Wave Energy Converters based on Dielectric Elastomer generators: Status and perspectives

Dielectric Elastomers (DEs) are a very promising technology for the development of energy harvesting devices based on the variable-capacitance electrostatic generator principle. This paper discusses the potentialities of DE technology for advancing the ocean wave energy sector. In particular, three innovative concepts of wave energy converters with DE-based power take-off system are introduced and described.

DOI: 10.12910/EAI2015-049

■ *M. Fontana, R. Vertechy*

Introduction

Among the intermittent renewable resources, ocean-wave power is very persistent and highly spatially concentrated:

- The time-averaged wave-power intensity acting on an area placed just below the sea surface and lying perpendicular to the direction of wave propagation is typically between 2 and 3 kW m^{-2}; that is nearly four times larger than the average wind-power intensity acting on an area perpendicular to the wind direction and nearly ten times larger than the average solar-power intensity acting on a horizontal surface of the earth [1].
- Depending on the specific location, wave-power time-availability ranges between 35% and 70%; that is larger than the typical 30% of wind and 15% of solar resources [1, 2].
- Wave-energy predictability is very reliable within 2 or 3 days; whereas wind-energy can be forecasted only within hours and solar-energy is almost unpredictable [2].

Similarly to off-shore wind, wave-energy provides optimal matching between resource availability and electricity consumption (a large part of the population indeed lives within 90 km off a coastline), features a natural seasonal variability that follows electricity demand (especially in temperate climates alike in Europe), and brings limited environmental impacts with negligible necessity of land usage [2]. In addition, wave resources are usually complementary to wind ones [2], and their absorption and conversion may help the prevention of coastal erosion.

Off the Europe coastline, the average theoretical wave-power potential has been recently estimated in 360 GW (with roughly 75 GW within the Mediterranean regions and 10 GW in the Baltic sea) [3]. Although this is only a small portion of solar and

■ Contact person: Marco Fontana
m.fontana@sssup.it

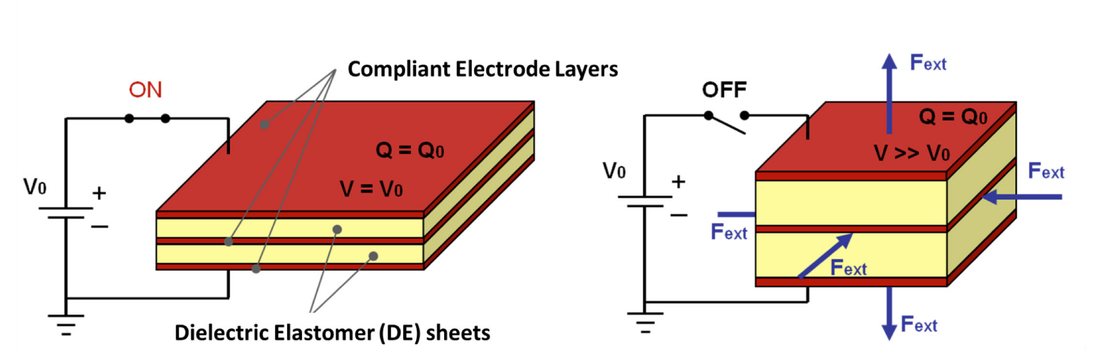

FIGURE 1 Schematic of a multi-layered DET: low electrical-energy and high elastic-energy state with no applied external force (left), high electrical-energy and low elastic-energy state with applied external force (right)

wind resources, for the reasons stated above, wave-power can be a good candidate to cover between 15% and 35% of the intermittent renewable energy mix in the future [2, 4].

Harvesting energy from waves is very challenging:

- ocean wave power is available at high forces and slow speeds (which limits the usability of direct drive generators and requires the adoption of speed reducers);
- machines need to operate well out of their nominal rating conditions;
- machine members must resist to extremely high occasional mechanical loads (especially during storms);
- machine components must resist to a very hostile (in particular, corrosive) environment;
- machines are difficult to install, maintain and test in real operational conditions;
- machine development, construction and testing is very expensive.

As compared to wind and solar, Wave Energy Converter (WEC) technology is still immature, high-risk and cost-uncompetitive [2, 4, 5]. Since the forties in Japan and the seventies in Europe and US, nearly a thousand of WEC concepts have been proposed, and nearly a hundred of reduced-scale physical devices have been constructed and tested both at University laboratories and at spin-off companies. Today, nearly fifteen pre-commercial WECs have been deployed in the ocean for short-duration testing programs, with only few of them having undertaken the first step towards commercialization.

The proposed WEC architectures are rather diverse, and optimal designs have yet to be converged upon [2, 4, 5]. Different systems have been developed for being deployed either off-shore, near-shore or on the shore-line, and which exploit very dissimilar working principles alike (point, multi-body, or large) wave-absorbers, wave-terminators, wave-attenuators, overtopping reservoirs and submerged seabed devices [6].

Irrespective of the architecture, the considered WECs have relied on traditional mechanical components (such as turbines, oscillating plates or heaving buoys), mechanical/hydraulic transmissions and electromagnetic generators (electric machines). Made by stiff, bulky, heavy and costly metallic materials (and rare-earth materials), these components did not succeed in making the proposed WEC designs to overcome all the challenges mentioned above.

To make ocean wave energy exploitable in an affordable manner, a major technological breakthrough is required.

In this context, this paper describes the Dielectric Elastomer Transducer (DET) technology and discusses its potentialities in the wave energy sector. In particular, three novel concepts of DET-based WEC are introduced: the Poly-Surge [12], the Poly-Buoy [13] and the Poly-OWC [14-16].

Dielectric Elastomer Generators

Dielectric Elastomers (DEs) are highly deformable rubber-like solids, which are mechanically incompressible and electrically non-conductive. The sequential stacking of multiple DE sheets separated by compliant electrode layers yields a deformable capacitive transducer (hereafter referred to as Dielectric Elastomer Transducer, or DET in short) that is capable of converting electricity into mechanical energy and vice-versa [9]. Typical materials used as DEs are natural rubbers, silicone elastomers, nitrile rubbers and polyacrylate elastomers (both in unfilled and filled form). Typical materials used for compliant electrodes are silicone compounds filled with conductive particles such as carbon black, carbon nanotubes, copper or silver.

DETs can be used as solid-state actuators, sensors and generators in any kind of machine featuring mechanical members with reciprocating motion [9]. In generator mode, DETs operate via the variable capacitance electrostatic generation principle, thereby increasing the voltage of the charges that lie on the electrodes as the DET capacitance decreases. A schematic of a simple DET generator made by three deformable electrode layers (in red) and two DE sheets (in yellow) is depicted in Fig. 1; the left figure shows the DET in its "low electrical-energy and high elastic-energy" state with no applied external force, whereas the right figure shows the DET in its "high electrical-energy and low elastic-energy" state with applied external force (figure on the right). In the schematic, V_0 indicates the battery voltage, V the DET voltage, Q the DET charge residing on each of its electrodes ($Q = Q_0$), and F_{ext} is an external force acting on the DET.

As shown, a possible operating sequence for a DET to convert mechanical energy into electricity is the following: 1) start from a configuration where DET capacitance is maximum and fully discharged (that is, with the DET having maximum area and minimum thickness as it is shown in Figure 1 on the left); 2) with the DET locked in the same configuration, connect the electrodes to a battery (with electric potential equalling V_0) so as to place there an amount of charge equalling Q_0; 3) as the charging process is completed, disconnect the DET from the power supply; 4) with the supply disconnected, apply the external force F_{ext} to reduce the DET capacitance (which makes the electric potential difference between electrode layers to increase to the value V, with $V >> V_0$); 5) as the capacitance reaches its minimum value, connect the electrodes to an external electric circuit so as to withdraw the charge Q_0 that is at the electric potential V; 6) as the discharging process is completed, bring the DET back to the starting configuration.

During this cyclical process, the amount of mechanical energy that can be converted into electricity equals

$$U=0.5Q_0(V\quad V_0) \qquad (1)$$

In practice, this energy results from the mechanical work that is performed by F_{ext} in a cycle to win the internal forces of electrostatic attraction that exist between oppositely charged electrodes of the DET as the electrodes are being separated. The related energy gain reads as

$$G=\frac{U}{0.5Q_0V_0}=\quad\frac{V}{V_0}\quad 1 \qquad (2)$$

The energy conversion process described above is only one of the possible alternatives. In practice, different energy conversion cycles can be performed by controlling in a different manner the flow of charge that enters/exits the electrodes as a function of DET deformation, with the best controller being the one that enables the regulation of the electric field acting within the DE sheets as the DET deforms [10, 11].

Irrespective of the considered control law, the maximal energy that can be converted by a specific DET in a cycle depends on: 1) type of deformation state (for instance, uniform and equi-biaxial or non-uniform and mono-axial); 2) dielectric strength and permittivity of the employed DE material; 3) elongation at break and stiffness of the employed DE material and compliant electrodes. For practical DETs, which feature:

- deformations up to 700% and Young's modulus in the range 0.01-20 MPa;
- dielectric strength in the range 20-400 MV m^{-1} and permittivity in the range 1.8-7;

typical values for the energy gain range between

3 and 15, which are significantly larger than those achievable with piezoelectric ceramics.

Due to the low mass density of DE materials (nearly 1000 kg m^{-3}), values for the energy density of DETs (namely, the amount of energy converted in a cycle per kilogram of transducer) typically range between 0.1 and 2 kJ kg^{-1}, which, for generators operating at low frequencies (for instance, at less than 1 Hz), compare very well (and sometimes are even better, especially as the operating frequency is smaller) with that of traditional electric machines.

Beside good energy density, other advantageous properties of DETs that could make them the optimal choice for the development of machines that generate electricity from low-frequency reciprocating motions are:

- rather good electromechanical conversion efficiency (usually in the range 60-90%);
- moderate or low cost (100 €/kg for small batches and less than 10 €/kg for large batches);
- solid-state monolithic embodiment with no sliding parts and very low internal friction;
- easy manufacturability, assembling and recyclability;
- good chemical resistance to corrosive environments;
- silent operation and no need of lubrication.

Wave Energy Converters based on Dielectric Elastomers Transducers

In ocean waves, energy travels without any substantial overall motion of water. In fact, as a wave passes, water particles undergo orbital motions, with the energy of this movement being transmitted to succeeding water particles in a progressive manner. As such, ocean wave energy is available in both kinetic and potential forms; to be harvested, it requires machine elements undergoing slow reciprocating motions and capable to withstand large forces/torques. In addition to motion and force requirements, machines (and components) for the conversion of ocean wave energy into electricity should also feature: good electro-mechanical conversion efficiency (in both directions); high impact and corrosion resistance; lightness and compactness; easy manufacturability and low cost; silent operation.

As described in the previous section, all these application requirements are perfectly matched by the properties of DETs, which are now opening a new frontier for the ocean wave energy sector.

Three very promising concepts of DET-based WECs are the polymeric wave-surge (Poly-Surge), the polymeric buoy (Poly-Buoy) and the polymeric oscillating water column (Poly-OWC) systems. Their concepts, operating principles and peculiarities are described in the following.

Poly-Surge sea-Wave Energy Converter

A first WEC architecture that could be suited for sea-wave energy harvesting via DETs is the oscillating flap. This type of system consists of a buoyant flap

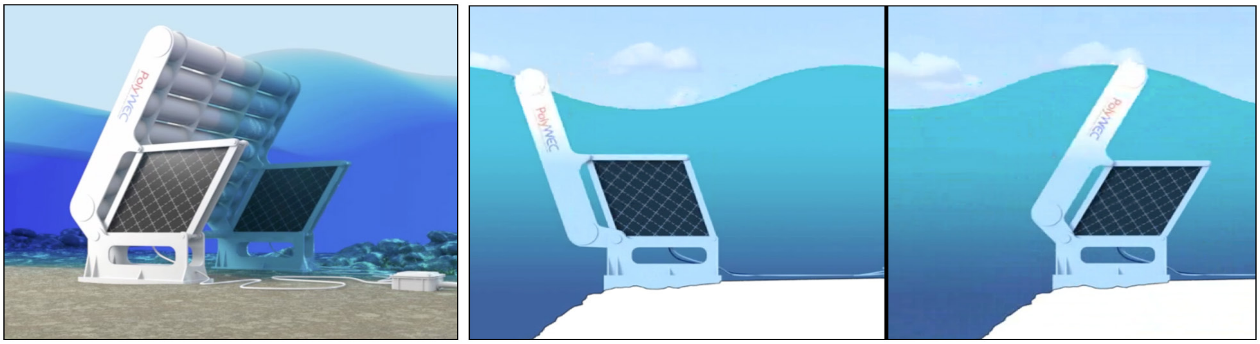

FIGURE 2 Poly-Surge – Oscillating Flap with a lozenge DET

hinged at the sea bottom and exploits the surging motion of waves. In traditional systems (such as the Oyster device by Aquamarine Power) the wave-induced oscillatory motion of the flap is used to pump water to the coast via hydraulic pistons and high-pressure flow lines. At the coast, the high-pressure water is then converted into electricity via a turbo-generator.

Replacement of the hydraulic power take-off system (and of the turbo-generator) with lozenge DETs [12, 13] could enable local conversion of wave energy into electricity without requiring any mechanical or hydraulic transmission. Besides simplifying the system and reducing part count, this replacement could improve system efficiency, simplify installation and reduce the noise pollution emitted at the coast by the turbo-generator.

An artistic drawing of a Poly-Surge WEC is reported in Figure 2.

Since they need to be attached to the seabed, Poly-Surge WECs are suited for near-shore installations at a nominal depth of nearly 10 m, possibly at locations where shoaling effects occur. At this depth, wave energy resource is still very significant, and usually characterized by limited maximum wave heights (due to wave breaking) and limited directional spread between longer and medium period waves.

As for the operating principle, Poly-Surge systems are excited by horizontal fluid accelerations mainly. Due to physical constraints in the oscillatory motion of the flap, Poly-Surge systems are likely to be not resonant in the working frequency range, and should be designed to maximize wave excitation force and to move at speeds that are adequate to limit vortex losses at the edges.

More details on Poly-Surge architecture, functioning principle, design issues and potential performances can be found in [12, 13].

Poly-Buoy sea-Wave Energy Converter

A second WEC architecture that could be suited for wave energy harvesting via DETs is the oscillating buoy. An oscillating buoy WEC consists of a floating body, either submerged or semi-submerged, that moves under the action of sea waves with respect to an appropriate number of submerged and nearly fixed reaction points.

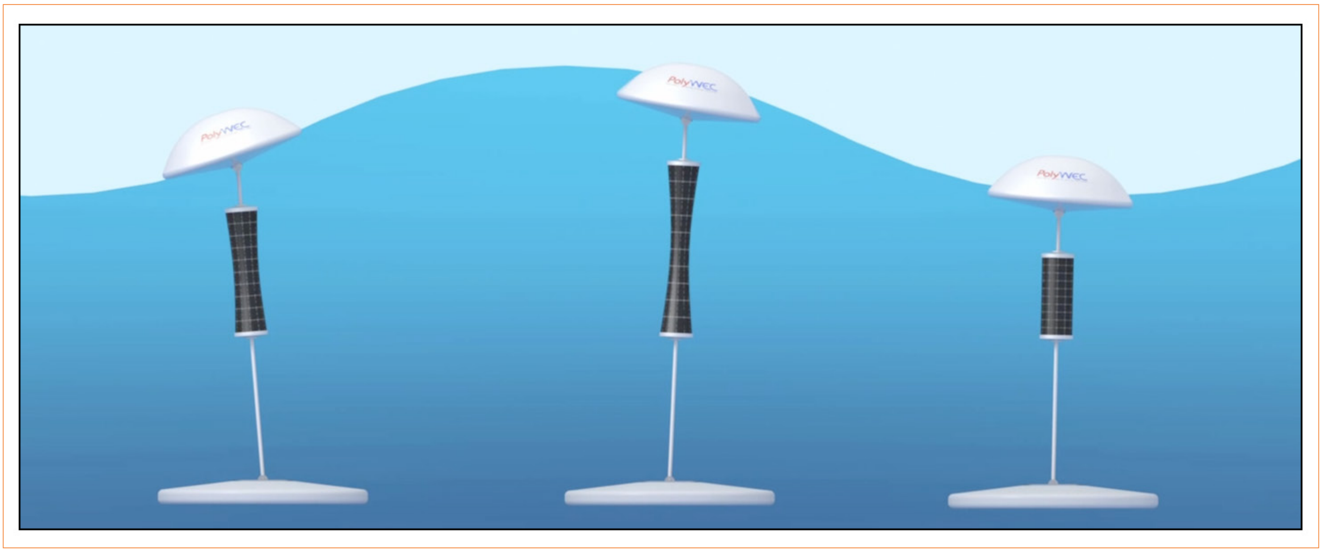

FIGURE 3 Poly-Buoy – Oscillating Buoy with a cylindrical DET

Depending on the water depth of installation, the reaction points can be located either on the seabed or on a floating body (namely a reaction body) that is submerged enough not to be excited by the wave field. Depending on the means of connection to the reaction points, the wave-induced oscillatory motion of the buoy can be in heave, surge or pitch (or a combination thereof).

During these oscillations, the distances between points of the buoy and those of reaction vary. These reciprocating changes in length can be used by power take-off systems with linear motions to extract energy from waves. As alternative to the traditional hydraulic rams or linear electrical generators, cylindrical DETs can be used for this purpose. Depending on the size of the device, the considered DET can be placed either inside the buoy, close to the reaction points (in particular on the seabed or inside the reaction body) or along the line connecting the reaction points and the buoy.

An artistic drawing of a Poly-Buoy WEC is reported in Figure 3.

In terms of hydrodynamic properties, Poly-Buoy systems are point absorbers that can be installed both on-shore and off-shore. For standard buoy shapes and aspect ratios, Poly-Buoys are likely to be designed so as to be resonant in the working frequency range, which makes their performances very sensitive to the intrinsic passive stiffness of the DET.

More details on Poly-Buoy architecture, functioning principle, design issues and potential performances can be found in [14].

Second-generation DET-based WECs

In this section, one concept of second-generation device is introduced and described.

Poly-OWC sea-Wave Energy Converter

Oscillating Water Column (OWC) wave energy converters are based on the reciprocating motion of a column of water enclosed in a chamber (tube or duct) that has at least one submerged opening. The water inside the closed chamber is moved by wave-induced oscillating pressures acting on this opening. In traditional OWC concepts, the movement of the oscillating water column induces a pressure variation inside a closed air chamber; such a pressure variation is used to drive a turbo-generator, which converts the stored pneumatic power into usable electricity. Due to reciprocating air-flow, energy harvesting from traditional OWC devices requires either a self-rectifying turbine or a complex system of non-return valves that makes it possible to rectify the flow passing through a conventional turbine.

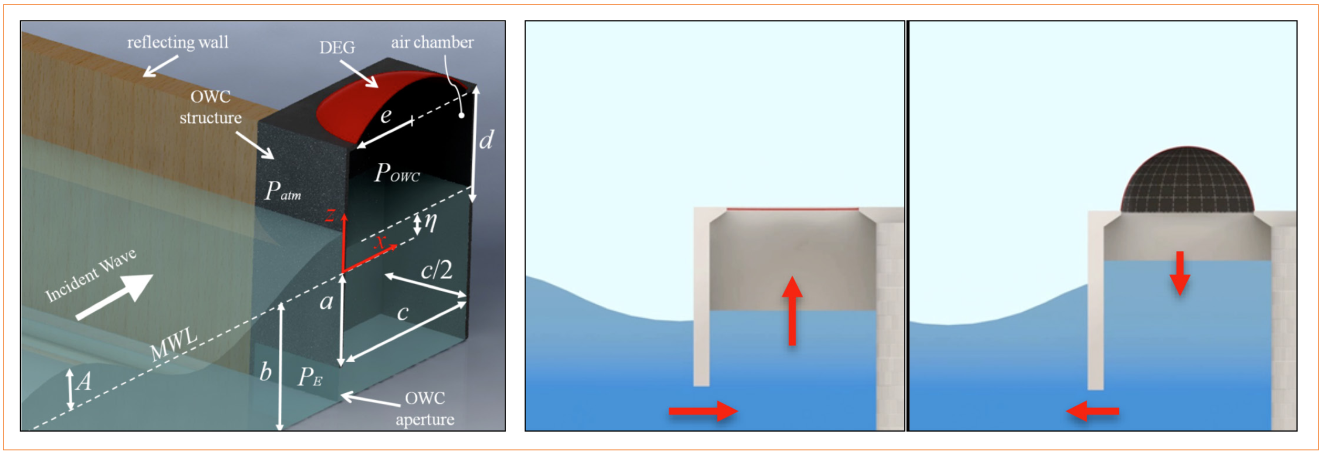

FIGURE 4 Poly-OWC – Osclillating Water Column with inflating circular diaphragm DET

In OWCs, replacement of the turbo generator by an inflating diaphragm DET could significantly simplify overall system architecture and installation, improve overall energetic efficiency and climate adaptability, and reduce operating noise.

An artistic drawing of a Poly-OWC WEC is reported in Figure 4.

In terms of hydrodynamic characteristics, Poly-OWCs can be installed both on the shore-line (with fixed structure) and off-shore (with floating structure); specifically, they are very suited for being integrated into breakwaters for harbour protection. For standard chamber shapes and aspect ratios, Poly-OWCs are likely to be designed so as to be resonant in the working frequency range, which makes their performances very sensitive to the intrinsic passive stiffness of the DET. Thanks to the presence of an air pocket, the dynamic response of a given Poly-OWC can be tuned to the prevalent frequency content of the incoming waves by simply acting on steady-state chamber pressurization.

More details on Poly-OWC architecture, functioning principle, design issues and potential performances can be found in [15-17].

Conclusions

This paper presented three different concepts of Wave Energy Converters (WECs) that employ Dielectric Elastomer Transducers (DETs) to convert ocean wave power into direct-current high-voltage electricity. As compared to traditional WECs with hydraulic or electromagnetic power take-off system, the presented machines offer the following potential features: reduced capital costs; easy installation and maintenance; good shock and corrosion resistance; good energy conversion efficiency; good climate adaptability; reduced noise during operation.

As of today, DET technology is however not yet ready to deliver fully-functional WEC systems that are capable to operate in real seas for sufficiently long periods of time. In this perspective, critical issues that need to be addressed are: assessing the long-term fatigue, ageing, degradation and reliability of the employed materials; conceiving better dielectric elastomers and conductive electrodes with improved electromechanical transduction properties and reduced dissipative effects; developing better design, optimization and control methodologies; conceiving alternative system architectures with reduced part counts and integrating multiple functionalities in single components.

Acknowledgements

The work presented in this paper is developed in the context of PolyWEC (www.polywec.org) an FP7 FET–Energy project. The research leading to these results has been funded from the European Union Seventh Framework Programme [FP7/2007–2013] under grant agreement n° 309139.

Marco Fontana
Scuola Superiore Sant'Anna, Perceptual Robotics Laboratory (PERCRO), Pisa, Italy

Rocco Vertechy
University of Bologna, Department of Industrial Engineering, Italy

references

[1] M. Leijon, A. Skoglund, R. Waters, A. Rehn, M. Lindahl, 2010, On the physics of power, energy and economics of renewable electric energy sources, in Renewable Energy, 35, pp. 1729–1734.

[2] Oceans of Energy – European Ocean Energy Roadmap 2010-2050, European Ocean Energy Association, 2009.

[3] G. Mork, S. Barstow, A. Kabuth, M.T. Pontes, Assessing Global Wave Energy Potential, in Proc. of 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering, OMAE2010, China, 2010.

[4] Future Marine Energy: Cost Competitiveness and Growth of Wave and Tidal Stream Energy, Carbon Trust, 2006.

[5] Implementing Agreement on Ocean Energy Systems - Annual Report 2010 and 2011, International Energy Agency, 2010 and 2011.

[6] A.F.O. Falcao, Wave energy utilization: A review of the technologies, in Renewable and Sustainable Energy Reviews, 14, pp. 899–918, 2010.

[7] Annual Energy Outlook 2010 With Projections to 2035, Energy Information Administration, 2010.

[8] J. Huckerby, A. Brito Melo, International Vision on Ocean Energy Systems, WavEC Seminar 2011: Offshore Renewable Energy and its Potential for the Outermost Regions, Portugal, 2011.

[9] F. Carpi, D. De Rossi, R. Kornbluh, Dielectric elastomers as electromechanical transducers: Fundamentals, materials, devices, models and applications of an emerging electroactive polymer technology, Elsevier Science, 2008.

[10] R. Pelrine, R. Kornbluh, J. Eckerle, P. Jeuck, S. Oh, Q. Pei, S. Stanford, Dielectric elastomers: Generator mode fundamentals and applications, in Proc. SPIE, Vol. 4329, pp. 148-156, 2001.

[11] A. Koh, C. Keplinger, T. Li, S. Bauer, Z. Suo, Dielectric elastomer generators: How much energy can be converted?, in IEEE/ASME Transactions on Mechatronics, 16(1), pp. 33–41, 2011.

[12] G. Moretti, D. Forehand, R. Vertechy, M. Fontana, D. Ingram, Modeling of an oscillating wave surge converter with dielectric elastomer power take-off, in Proc. of ASME 33rd International Conference on Ocean, Offshore and Arctic Engineering, Paper No. OMAE2014-23559, San Francisco, CA, USA, 8-13 June, 2014.

[13] G. Moretti, M. Fontana, R. Vertechy, Parallelogram-shaped dielectric elastomer generators: Analytical model and experimental validation, in Journal of Intelligent Material Systems and Structures, first published on December 19, doi:10.1177/1045389X14563861, 2014.

[14] G. Moretti, R. Vertechy, M. Fontana, Modelling of a heaving buoy wave energy converter with stacked dielectric elastomer generator, in Proc. of ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, Paper No. SMASIS2014-7565, Newport, Rhode Island, Sept. 8-10, 2014.

[15] R. Vertechy, M. Fontana, G.P. Rosati Papini, M. Bergamasco, Oscillating-water-column wave-energy-converter based on dielectric elastomer generator, in Proc. of SPIE, Vol. 8687, pp. 86870I-86870I, 2013.

[16] R. Vertechy, G.P. Papini Rosati, M. Fontana, Reduced Model and Application of Inflating Circular Diaphragm Dielectric Elastomer Generators for Wave Energy Harvesting, in ASME Journal of Vibration and Acoustics, 137(1), pp. 011004 (9 pages), doi:10.1115/1.4028508, 2015.

[17] R. Vertechy, M. Fontana, G.P. Rosati Papini, D. Forehand, In-tank tests of a dielectric elastomer generator for wave energy harvesting, in Proc. of SPIE, Vol. 9056, pp. 90561G, 2014.