Inflatable Dielectric Elastomer Generator PTO

WES Power Take Off Stage 2 Public Report

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This project has been supported by Wave Energy Scotland

Project Introduction

This project focusses on the advancement of a novel wave energy converter based on Dielectric Elastomer Generators (DEGs) technology. This device has been initially conceived within the project PolyWEC funded by the European Commission, and it was further developed the Stage 1 WES-PTO Project.

This document summarizes the lessons learned during the project “Direct contact dielectric elastomer PTO for submerged wave energy converters” in order to capture the project’s positive and negative aspects for use by other similar future projects.

The Project is supported by Wave Energy Scotland under the PTO call Stage 2 and it is developed by a team of researcher of Scuola Superiore Sant’Anna - SSSA (Pisa, IT), University of Bologna - UNIBO (Bologna, IT) and the University of Edinburgh - UEDIN (Edinburgh, UK) and the company CHEROS Engineering (Pisa, Italy).

The purpose of the lessons learned document for the project “Direct contact dielectric elastomer PTO for submerged wave energy converters” (here below called the Project) is to capture the project’s lessons learned for use by other similar future projects.

This document may be used as part of new project planning for similar projects in order to determine what problems occurred and how those problems were handled and may be avoided or mitigated in the future. Additionally, this document details positive and particularly successful aspects of the Project and why, so that future projects may capitalise on these actions.

Description of Project Technology

Dielectric Elastomers (DEs) are multifunctional polymeric materials that are employed to conceive light-weight and low-cost electro-mechanical transducers. From a functional standpoint, DEs are dielectric media, usually shaped in films or membranes, which are coated by compliant electrodes to form variable capacitance electrostatic devices. Such devices can be both employed as actuators or generators. Materials typically employed as DEs are natural and synthetic rubber, silicones and acrylic polymers.

DE Generators (DEGs), in particular, are solid-state devices capable of converting mechanical work (provided by an external energy source) into high-voltage direct current electric energy. With reference to a single layer of DE material (with a couple of electrodes), the cyclic energy conversion principle is as follows: mechanical work from external loads provokes a deformation of the DEG from an initial configuration to a maximally stretched configuration, in which the device has maximum capacitance. The device is instantly charged (spending an amount of electric energy, namely activation energy), and it is then forced to return to its undeformed shape. In this passage, DEG capacitance progressively increases, and external forces make work against electrostatic forces. Once undeformed, the DEG is discharged, stored electrostatic potential energy is recovered, and a net gain of electrostatic energy is obtained.

Recently, interest towards DEGs has grown thanks to their potential application as Power Take-Off (PTO) systems in Wave Energy Converters (WEC). In fact, DEs may allow to conceive simplified WEC architectures, free from heavy and bulky components and capable of converting wave energy into direct current electricity within a wide range of operating sea conditions.

Practical application of DEGs for WEC PTOs has been attempted in a limited number of projects.
The European project PolyWEC, in particular, has driven attention towards this topic proposing a number of DEG-PTO architectures, setting-up modelling approaches, and carrying out experimental tank tests and techno-economic projections. Concepts proposed within PolyWEC are both based on existing WEC architectures

(heaving buoys, pitching flaps, oscillating water columns) with new DEG-PTOs, or completely new WECs, namely Direct Contact (DC) DE-WECs, in which the deformable DEG unit (directly contacting sea water) is the only movable part of the device, thereby integrating primary interface and energy conversion functions in one single element.

In the framework of this project, a specific DC-DE-WEC has been studied, which exploits a particularly promising hydrodynamic layout, in which a submerged circular DEG is installed on top of a closed submerged air chamber and in contact to sea water through its upper face. This device, that takes the name of DRUM-WEC, has been conceived by the partners of this project in the framework of the abovementioned EU project PolyWEC, and was further developed in the stage 1 project. The DRUM-WEC has demonstrated interesting potentially allowing large deformations of the PTO even in presence of relatively modest wave-induced loads.

In this Project, a broader approach is assumed and the focus is set on the general advancement of the PTO technology. Specifically, the aim objectives of the Stage 2 project are:

1) Long term assessment of DEG-PTO performances and failure mode analysis: data for understanding the electrical-stress life of the ECU membrane are required together with results on the degradation of ECU energy conversion density, efficiency and response. These data are necessary to define appropriate admissible loadings for the ECU membrane. In the Stage 1 project, preliminary electrical-stress life data have been obtained by a first campaign of limited duration (4-5 weeks) carried out on a
selected promising material. In a Stage 2 project, it is proposed to further improve these results with tests of longer duration and to proceed also with the long-term testing of DEG-PTO components (assembled ECU and power electronics) so as to investigate performance degradation and modes and rates of failures of DEG-PTO principal components.
2) Design and manufacturing of larger scale prototype and implementation/tests of improved controllers: up to this stage small scale prototypes with sub-optimal controllers have been implemented. In this Project, a specific prototype of the DEG and the related setup for hardware in the loop testing is going to be implemented.
3) Definition of commercialisation roadmap: a commercialisation roadmap with a detailed plan for the future commercial and deployment has been drawn in the Stage 2 project.

Scope of Work

In this Stage 2 project several advancements have been achieved including the following major results:

- The realization and test of an upscaled prototype of the PTO in a scale range of 1:15 to 1:25;
- The definition of a manufacturing procedure for DEG systems;
- The realization and test of a preliminary prototype of the control electronics;
- The development of an upscaled hardware in the loop (HIL) setup;
- The validation of the HIL setup against (previously) available tank test data;
- The test in HIL of some simple but yet effective control strategies for the DEG-PTO system;
- The characterization of reliability and lifetime response of DEG-PTO components through a campaign of repetitive cyclical tests;
- The improvement of the technoeconomic study of the novel PTO system

Project Achievements

Modelling activities:

The models that were settled for Stage 1 project have been further developed including the important aspects of 1) leakages due to imperfect insulation of dielectric materials; 2) more realistic model of the power/control electronics. This means that an important tool for future development, optimization studies and design is now available.

Experimental activities:

A novel custom setup that is able to run hydrodynamic simulations and drive the DEG-PTO accordingly has been developed. The system dynamic response was first validated against a set of wave-tank experiments conducted in a previous project. To this aim, a simulated hydrodynamics of the same WEC employed in the experiments has been created in order to feedback signals to the real-model of the PTO. This system makes it possible to test different types of DEG-PTOs coupled with different WEC hydrodynamics.

Demonstration of simple but effective sensing and control strategies. The developed control strategy is based on the employment of a single pressure sensor that is employed to trigger the charge controller. This sensing procedure is suboptimal but provides results that are already a large fraction of the maximum harvestable energy that is theoretically achievable. This demonstrates the controllability of the system even if several margins of improvement are still possible.

The Styrene-Butadiene Rubber that was initially considered as the most promising material for DEG-PTO implementation demonstrated a sub-optimal response to long-term cyclical electrical loads. This behaviour can be attributed to manufacturing imperfections, since the material is not manufactured for this kind of application. The Contractor decided to focus on a different silicone-based material that has been recently commercialized by Wacker Chemie AG and lately on a new material produced by Parker Hannifin. These new materials are slightly more expensive with respect to the styrenic rubber but demonstrated a very good response to long-term cyclical loads.

Successful demonstration of lifetime and reliability of DEG-PTOs based on a silicone elastomer membrane commercialised by the company Wacker Chemie AG. DEG PTO specimens made with this material have sustained more than 1.4 million cycles at an electric field level of 75 MV/m without experiencing any rupture. Based on this result and assuming a shape for the probability of failure similar to that measured for broken DEG-PTO specimens made with a custom made styrenic material, DEG-PTO specimens made with the Wacker silicon elastomer are expected to have a MCTF higher than 20 million if operated at 55 MV/m. In a wave energy converter, this corresponds to: a nominal power density in the range 30-40 W/kg, a CAPEX in the range 0.3-0.8 M£/MW; a lifetime in the range 9-11 years; an OPEX in the range 30-90 k£/MW/year. Higher MCTF can be obtained by operating the DEG-PTO at lower electric field levels; for instance: a MCTF of 50 million should be obtained at 45 MV/m, corresponding to a nominal power density in the range 20-27 W/kg, a CAPEX in the range 0.45-1.2 M£/MW; a lifetime in the range 20-25 years.

The lifetime demonstrated by DEG-PTO specimens made with the silicone elastomer film commercialized by Wacker, when operated at 55 MV/m, is very promising; though it is still below the 15-20 years design lifetime targeted in the WES-PTO stage gate guidelines drafted by Wave Energy Scotland. Several margins of improvements are still possible owing to the relative immaturity of the technology.

Thanks to the low cost of the employed materials, the results obtained on the silicone elastomer film commercialized by Wacker already open two possible routes for DEG-PTO implementation in wave energy converters:

- develop a DEG-PTO with high performance (thus, with higher power density and lower CAPEX) that needs to be replaced about every 10 years as part of a pre-defined maintenance schedule (thus, with higher OPEX)
- develop a DEG-PTO with lower performance (thus, with lower power density and lower CAPEX) that does not require to be replaced over the entire life of the wave energy converter(thus, with lower OPEX).

The specific choice will be led by techno-economic considerations and based on the site considered for the installation.

Engineering and Manufacturing:

Successful definition and implementation of a manufacturing process for the production of a realistic prototype of DEG based on silicone rubbers: the developed prototype is manufactured according to up-scalable techniques of shadow masking of electrodes on commercially available layers of dielectric or on custom developed dielectric elastomer layers. The fabrication procedure has been tested first at small-scale in order to verify the effectiveness of the process. The fabricated DEG-PTO is based on a commercial material developed by Wacker Chemie AG that has been purposely conceived for dielectric elastomer transducer applications, and it has been equipped with custom-made polymeric compliant electrodes. The developed prototype has been tested showing suitable (as foreseen) results in terms of energy density and efficiency.

The tested production technique makes it also possible to demonstrate the feasibility of a 350 mm large multilayer prototype that features custom made DE layers and conductive electrodes. This novel prototype features improved reliability, is easier to handle and possesses high performances in terms of deformability and dielectric strength. The procedure that has been developed to manufacture DEG-PTOs based on the silicone elastomers commercialised by Wacker Chemie AG is completely up-scalable. Thus, it can be replicated to manufacture DEG-PTOs featuring larger sizes like the ones to be developed in the next stages of the project to full scale.

Successful demonstration of a module of power driver-electronics for DEG-PTO. The modularity of these electronics allows to separate the control board from the power section in order to guarantee up-scalability of the obtained prototype. The estimated efficiency and the overall performance are still sub-optimal in the obtained efficiency but already enough for the implementation of effective DEG-PTOs. Large margins of improvement are also foreseen for future developments. The availability of a scalable control electronics makes it possible to easily scale-up the power controller for the DEG-PTO system. An up-scaled system can actually be based on the current electronic circuit in which the power section is replaced with components of increased power.

A very promising silicone membrane produced by the company Parker Hannifin has been identified for the manufacturing of intermediate/large scale DEG-PTOs, with diameter in the range of 1-1.4m. Unfortunately, the procedure for the manufacturing and bonding of conductive layers which has been developed for smaller scale DEG-PTOs made with the Wacker silicone films does not work on the Parker Hannifin material. The engineering and manufacturing of DEG-PTOs based on the identified silicone film produced by Parker Hannifin has been postponed to a later Stage of the project.

Techno-economic analysis:

Techno-economic analysis of the DEG-PTO confirms the promising perspective due to the positive balance between level of performance and reduced CAPEX/OPEX of the DEG-PTO. The analysis that considered the DEG-PTO component has set very good perspectives for future development of this technology.

Management:

The high dynamism of the sector determines a quite frequent introduction of important novelties in materials and components. On the one side, this is a positive aspect that highlights the large margin of improvement of DEG-PTO technology; on the other side this introduces complexity in the choice related to management and road-mapping. Some very promising materials and components have been released and commercialized by some companies in a quite late phase of the Project and it was not possible to completely include them in our testing campaign.

Some delays have been experienced during the development of the Project due to delays in procurement due to problems in the management of Project-cash flow. The impact of Project cash-flow has been underestimated. This became a source of delays in the project plan due to the delay in the acquisition of larger equipment and expensive components.

Communications and Publicity Activity

None.

Recommendations for Further Work

Modelling activities:

Future projects should make use of this project's simulation tool and refine/improve it where necessary.

Experimental activities:

Future projects should include the development of a set-up capable to also study the response of the DEG-PTO in combination with other balance of plant components.

To get accurate estimates for the lifetime of the silicone elastomer membrane commercialised by the company Wacker Chemie AG, lifetime tests need to be continued to bring all the DEG-PTO specimens that are still alive to rupture. Further tests should also be performed to verify that the lifetime of DEG-PTO specimens made with the Wacker silicone elastomer has little dependence on specimen size and operation frequency (as it has been demonstrated with the lifetime tests conducted on the custom made styrenic rubber).

DEG-PTO upscaling to diameters in the range of 1-1.4m should require:

- the upscaling of the manufacturing process employed by Wacker to make films larger than those that are within the capabilities of their current equipment.
- use of different silicone elastomer films that are already manufactured with suitable sizes (for instance resorting to the silicone elastomer films that have been developed for this application by Parker Hannifin)

In both cases, the lifetime performances of DEG-PTOs with larger sizes made in these ways should also be verified.

Future directions in the search of novel materials should also consider improved manufacturing processes for Styrenic Rubbers.

Engineering and Manufacturing:

Larger scale manufacturing of DEG-PTOs based on the silicone elastomers commercialized by Wacker Chemie AG requires up-scaling of the manufacturing tools that are currently available at the premises of both contractor and silicone elastomer film provider (Wacker Chemie AG). Due to the relative simplicity of the processes involved, this does not constitute a technical problem but requires investments in terms of time and cost.

Since manufacturers already exist that commercialise silicone elastomer films having larger sizes (for instance, the company Parker Hannifin is already producing films specifically developed for this application that comes with a width of around 1.4 m), future development of the project could consider a change of material provider, which however would require a modification of the process to manufacture the electrodes (for instance, realisation of electrodes via screen printing has been demonstrated to be the optimal process to be used with the silicone elastomer film commercialized by Parker Hannifin).

Future developments should consider the optimisation of the control firmware in order to bring the efficiency of the electronics from the current range of 80-86% up to the expected values of 90-95%.

DEG-PTO development to be done in Stage 3 project should consider the silicone film produced by Parker Hannifin. To resolve the manufacturing issue, a partner has been identified that already has in place an automated manufacturing process to deposit compliant electrodes on the silicone film produced by Parker Hannifin.

Techno-economic analysis:

The same techno-economic analysis has however highlighted that for wave energy converters equipped with DEG-PTO, the bottleneck for cost reduction becomes the structure and prime mover. Future work should then consider the combination of DEG-PTO technology with innovative forms of structure and primary mover; for instance within wave energy converters made with deformable fabric/elastomeric structures like the ones that are being studied in the context of the project ELASTO funded by Wave Energy Scotland through the Material programme.

Management:

Any management issues are slightly mitigated for future projects since the Contractor has now established links and contacts with several of the major manufacturer and their collaborators. This should guarantee to be acknowledged on the most recent development plans for new materials and components well in advance before their commercialization. Procurements and external services should be managed by a single partner of the project and planned since the beginning more carefully.

In case of continuation to Stage 3 level the Contractor is suggested to apply for a request of an advanced payment for activities that needs acquisition of expensive materials and equipment.