Current Status and Future Prospects of Electric Generators Using Electroactive Polymer Artificial Muscle

Seiki Chiba[1], Mikio Waki [2], Koichi Masuda[3], Tomoki Ikoma[3]
[1] SRI International, [2]HYPER DRIVE Corporation, [3]CST/ Nihon University

Abstract **The type of electroactive polymer known as dielectric elastomers has shown considerable promise for harvesting energy from environmental sources such as ocean waves, wind, water currents, human motion, etc. The high energy density and conversion efficiency of dielectric elastomers can allow for very simple and robust "DIRECT DRIVE" generators. Various types of energy harvesting generators based on dielectric elastomers have been tested. For example, buoy-mounted generators that harvest the energy of ocean waves were tested at sea for two weeks. Each generator uses a proof-mass to provide the mechanical forces that stretch and contract the dielectric elastomer generator. Those generators operated successfully during the sea trials. The buoy-mounted generators will be scaled up to produce larger amounts of power. The use of significantly larger amounts of dielectric elastomer material to produce generator modules with outputs in the MEGAWATT at range is being investigated for application to ocean wave power systems.**

I. Background on Electroactive Polymer Artificial Muscle (EPAM)

Electroactive polymer artificial muscle (EPAM) is a new smart material with characteristics and properties not seen in other materials [1-4] that has been under development at SRI International since 1991.

The basic element of EPAM is a very simple structure comprised of thin polymer films (elastomers) sandwiched by two electrodes made of a flexible and elastic material, and can operate as an electric control actuator.

When a voltage difference is applied between the electrodes, they are attracted to each other by electrostatic forces (Coulomb forces) leading to a thickness-wise contraction and plane-wise expansion of the elastomer [1].

Using an EPAM actuator makes it possible to achieve a highly efficient transduction from electric energy into mechanical energy (the theoretical transduction efficiency is 80-90% [1]), which translates into a considerable energy saving compared to other actuator technologies such as electric motors with gearboxes. At the material level, this material has fast speed of response (over 50,000 Hz has been demonstrated for small strains), with a high strain rate (up to 400%), high pressure (up to 8 MPa), and power density of 1 W/g (for comparison, human muscle is 0.2 W/g and an electric motor with gearbox is 0.05 W/g) [5].

In a recent experiment, we have verified [6] that the dielectric elastomer type of electroactive polymer can maintain good operational characteristics even in an ultrahigh-pressure environment by showing that the electroactive strain response to an applied voltage was unaffected by externally applied pressures of up to 100 MPa. Fig 1 shows the deformation ratio of EPAM at different ambient pressures and applied voltages [6].

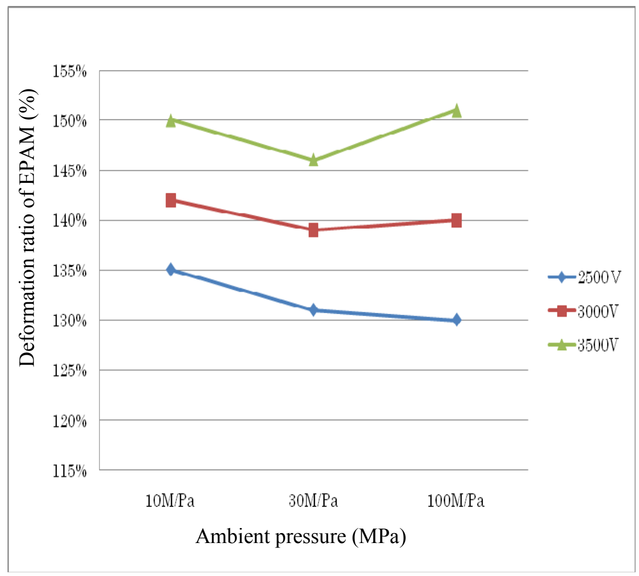


Figure 1. Deformation ratio of EPAM at different ambient pressures and applied voltages

II. EPAM-Based Electric Generator

The operation principle in the generator mode is the transformation of mechanical energy into electric energy by deformation of the EPAM. Functionally, this mode resembles piezoelectricity, but its power generation mechanism is fundamentally different. With EPAM, electric power can be generated even by a slow change in the EPAM shape, while for piezoelectric devices impulsive mechanical forces are needed to generated the electric power. Also, the amount of electric energy generated and conversion efficiency from mechanical to electrical energy can be greater than that from piezoelectricity [7]. Fig.2 shows the basic operating principal of EPAM power generation.

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

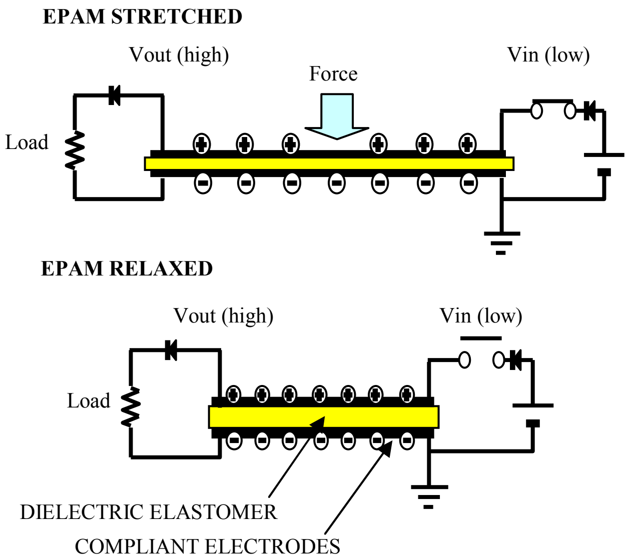


Figure 2. Operating Principle of EPAM Power Generation

Application of mechanical energy to EPAM to stretch it causes compression in thickness and expansion of the surface area. At this moment, electrostatic energy is produced and stored on the polymer as electric charge. When the mechanical energy decreases, the recovery force of the EPAM acts to restore the original thickness and to decrease the in-plane area. At this time, the electric charge is pushed out to the electrode direction. This change in electric charge increases the voltage difference, resulting in an increase of electrostatic energy.

$$C = \varepsilon_0 \varepsilon A/t = \varepsilon_0 \varepsilon b/t^2 \qquad (1)$$

where ε_0 is the dielectric permittivity of free space, ε is the dielectric constant of the polymer film, A is the active polymer area, and t and b are the thickness and the volume of the polymer. The second equality in Equation (1) can be written because the volume of elastomer is essentially constant, i.e., $At = b$ = constant.

The energy output of an EPAM generator per cycle of stretching and contraction is

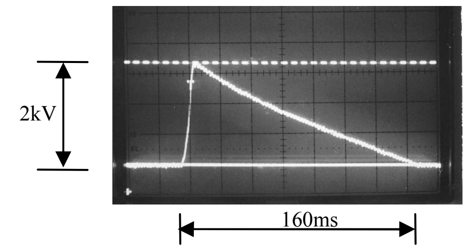
$$E = 0.5 C_1 V_b{}^2 (C_1/C_2 - 1) \qquad (2)$$

where C_1 and C_2 are the total capacitances of the dielectric elastomer films in the stretched and contracted states, respectively, and V_b is the bias voltage.

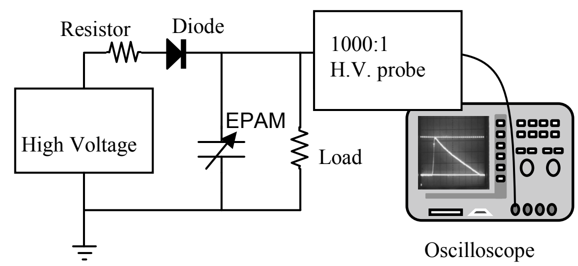
Considering then changes with respect to voltages, the electric charge Q on an EPAM film can be considered to be constant over a short period of time and in the basic circuit. Since $V = Q/C$, the voltages in the stretched state and the contracted state can be expressed as V_1 and V_2, respectively, and the following equation is obtained:

$$V_2 = Q/C_2 = (C_1/C_2)\,(Q/C_1) = (C_1/C_2)\,V_1 \qquad (3)$$

Since $C_2 < C_1$, the contracted voltage is higher than the stretched voltage, corresponding to the energy argument noted above. The higher voltage can be measured and compared with predictions based on the dielectric elastomer theory. In general, experimental data based on high impedance measurements are in excellent agreement with predictions. When the conductivity is assumed to be preserved in the range of electric charging, Q remains constant.



(a) Typical scope trace from EPAM contraction. Voltage spike occurs at contraction and gradually back to (stretched) voltage due to load resistance.



(b) Measurement circuit of generated Energy

Figure 3. Voltage for EPAM compression and measurement circuit

Figure 3(a) shows a typical scope trace from EPAM contraction. Figure 3(b) shows a simplified circuit for oscilloscope measurement of voltage. Though the voltage wave generated for one impact has on the order of a few ms to several tens of ms for a piezo-electric element, in the case of EPAM it is on the order of 150-200 ms [8]. Due to both the long pulse duration and the high energy density of EPAM in power generation mode, mechanical energy can be effectively converted to electric energy even at low frequencies.

A. Wave Generation

In August of 2007, we carried out ocean experiments on generating electric power from natural wave motion with the EPAM generator installed on a buoy [8]. These experiments were carried out on Tampa Bay, 1.6 km off the coast of St. Petersburg, Florida, at a water depth of about 5 m. Our objectives in these experiments were to:

- Confirm that the EPAM can operate in the marine environment,
- Demonstrate that electric power can be generated by natural wave motion,

- Correlate the wave and buoy motion to the measured energy output of the EPAM generator.

The power generation unit used in the experiments (See Photo 1.) was a cylindrical tube with a diameter of 40 cm and a height of 1.2 m. Inside the tube were two roll-type EPAM modules, each about 30 cm in diameter and 20 cm in height (in the stretched state). About 150 g of EPAM film (including electrodes) was used in each roll. The maximum measured electrical output capacity, verified in laboratory tests, was 12.5W for each roll. However, wave activity was minimal during the test period. Wave heights were on the order of few centimeters, which made it very difficult to carry out tests for wave-powered generators. On occasion the weather generated waves 10 centimeters high. Despite the low wave activity and non-ideal motion of the buoy, the generator was shown to function. Even with the small wave height of 10 centimeters, we were able to generate a peak power of 1.2 W with an average power of 0.25 W (See Figure 4.). While this amount of power is small, we can extrapolate these numbers to estimate the potential of an EPAM generator mounted on a buoy.

At this time, bias voltage was approximately 1,800V, but when the bias voltage is set to approximately 5,000V, A maximum electric energy of 11 W could be obtained under the same condition.

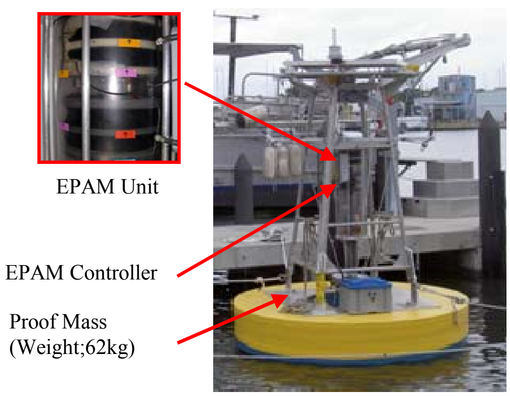


Photo 1. EPAM generator system on the test buoy

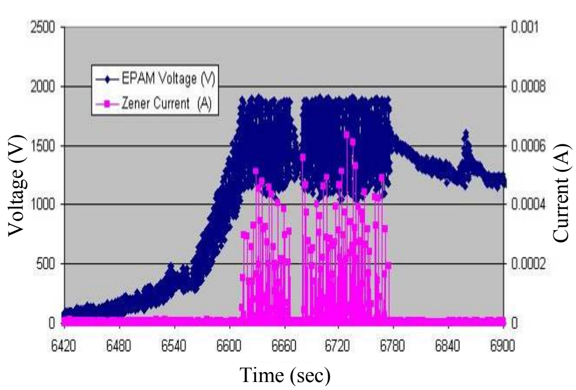


Figure 4. Electricity generated by ten centimeters waves

Based on data from laboratory testing, we estimated that the energy conversion efficiency of EPAM generator is 70-75% (not including hydrodynamic losses) [8].

In December 2008, oceanic tests were also carried out in California, USA, and it was confirmed that generated electric power was constantly stored in a battery.

An energy transduction technology that operates efficiently over a range of frequencies is important for practical energy harvesting devices such as ocean wave power generators. EPAM is based on the change in capacitive energy of a deformable dielectric and is a candidate for such applications. A simple scale model of EPAM-based wave energy harvesting system was tested in a wave tank over a range of wave periods from 0.7 to 3 seconds and wave heights of 3 cm and 6 cm. The energy output was found to be largely independent of wave period (See Figure 5.) [9].

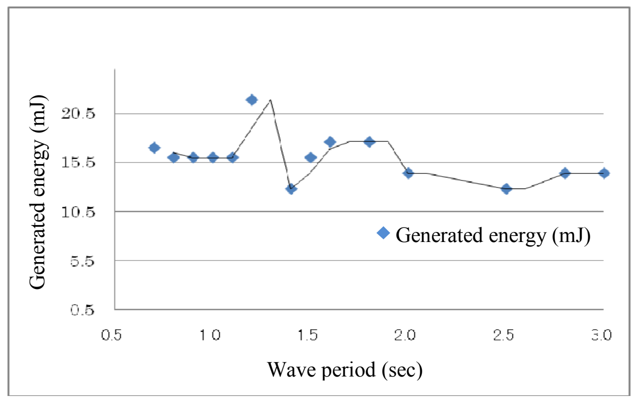


Figure 5. Generated energy as a function of Wave period

B. Water Current Generation

Large-scale hydroelectric power generation is a clean and renewable energy resource, but it has a great environmental impact as a result of the dam, reservoir, and modification of the riverbed. Also, there are few new suitable locations for hydroelectric power. In contrast to "big hydro," with so-called micro hydro, generators are placed into flowing rivers or streams without the need for large dams (or in many cases, any dam at all) or modification to the riverbed.

An EPAM generator can be well suited for micro hydro [8]. As with wave power, the fact that EPAM can operate efficiently over a range of frequencies suggests that an EPAM generator can operate efficiently in the widely varying flow rates of many undammed streams and rivers. Since the EPAM material has a high energy density, EPAM generators do not require high-speed rotation from a converter. A simple structure that induces stretching and contracting of the EPAM is enough to generate electricity.

Photo 2 shows a water mill device that is 80 cm in diameter. This proof-of-principle device was tested in the laboratory. A small water pump (1.12 L/sec flow rate) was fixed to a test tank to move water that spun the waterwheel. The waterwheel was attached to a crankshaft with a push rod that was then attached to a diaphragm-type of EPAM device. The up and down motion of the push rod stretched and contracted the EPAM in the diaphragm. In this simple test, each turn of the wheel produced 5W of electricity.

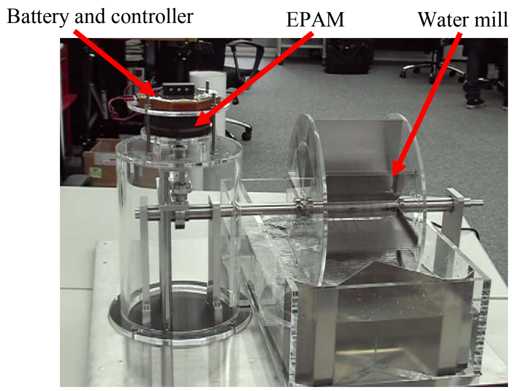


Photo 2. Water Mill generator using EPAM

C. Experiments for Generation of Hydrogen with EPAM Generators

At the time of field tests for wave power generation, we also carried out experiments on hydrogen production [10]. In the experiments, the generated energy was first stored in a small battery (12V/600mAh). This battery was connected to a hydrogen generation system via a DC-DC converter. The hydrogen generation equipment used in the experiments was a simple electrolytic cell that used nickel electrodes of a mesh of 0.1 mm (150 mm×100 mm). Instead of seawater, a 3% aqueous solution of sodium hydroxide was used as a raw material. Applied voltages were reduced to 3 V by the DC-DC converter. The hydrogen generation equipment used in the experiments was a simple electrolytic cell that used nickel electrodes of a mesh of 0.1 mm (150 mm×100 mm). Instead of seawater, a 3% aqueous solution of sodium hydroxide was used as a raw material. Applied voltages were reduced to 3 V by the DC-DC converter.

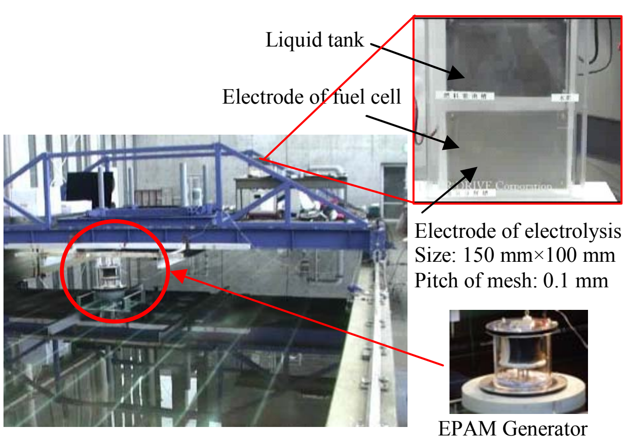


Photo 3. Hydrogen generation equipment by electrolysis

As mentioned above, we have found that approximately 11 W can be obtained by waves of just 10 cm in height, thus enabling the generation of 1.76 liters of hydrogen in about one hour (estimated for charging and discharging battery efficiencies of 80% [10]). As with the production of electrical energy, the process could be scaled up by several orders of magnitude.

III. Analysis of Power Generation Cost

Even without EPAM technology, ocean wave power is beginning to flourish in several countries. These ocean wave power systems typically use hydraulic pistons that are pumped by the wave action. The hydraulic fluid flows through a transmission and then a turbine to spin a rotary electromagnetic generator. When these systems are successfully developed for commercial use, the unit price of a power generation of kWh is estimated to be about 20 US Cents [10]. These wave power systems are typically designed for ocean waves exceeding 2 - 3 m in height. At significantly smaller wave heights, the systems become less economically attractive.

Because of its simplicity, efficiency, and size scalability, we believe that EPAM-based wave generator systems can be attractive not only for large wave applications but for many applications where the waves are much smaller. An estimate based on data from our sea trial demonstration experiments has shown that even in seas where the wave height is only 1 m throughout the year (e.g., the sea close to Japan), if there are spaces of approximately 500 m in length and 10 m in width, the establishment of a sea-based facility generating 6 MW of power is possible [10]. This is a useful amount of power, be it for general use or for providing energy for nearby residential or industrial needs. The ability to produce the power where it is needed can eliminate the losses and costs associated with power transmission over long distances and make wave power even more attractive. The power generation efficiency estimated on the basis of the data obtained from in-tank experiments in 2006 [11,12] and ocean demonstration experiments in 2007 [8] and 2008 is approximately 19 US cents/kWh. In the near future, we expect that the electric power generation per unit mass or volume of EPAM material can double, and that the expected power generation cost per kilowatt-hour is 5 - 7.5 US cents. This value is comparable to that for fossil fuel thermal power plants. Of course, the wave power systems have the additional benefit of not releasing any pollution or greenhouse gasses.

Figure 6. Conceptual rendering of EPAM wave power generator system.

IV. FUTURE WORK

Helping to address critical issues such as global warming through the enabling of effective harvesting of highly distributed natural power sources is clearly a great potential benefit of EPAM. We are expecting the EPAM generators may become one of the promising technologies、not only to produce the power, but also to produce hydrogen in ocean and deserts in future [12].

We plan to further investigate more effective structure and methods for water power transmission and realize a power generation unit of 2 kW in the very near future.

REFERENCES

[1] R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph, “High Speed Electrically Actuated Elastomers with Over 100% Strain,” Science 287:5454, pp 836–839, 2000.

[2] R. Pelrine, J. Eckerle and S. Chiba, “Review of Artificial Muscle Approaches”, (Invited) Proc. Third International Symposium on Micromachine and Human Science, Nagoya, Japan, pp 1–9, October 1992.

[3] R. Pelrine, R. Kornbluh, H. Prahlad, R. Heydt, and S. Chiba, “Micro and Nano Fluidic Devices Using Electroactive Polymer Artificial Muscle “, Proc., Tenth International Conference on Miniaturized System for Chemistry and Life Science, Vol.1, pp278-280, Tokyo, Japan, Nov. 5-9, 2006.

[4] S. Chiba, S. Stanford, R. Pelrine, R. Kornbluh, and H. Prahlad, “ Electroactive Polymer Artificial Muscle “, JRSJ, Vol. 24, No. 4, pp 38-42. 2006.

[5] Prahlad, Harsha, Roy Kornbluh, Ron Pelrine, Scott Stanford, Joseph Eckerle, and Seajin Oh, “Polymer power: Dielectric elastomers and their applications in distributed actuation and power generation,” Proceedings of ISSS 2005, International Conference on Smart Materials Structures and Systems, July 28–30, Bangalore, India, 2005.

[6] S. Chiba, T. Sawa, H. Yoshida, M. Waki, R. Kornbluh, and R. Pelrine, “Electroactive Polymer Artificial Muscle Operable in Ultra-High Hydrostatic Pressure Environment”, Submitted to IEEE in 2009

[7] R. Pelrine, R. Kornbluh, J. Eckerle, P. Jeuck, S. Oh, Q. Pei, and S. Stanford, “ Dielectric Elastomers: Generation Mode Fundametals and Applications “, Smart Structures and Matrials 2001: Electroactive Polymer Actuators and Devices, ed. Bar-Cohen, Proc., SPIE, Vol. 4329, pp 148-156, 2001.

[8] S. Chiba, M. Waki, R. Kormbluh, and R. Pelrine, “ Innovative Power Generators for Energy Harvesting Using Electroactive Polymer Artificial Muscles “, Electroactive Polymer Actuators and Devices (EAPAD) 2008, ed. Y. Bar-Cohen, Proc. SPIE. Vol. 6927, 692715 (1-9), 2008.

[9] S. Chiba, M. Waki, K. Masuda, T. Ikoma, R. Kornbluh, and R. Pelrine, “ Consistent Ocean Wave Energy Harvesting Using Electroactive polymer Artificial Muscle Generators “, Submitted to OES, IEEE in 2009

[10] S. Chiba, R. Kornbluh, R. Pelrine, and M. Waki, “Low-cost Hydrogen Production From Electroactive Polymer Artificial Muscle Wave Power Generators”, Proc. of World Hydrogen Energy Conference 2008, Brisbane, Australia, June 16-20, 2008.

[11] S. Chiba, H. Prahad, R. Pelrine, R. Konbluh, S. Stanford, and J. Eckerle, “ Electro Power Generation Using Electro active Polymers (EPAM) “, Proc. of 15th Japan Institute of Energy Conference, pp 297-298, JIE, Kogakuuin University, Japan, August 3-4, 2006

[12] S. Chiba, R. Pelrine, R. Kornbluh, H. Prahlad, S. Stanford, and J. Eckerle, “ New Opportunities in Electric Generation Using Electroactive Polymer Artificial Muscle (EPAM) “, J.Jpn. Inst. Energy, Vol. 86, No. 9, pp 38-42.pp 743-747, 2007.