Direct Contact Dielectric Elastomer PTO for Submerged Wave Energy Converters.

WES Power Take Off Stage 1 Project Public Report

Scuola Superiore Sant'Anna

This project has been supported by Wave Energy Scotland

1 Project Report

1.1 Project Introduction

This project aims at developing a breakthrough technology for the direct conversion of oscillating mechanical energy of ocean waves into electricity through the employment of dielectric elastomer generators (DEGs). Such technology allows the merging of several conventional components of a Wave Energy Converter into a single, solid state, highly deformable body that interacts directly or indirectly with the hydrodynamic forces of ocean waves.

Such a new generation of conversion system potentially features: low mass density (close to 1000 kg/m^3); large deformability (deformations up to 700% and Young's modulus in the range 0.01-20MPa); high energy density (usually in the range 0.1-3.5 kJ/kg); large break-down strength (usually in the range 20-400MV/m); moderate (relative) dielectric permittivity (usually in the range 1.8-7); rather good electro-mechanical conversion efficiency (usually in the range 40-90%); 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.

This new generation of conversion system is extremely promising from the point of view of efficiency and low cost. However, it is still on a low level of technological readiness and studies/advances are required on various different aspects to obtain solutions that are effective for both performance and reliability.

Within this project, investigations have been conducted on the optimization/improvement of a specific configuration of a DEG based WEC, in which the DEG is in direct contact with the water. Modelling and tank-tests have been undertaken to evaluate the performance of the system. Additionally, a preliminary testing campaign has been initiated to assess the reliability of these converters.

The project has been managed by Scuola Superiore Sant'Anna, an Italian university that is conducting research on DEG for wave energy conversion since 2012. The activities have been conducted in collaboration with University of Bologna, which provides contributions on material testing and modelling thanks to their expertise in dielectric elastomer materials characterization, and University of Edinburgh, which provides contributions on tank testing of ocean energy devices.

1.2 Description of Project Technology

This project aimed at the investigation of a new Power-Take-Off (PTO) system for Wave Energy Converters that is based on Dielectric Elastomers Transducers (DETs). Among the various electro-active polymers, DET technology is one of the most promising and is the one having the highest technological readiness level.

Dielectric Elastomers (DE) are electrically insulating, incompressible polymeric solids that undergo finite elastic deformations. Stacking multiple DE films separated by compliant electrodes makes a deformable capacitor transducer, namely the DET, that can be used to convert mechanical energy into direct electricity and vice-versa.

DETs can be used as actuators, sensors and generators. In generator mode (hereafter referred to as DEGs), DETs operate via the variable capacitance electrostatic generation principle.

DEGs acts as charge pumps; that is, they increase the voltage of the charges that lie on their electrodes as they recover from a deformation. The basic working principle of DEGs can be described as it follows: 1) starting from an initial slightly deformed configuration and with no charge residing on the DEG electrodes, the DEG is stretched up to its maximum deformation; 2) as the DEG reaches this configuration, that corresponds to the maximum value of its capacitance, the DEG is activated by charging it via an external power supply; 3) after charging, the DEG is disconnected from the power supply and it is brought back to its initial slightly deformed configuration. In this third phase, the capacitance of the DEG decreases so that the charge that lies on the DEG electrodes is forced to increase its electric potential. This increase in electrical energy that is stored in the DEG occurs at the expenses of the forces that are required to bring the DEG back to its initial slightly deformed configuration. As the third phase is completed, the electrical energy stored in the DEG can be extracted and made available to an end user.

Since DEGs are incompressible and since they can undergo very large deformations, during operation DEGs can vary their capacitance by more than ten times. This means that the energy that can be converted by the DEG is more than ten times the energy that is required for its initial activation. Since the dielectric strength of the DEG can be very large and since its specific weight and cost are low, DEG can feature very large energy conversion densities and rather low capital cost. Due to the capacitive nature, DEGs are electrostatic generators and their efficiency is rather independent of the speed of deformation (thus, it is rather independent of cycle frequency and amplitude). Given the electrostatic generation principle and the resistance to large electric fields, DEGs can produce direct current electricity at high voltages; in particular at values that directly match those required by electric power transmission lines without requiring a step-up converter.

In summary, as compared to other energy generation technologies (such as electric machines) DEGs feature the following properties/performances: low mass density (close to 1000 kg/m3); large deformability (deformations up to 600% and Young’s modulus in the range 15-500kPa); high energy density (in the range 0.1-3.5kJ/kg); large break-down strength (in the range 30-400MV/m); moderate (relative) dielectric permittivity (in the range 1.8-7); rather good electro-mechanical conversion efficiency that is rather independent of cycle frequency and amplitude (theoretical efficiency can be larger than 90%); moderate or low cost (between 5£/kg and 15£/kg); solid-state monolithic embodiment with no sliding parts and with limited internal friction; possibility to be conformed into any shape to fit machine space availability; good chemical resistance to corrosive environments; silent operation and no need of lubrication; easy manufacturability, assembling, deployment and recyclability; integrated generation and sensing capabilities. Thanks to the features mentioned above, DEGs could provide the technological breakthrough that is required to make wave energy exploitable.

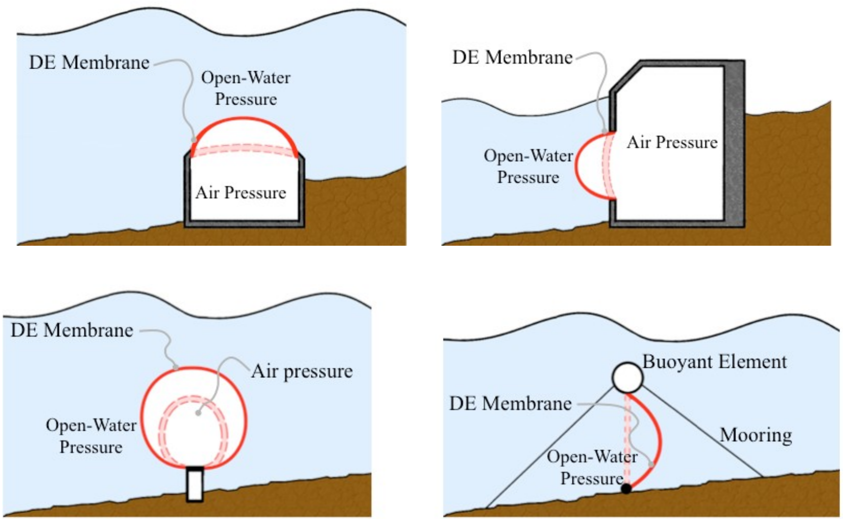

Figure 1 Schematics of possible implementations of DEGs in direct contact with water and acting as energy conversion element and as primary interface at the same time.

Different possible concepts of wave energy converter may exist that exploit DEGs as both mechanical-to-electrical energy conversion system and primary interface (examples are shown in Figure 1). In the context of previous projects run by the partners, a novel concept of direct contact device has been developed and a Patent request has been filed. The concept is based on the scheme depicted in the top pictures of Figure 1. The system consists in a hollow structure (made of steel, concrete or other rigid material) with one submerged opening closed by a DEG membrane. The system is intended to be installed on the shore-line or near-shore with the structure firmly attached to the sea bottom. It can be integrated into an existing breakwater or it can be used to build new ones, thereby having the potential to deliver the added benefit of electricity production to marine structures principally intended to provide safe harbourage, prevent coastal erosion or protect gently sloping beaches. The structure can be only partially submerged (as in the top-right picture) or fully submerged (as in the top-left figure). The chamber enclosed by the rigid structure and the DEG membrane can be: 1) filled with air or water and connected to the ambient air pressure; 2) closed and filled with pressurized air. The membrane can be arranged orthogonal (as in the top-right picture) or parallel (as in the top-left picture) to the wave direction or an in any inclined orientation in between. Irrespective of the configuration, the working principle of the considered DEG-based WEC is the following: as the wave arrives/passes, time varying pressure differences are induced between the surfaces of the DEG which make it expand in area; this deformation is used to generate electricity according to the electrostatic principle described before (and represented in Figure 1). The system can be deployed as single unit or in an array. In case of an array of on-the-shore devices, the units are placed in parallel along the direction of the shore line. In case of an array of near-shore devices, the arrangement can also be in series with respect to the prevalent direction of the waves.

The previously conceived embodiment has been improved with a specific hydrodynamic solution that has been studied and tested in this project. An optimized scaled model of the device has been developed and tested in a wave tank in both regular and irregular waves to verify system performances, and also in extreme sea states to verify system survivability. Additionally, experimental investigations on the fatigue-lifetime of DEGs has been conducted to find practical values which will be used for the assessment of this new technology.

1.3 Scope of Work

The Project aimed at assessing the feasibility and identify the main potentialities of the WEC concept presented in the previous section. The work developed in this project included both modelling and experimental activities. The tasks were organised in three main work packages (WP):

- WP1 “Modelling and test design/plan” which aimed to the formulation of mathematical models and to the design of experimental setup for running tests: on the basis of the previous modelling experience acquired by the partners of the project a hydrodynamic model of the device that includes the aforementioned hydrodynamic improvements has been developed.
- WP2 “Testing” that is dedicated to the testing activities both on dry-run and wave-flume test-benches that were required to get data respectively on hydrodynamic response and reliability performances.
- WP3 “Analysis and assessment” that aims at the development of the necessary analysis of experimental data and the evaluation of the performances of the proposed system.

1.4 Project Achievements

Project achievements are schematically summarised in the following table:

Category	Achievement	Impact	Recommendations
Modelling activities	The models developed to forecast and design the hydrodynamic improvements have been successfully developed and validated against experimental results.	An important tool for future development, optimization studies and design is now available.	Future projects should make use of this simulation tool and refine/improve it where necessary.
Experimental activities	In-tank tests have been successfully completed providing a fundamental feedback for the validation of hydrodynamic models.	The experimental validation enables the future employment of these models for the design improvement and the study of possible different architectures.	No recommendation
Experimental activities	First insights on the fatigue lifetime of Dielectric Elastomer Generators (DEGs) have been provided by the experimental campaign and the analysis of data based on recognized procedures.	An estimation of the relationship between dielectric elastomer material performances and fatigue lifetime has been provided showing the compatibility of DEG technology with the typical requirements of WEC systems.	Results of these tests should be considered for future system developments and techno-economic studies.

Concept verification	The proposed WEC concept demonstrated very promising performances. In particular, as it was expected, the introduction of shape modifications improved the wave force capture and the response of the system in the low wave-frequency range.	This improvement enables to build up a simplified road-map that could go through the development of a first generation of devices that feature smaller dimensions and, consequently, a reduced capital costs for their deployment.	Future developments should consider the proposed WEC concept as well as other solutions that are intended to further improve it.
Management	Smooth interaction between contractors and client both on technical, contractual and financial issues. Specifically, interaction through physical, email exchange and the Objective Connect tool.	Developments and communications have been smoothly managed.	Future projects might consider a similar form of interaction between clients and contractors.

During the project there have been also few issues that could have been managed in a better way. These issues are summarised in the following table.

Category	**Issue**	**Impact**	**Recommendations**
Experimental issues	A problem has occurred in one of the two experimental setups. Specifically, the commercial high voltage power supply that has been purchased for the fatigue testing setup went out of order during the tests due to unknown reasons.	A delay of roughly one month on the activity with respect to the initial plans has been recorded due to this issue.	In the future, experimental setups should consider the use of components with significantly oversized ratings and the purchase of back-up parts in order to avoid similar occurrences.

Choice of materials	A specific commercial material that was initially considered as the best-choice for the deformable dielectric showed sub-optimal response due to its limited deformation capabilities.	The impact of this issue was mitigated by the decision of testing different types of materials that made it possible to identify the most promising ones. Among them a very good candidate was found in a styrene-based rubber.	Future research should consider the outcomes of the tests conducted on different materials and the intrinsic limitations that have been identified for some of them.

1.5 Applicability to WEC Device Types

WEC technologies that are compatible with the DEG-PTO are reported in the following table starting from the ones that have stronger potential to the ones that are practically not compatible according to the current state of the technology.

Device Family	**Applicability (Y/N)**	**Comments**
Oscillating Water Column (OWC)	Y	Study of this concept has been performed in the context of previous project.
Submerged Pressure Differential	Y	Study of this concept has been performed in the context of WES PTO Stage 1 project.
Point Absorber	Y	A DEG cylinder, which varies its capacitance as it is stretched/compressed in the axial direction by the relative motion of two floats. As of to date, this concept is being investigated by BOSCH company.
Bulge Wave	Y	In this application, the DEG will coincide with the flexible tube, thereby acting as both prime mover and energy conversion system). The company SBM is investigating this concept under the name “Standing wave tube electro active polymer wave energy converter”.
Attenuator	Y	DEG technology might also be used to convert the mechanical energy of higher pressure fluids such as those pumped by the hydraulic rams that are employed in attenuator type WECs like the Pelamis.
Oscillating Wave Surge Converter	Y	DEG technology might also be used to convert the mechanical energy of higher pressure fluids such as those pumped by the hydraulic rams that are employed in attenuator type WECs like the Oyster.
Rotating Mass	N	-

Overtopping/Terminator	N	-

1.6 Summary of Performance against Target Outcome Metrics

In the context of this Project, an improved hydrodynamic design of the proposed DEG-based concept has been studied, which makes use of purposely designed collector shapes that are dimensioned in combination with the main DEG-PTO. A small-scale prototype of the device has been realised for wave-tank testing in Edinburgh University Curved Wave-Tank. This prototype has been tested in three different shapes and two different types of DEG membranes, one made of commercial silicone elastomer and the other of commercial styrenic rubber. Regular (monochromatic) and irregular (panchromatic) wave tests have been performed. Tests have been completed and dataset have been acquired and post-processed. Preliminary observations confirm a relevant positive influence of the introduced modifications in the hydrodynamic response of the system for both the tested DEG membranes. A further qualitative comparison of the deformation of the DEG for the two different materials leads to the conclusion that the deformability of the silicone elastomer membrane is largely smaller than that of styrenic rubber membrane and it is too limited to be effective in this configuration. The results have been evaluated in detail and compared to models predictions showing acceptable matching.

Regarding reliability studies, a setup for a preliminary analysis of the failure of the employed DE material due to high-cycle electrical loading has been developed. The setup has been conceived to obtain consistent information on a sufficiently large quantity of DEG specimens subjected to numerous loading cycles in a limited testing-time (one/two month). Given the clear superior performances of the styrenic rubber membrane observed during the tank testing, a decision has been taken to focus the fatigue testing on this material in order to have an in-depth analysis of its response. Tests have been completed and dataset have been acquired and used to identify the parameters of the Weibull distribution models for the cumulative probability of electrical breakdown. Extrapolations performed with these models highlighted that the considered styrene-based rubber (commercialized under the brand Theraband Yellow 11726) is suited for WEC application, having the potential to exhibit a mean-cycle-between-failure (MCBF) in the order of millions of cycles when operated at the electric field values required by ocean wave energy systems.

1.7 Communications and Publicity Activity

Type	Title, Authors	Event, Place, Date
Poster	A Roadmap towards Implementation of Wave Energy Converters based on Dielectric Elastomers, Moretti, G.1 *, Vertechy, R.2, and Fontana, M.1	Offshore Energy & Storage Symposium and Industry Connector Event. Malta 13-15 July 2016
Presentation	Modellazione e progetto di macchine innovative per la produzione di elettricità da fonti rinnovabili. M. Fontana.	Seminar of the Italian Association of Mechanisms of Machines. 21-22 luglio 2016, Università degli Studi di Napoli Federico II

Presentation	Direct contact dielectric elastomer PTO for submerged wave energy converters PTO –Stage 1	WES Inception Workshop, 17-18 Nov 2015 ,Glasgow
Poster	Poster presentation.	WES Novel Wave Energy Convertor Workshop. 18-19 April 2016, Glasgow.
Presentation	Overview of Dielectric Elastomer Technology for Wave Energy Converters	"Green Ports" Event, Reggio Calabria, 28 Jan 2016
Presentation	High performance dielectric elastomer generators based on synthetic rubber**,**	SPIE. Smart Structures/NDE, Las Vegas, 20-24 March 2016

1.8 Recommendations for Further Work

In the project, a clear roadmap for the commercial development of the technology has been drafted that considers a gradual scaling up of the system.

The key areas that requires research and development efforts are:

- improve the modelling by taking into account in an accurate manner the dissipative contributions of the finite electrical resistance of electrodes and the non-zero electrical conductivity of dielectrics and improving the coupled response of fluid-elastomer interaction;
- develop a larger scale (in the range of 4-10 W) laboratory Hardware In the Loop (HIL) prototype that makes it possible to implement a fully functional control electronics and to test control strategies;
- develop real-time models that can be employed to control such HIL prototype and the custom power control electronics that is able to efficiently charge and discharge the DEG;
- perform further reliability tests to obtain more extensive datasets (specifically, with samples tested for longer periods of times);
- Investigate scalability issues (e.g. with samples of larger sizes);
- assess the fatigue lifetime of specific DEG-PTO architectures (including the durability of dielectric-electrode interfaces under mixed electro-mechanical solicitations).