control algorithms remain the same. The solar circuit is essentially the same circuit that was used on the original board for wave energy harvesting, with the addition of the MPPT algorithm. Further, wireless communications were improved by using more robust communications modules and on-board data storage capacity was increased from 256 MB to 16 GB.

E. Supercapacitors for Energy Storage

Instead of charging a battery bank, the hybrid starspar buoy will utilize lithium ion supercapacitors (LiC) for energy storage [10]. The LiC supercapacitors are a cross between lithium ion batteries (LiB) and electric double-layer supercapacitors (ELDC). They have the ability to handle power pulses much better than batteries, have very low energy leakage and can transfer energy very rapidly. In addition, the LiC supercapacitors have a very high cycle life, with approximately 1 million full charge and discharge cycles. Since batteries do have a higher energy density, if needed, the LiC supercapacitors can be combined with batteries to create a hybrid LiC/battery energy bank.

IV. Laboratory Testing

The new LEG was tested on the dry test bench at ESL as well as within the buoy using the deep water tank at URI. For dry testing, the LEG was tested with both sinusoidal and irregular JONSWAP wave profiles under various electrical loading conditions. Figure 3 shows the voltage across one phase of the LEG when forced with a sine wave of amplitude A = 0.3 m and period T = 5 s and loaded with a resistance of R_L = 125 Ω per phase. Figure 4 shows the power generated for this case. Likewise, Figures 5-6 show voltage and power when using a JONSWAP wave profile matching the June 2012 field test. Figure 7 shows a comparison between the running average power for the simulation and bench test using the new LEG and the model simulation using the previous LEG. The results of the dry testing match relatively well with model simulations, however the model seems to slightly over-predict the generated electrical power during the irregular wave tests. This suggests that the generator has a lower efficiency than anticipated, due to some combination of frictional heat loss and copper losses, hysteresis or eddy currents that are not considered to be significant in the model. The results of the bench test show that the new LEG is capable of generating over 500% more power than the previous LEG under these conditions.

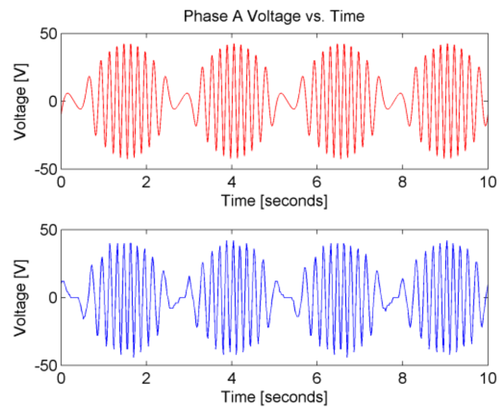

Fig. 3. Simulated voltage across single phase for 30 cm, 5 second sine wave (*top*) and bench test results (*bottom*)

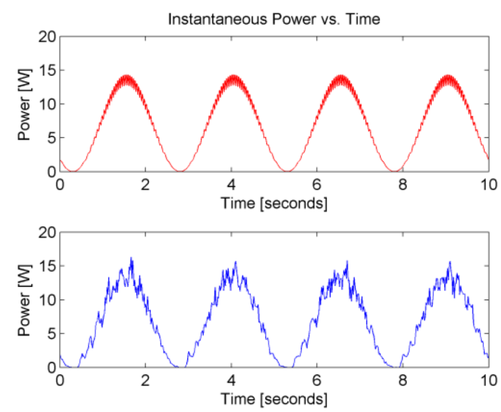

Fig. 4. Simulated power generated from single phase for 30 cm, 5 second sine wave (*top*) and bench test results (*bottom*)

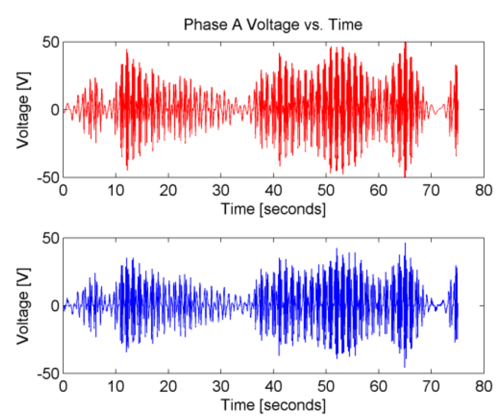

Fig. 5. Simulated voltage across single phase for JONSWAP wave profile from 6/5/2012 test (*top*) and bench test results (*bottom*)

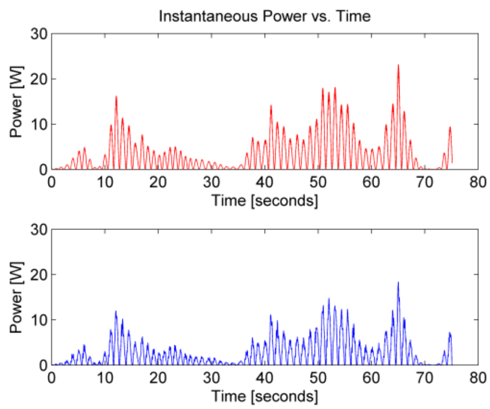

Fig. 6. Simulated power generated from single phase for JONSWAP wave profile from 6/5/2012 test (*top*) and bench test results (*bottom*)

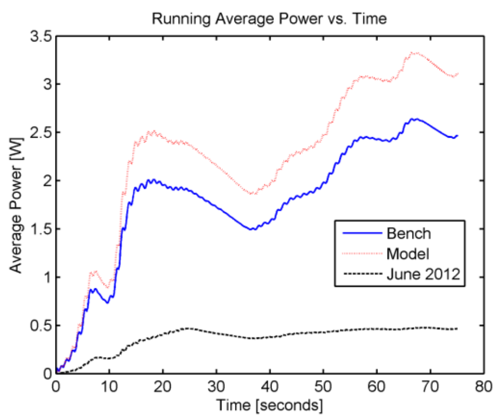

Fig. 7. Comparison of running average power between simulation and bench test with the new LEG and the LEG used in the 6/5/2012 test

The hybrid starspar buoy requires a greater water depth than is available in the URI wavetank and therefore it was necessary to use the deep water tank at URI for testing of the new LEG (Figure 8). Because of the lack of controlled wave generation capabilities in the deep water tank, testing relied on manual forcing of the buoy. Free response and periodic driving tests were performed for various electrical loading conditions. Figure 9 shows the armature motion during free response tests with the LEG unloaded (open circuit) and loaded with a resistance of $R_L = 100\ \Omega$ per phase. For the latter case, an average power of 1.2 W with a peak power over 30 W was generated by the LEG. Similarly, Figure 10 shows the armature motion when the buoy was periodically forced (pushed) at a frequency roughly equal to the buoy system natural resonant frequency under the same electrical loading conditions. It can be seen that the armature was hitting the bottom end stops during the unloaded case. With the electrical load resistance applied, the LEG generated 10.2 W average power with peaks greater than 70 W.

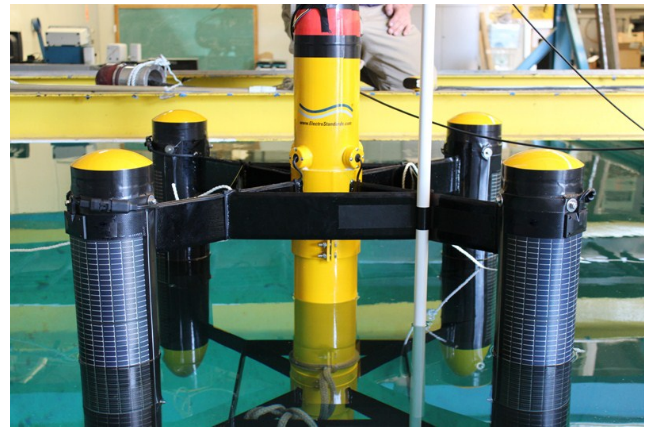

Fig. 8. Hybrid starspar buoy during testing in the deep water tank at URI

In addition to laboratory testing of the new LEG, laboratory and field testing of the new solar panels and MPPT algorithm was performed. Testing of the MPPT algorithm was accomplished using a small array of solar cells prior to the selection of the actual solar panels to be used for the hybrid starspar buoy. In conditions with approximately 25,000 lux, the solar cells were harvesting 0.05 W prior to turning on MPPT. After MPPT was turned on, the harvested power was increased to 0.325-0.425 W (650-850%). While MPPT is expected to increase harvested power, the magnitude of this increase is most likely due to relatively low illumination experienced during testing. It is expected that the improvement from MPPT in better light conditions will be more modest. A test of the actual solar panels, mounted to the starspar buoy was performed at ESL on a sunny day in May 2013 (100,000 lux). The four solar panels, connected in series, were able to harvest an average power of just under 1 W without using MPPT. Testing of the solar panels mounted on the hybrid starspar using MPPT has not yet been performed, however an increase of 150-200% can reasonably be expected under the same conditions.

A field test of the 1:4 scale hybrid starspar buoy, has not yet been performed, but is planned to take place in Narragansett Bay during the second half of 2013. Based on results of model simulations and the testing described above, anticipated average harvested power from waves is expected to be in the 2-5 W range with 1-2 W of average power from solar, for a total of 3-7 W.

V. CONCLUSION

With the goal of increasing the power harvesting capabilities of the original starspar resonant buoy developed by ESL and URI, modifications were made to create a hybrid resonant wave and solar energy harvesting buoy. The major modifications included upgrading the LEG to produce more power and implementing solar energy harvesting with MPPT. Laboratory testing has shown that wave energy power can be expected to increase by at least 500% and with the contribution of solar power, the hybrid starspar buoy should be able to produce enough power for sensor and instrumentation

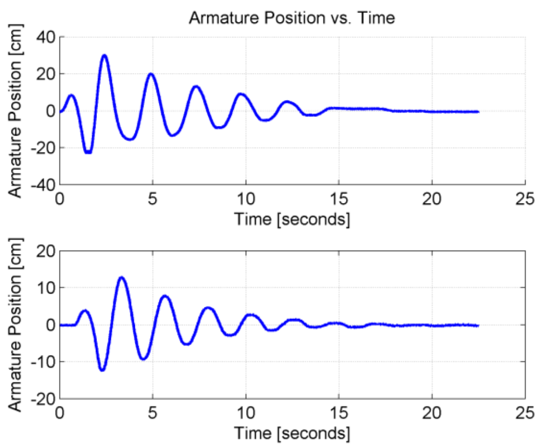

Fig. 9. Armature displacement during free response tests in deep water tank for unloaded (*top*) and loaded with 100 Ω (*bottom*)

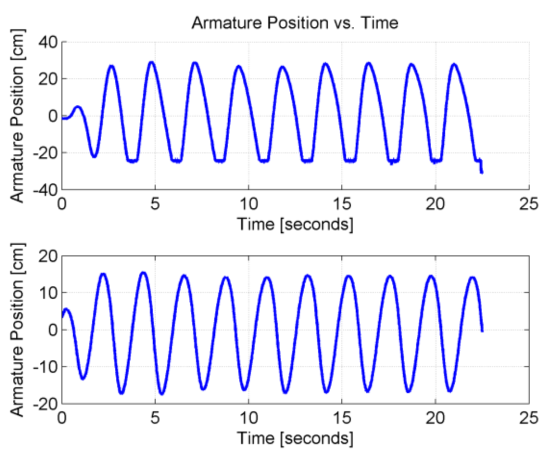

Fig. 10. Armature displacement during manually driven tests in deep water tank for unloaded (*top*) and loaded with 100 Ω (*bottom*)

applications requiring up to 10 W. Field testing is planned during the second half of 2013.

Given that the hybrid starspar buoy is a resonant system, further improvements to broaden the response band of the system will be considered, but were outside of the scope of this work. Specifically, automatic tuning which actively controls the system dynamics in response to changing wave conditions could be implemented. However, it may be necessary to predict what the wave conditions will be in the near future to be successful. In addition to further work improving the 1:4 scale buoy, work is ongoing to design and build a full scale hybrid starspar buoy capable of harvesting at least 250 W.

ACKNOWLEDGMENT

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