Control of WECs based on Dielectric Elastomer Generators

WES Control Systems Stage 1
Public Report

Cheros S.r.l.

This project has been supported by Wave Energy Scotland

1 Project Introduction

This document summarizes the outcomes of the project "Control of WECs based on Dielectric Elastomer Generators" (here below called the Project), funded by Wave Energy Scotland (WES) in the framework of the Control Systems Programme, and led by the Italian company Cheros Srl.

Specifically, the Project deals with the deployment of a feasibility study on control strategies for a special kind of power take-off (PTO) system, namely dielectric elastomer generator (DEG), and the definition of a proposed control architecture for wave energy converter (WEC) devices mounting this type of PTO.

DEGs [1][2] are a class of PTO system made of polymeric rubber-like materials, which exploit a variable-capacitance electrostatic principle to directly convert wave energy into electrical energy. DEGs feature promising performance in terms of efficiency, adaptability to different WECs, LCOE and architectural simplicity.

Attention is focused on a specific topology of DEG, i.e., a circular diaphragm inflatable DEG [3]. This kind of DEG is particularly suitable for application on oscillating water columns (OWCs) and pressure differential (PD) WECs [4].

Compared to other PTO systems, DEGs show some peculiar features:

- DEGs contribute to the dynamics of coupled WECs not only through controllable (electrostatic) loads, but also through their rubber-like elastic response, which is non-linear.
- Their power electronics (namely, a bidirectional DC-DC converter) is different from the electrical machines usually involved in the operation of other PTO systems, and require dedicated drivers.

Consequently, DEG PTOs require dedicated control logics and control systems, able to practically drive the electrical state of these devices in a way to guarantee robust, reliable and efficient performance of coupled DEG-WEC systems.

In the Project, control logics for DEG PTOs are studied at two different levels:

1) **High-level**, which concerns the operation of WEC units and WEC farm as a whole, the identification of optimal profiles of the control variables (e.g., the DEG electrical variables) to maximise the WEC performance in operating conditions, as well as the control of security systems and implementation of monitoring and supervisory controls;
2) **Low-level**, which concerns the management/driving of DC-DC power converters to pilot the DEG.

Based on the identified control tasks/requirements, a general definition of the architecture for the control system of a farm of WEC devices with DEG PTO has been proposed.

The project team composition is as follows:

- Cheros Srl is the Principal Contractor. Cheros are responsible for project management and coordination, and they deal with the integration of elaborated high-level and low-level control strategies and definition of the general control system architecture.
- Cheros has the following subcontractors:
    - The University of Edinburgh are responsible for the investigation of high-level control logics, with an emphasis on model-based optimisation of DEG-based WECs in operating conditions.
    - The University of Bologna provided numerical models, specifications and requirements for DEGs, identifying solutions for DEG monitoring and needed control actions to extend their lifetime.
    - The University of Trento evaluated low-level control strategies for the DC-DC power converter, including hybrid controls.

2 Description of Project Technology

To date, simple predictionless control laws have been employed to control DEGs mounted on WECs. It is expected that a significant improvement in the coupled DEG-WEC systems performance can be obtained by acting on the control strategies of the DEGs, without any significant hardware modification of the DEG layout and of its power electronics.

We propose a control methodology for DEG-based WECs based on the definition of two macroscopic control tasks (see Figure 1):

- **High-level control**, which deals with the investigation of optimal trajectories for the DEG electrical state aimed at maximising the produced power output while enforcing the respect of operating constraints, the monitoring of the DEG ageing state, the control and piloting of active security systems aimed at guaranteeing the security of the plant.
- **Low-level control**, which deals with the driving of the conditioning electronics (bidirectional DC-DC power converter) in order to track trajectories (in terms of the DEG electrical variables) elaborated by high-level controls while guaranteeing high efficiency of the power electronics.

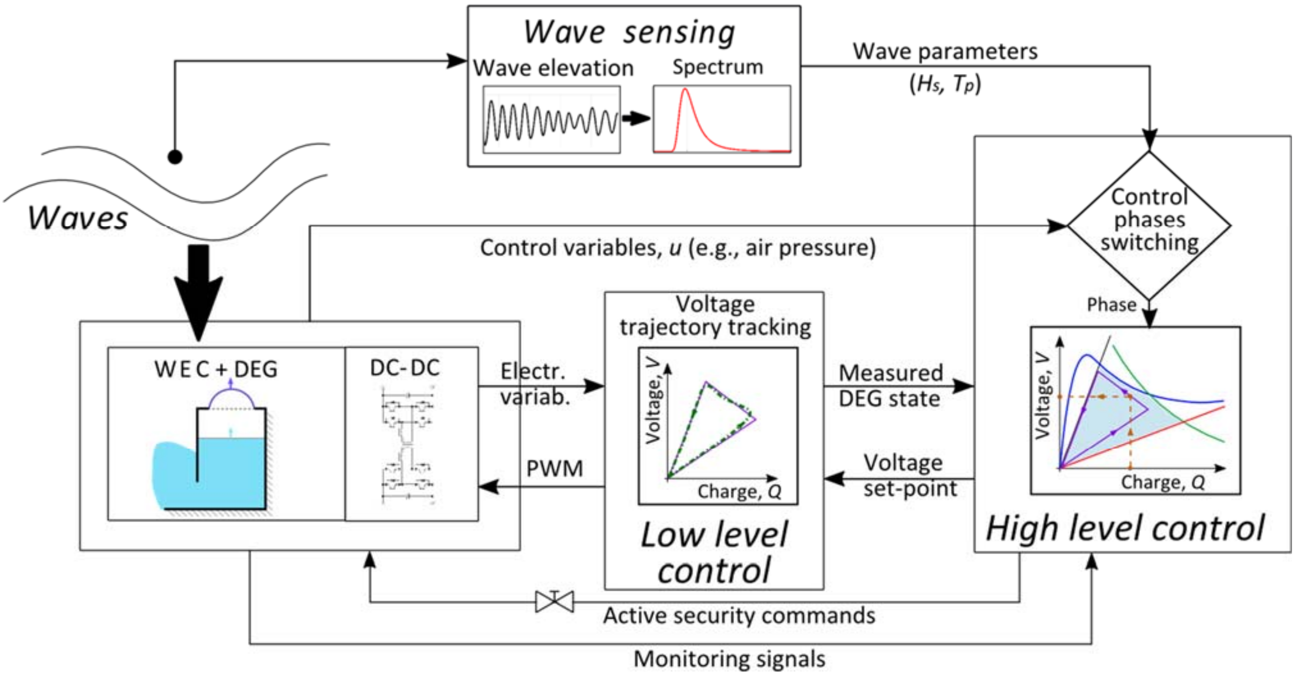

Figure 1. Logical block diagram of the proposed control methodology

The following control techniques are employed in the two blocks:

- High-level control is expected to implement control heuristics for the DEG PTO aimed at optimising the WEC power output and respecting operating constraints (in terms of maximum admissible electrical and mechanical DEG loading) relying on the measurement of the DEG state variables and of the current sea state (either by punctual measurement of the wave profiles or by knowledge of statistical macroscopic wave parameters). A control heuristic is a sequence of pre-defined electrical operations (e.g., DEG charging up to a threshold voltage, DEG discharging, DEG piloting at constant voltage, etc.), whose sequence and composition should be designed based on a model-based investigation of the DEG-WEC dynamical performance. Compared to the use of in-line optimisation procedures, which are very computationally expensive (especially in the case of DEGs), identification of control heuristic can provide an effective way of practically driving the WEC while guaranteeing nearly optimal power capture performance. Control heuristics can be tuned to different sea states upon modification of a set of control parameters. Such a tuning can be done on a wave-by-wave basis, although it is expected that the most promising solution consists in performing a slow-adaptive control, in which the controller parameters are updated on a mid-term basis as a function of average spectral parameters (e.g., significant wave height and peak period).

- Power electronics for DEGs driving consists in switching DC-DC converters, therefore, low-level control should generate pulse-width modulation (PWM) signals to drive the switching components of the power converter in order to implement the desired voltage profiles on the DEG. Techniques to generate such PWM signals in order to optimally track the prescribed voltage trajectories have been investigated before, but they should be extended to the special topologies of bidirectional DC-DC converters used for DEG PTO application. A particularly promising approach to investigate the most efficient way of driving the switching components in power converters with the aim of achieving a desired electrical output is offered by hybrid control systems.

3 Scope of Work

The main activities undertaken in the framework of the Project can be summarised as follows:

- Identification of models of WEC-DEG systems with different level of complexity, in order to set-up model based optimisation, validation, assessment.
- Individuation and preliminary development of mathematical tools for model-based control optimization. Identification of possible control heuristics based on the results of model-based optimisations.
- Study of the applicability of machine learning techniques to solve control-related problems which would otherwise difficult to tackle with conventional approaches.
- Identification of the relevant signals for monitoring the PTO modules state, DEG ageing and security conditions. Identification of plausible control actions to prevent DEG failure in extreme conditions.
- Modelling of the DC-DC converter aimed at setting-up low-level control strategies.
- Characterisation of the switching sequences of DC-DC converters. Study of hybrid controls aimed at optimizing the DC-DC efficiency while pursuing reference high-level tasks.
- Identification of the required hardware components for sensing, monitoring and safety, and data processing procedures for wave sensing.
- Preliminary definition of complete control architectures for a farm of WECs with DEG PTO and assessment of their readiness level.
- Planning of the activities for the next project stages, involvement of stakeholders and control system developers, compilation of a full proposal for Stage 2 and high-level definition of a plan for Stage 3.

4 Project Achievements

Overall, the project proceeded smoothly. The main achievements of the Project can be shortly summarised as follows.

- High-level policies for controlling DEG PTOs have been studied in good detail. At this first stage, particular attention has been addressed to the definition of optimum control strategies to maximise DEG-WEC power in operating conditions. The mathematical problem of optimising the power of an OWC with inflatable DEG PTO has been extensively tackled, and the solution has been used to deduce a simplified control heuristic. The proposed control heuristic features minimal requirements in terms of sensing and it does not require prediction of the incoming wave profiles, as it just relies on the knowledge of average sea state parameters (significant wave height, peak period). Preliminary analysis and robustness assessment of the control heuristic has been done. The methodology used to build and solve the optimisation problem based on a discrete state-space representation of the WEC dynamics can be easily extended to different devices.
- Low-level control tasks have been defined. With reference to a selected topology of DC-DC converter, suitable for DEG PTO application, switching policies for DC-DC power converters have been investigated,

both reviewing existing switching policies and by preliminary evaluation of hybrid controls applicability. Numerical models for the DC-DC converter have been put in a suitable form which enables straightforward implementation of hybrid control theory.

- Practical architectures for the control system of DEG-based WECs have been investigated. In particular, a control system architecture has been drafted, making reference to a farm of devices (see Figure 2). The control system features hierarchical architecture and includes several nodes, where control logics are processed and control actions are executed. Nodes are delocalized throughout the farm and are responsible for different areas/processes, ranging from Supervisory processes (Node 1), farm area aggregation processes (Node 2), WEC processes (Node 3), individual DEG module processes (Node 4) and power converter control (Node 5). Preliminary evaluation of hardware requirements, in terms of sensing equipment, communication networks and security devices, has been performed.
- Plan of the activities for a Stage 2 project has been defined.
- In terms of project management, communication among partners has been smooth and effective thanks to regular physical and conference meetings. Information sharing has been effectively implemented through cloud data storage. Quality assessment has been efficiently performed thanks to the appointment of a Scientific Supervisor.

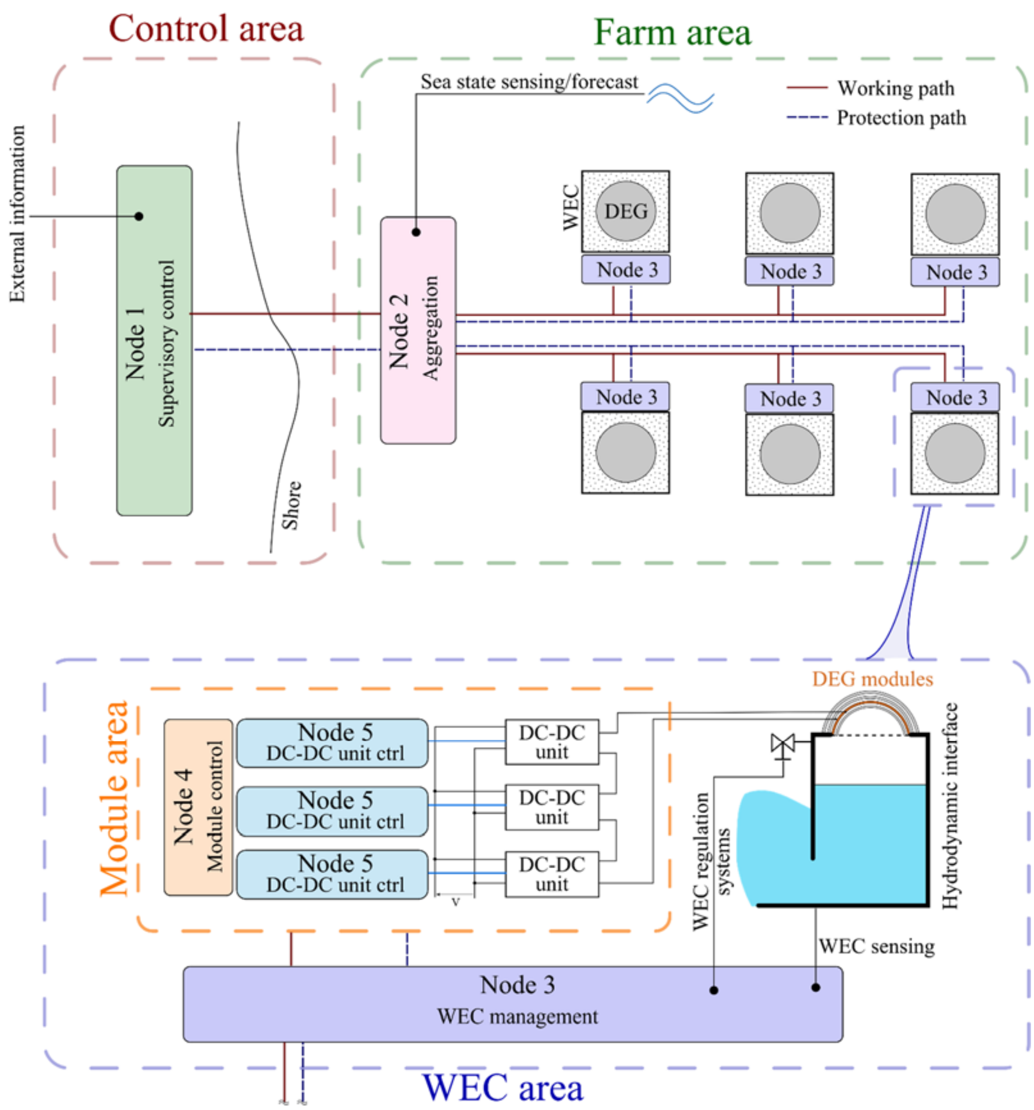

Figure 2. Proposed architecture of the control system

In contrast, main criticalities and deviations from the plan can be summarised as follows:

- Owing to the short duration of the project (3 months), there was no time to analyse in depth some of the topics under investigation. In some cases (e.g., hybrid control for power converter piloting), the detailed implementation of mathematical procedures aimed at synthesising control strategies was not possible, and attention was thus focused on the definition of models, procedures, and tools to preliminary set up such procedures, in view of a thorough deployment at possible successive stages. In other cases, we decided to spend more time than planned on some particularly promising topics (e.g., model-based optimisation and definition of high-level heuristics), thus tackling certain other topics (e.g., machine learning techniques for high-level control) with lower level of detail. Nonetheless, no significant deviation from the original project plan was done, and all the expected topics were investigated.

- There was some delay in the actual starting date of the problem, due to bureaucratic time needed to set up insurance policies with the requested features and level of coverage.

5 Recommendations for Further Work

In the framework of the Project, a preliminary architecture for the control system of DEG-based WECs was defined, tools/mathematical techniques to deploy high and low-level control logics were identified, high-level definition of hardware components, sensing equipment, and active security systems was provided.

Owing to the high-level nature of the activities carried out so far, a lot of technical effort has still to be performed in order to develop the proposed control system for DEG-WECs. In particular, a set of recommended future activities is schematically presented in the following:

- Model-based dynamical optimisation procedures have been demonstrated to be an effective tool to generate high-level control heuristics for DEG-based WECs. Optimal solutions (that maximise the power output) for non-linear WECs are particularly useful to identify/build synthetic control heuristics which do not require the implementation of a real-time solution of the optimisation problem. To date, application of those techniques has been limited to the case of an OWC with circular diaphragm inflating DEG. In the future, the same technique should be extended to other scenarios (e.g., different devices, like, e.g., PD WECs, or different OWC architectures) to build alternative control heuristics for different devices. Functional features of such controls (robustness, stability) should be investigated.
- Hybrid control procedures to pilot DC-DC power converters for DEG PTOs have been preliminarily described. In the future, detailed numerical simulations should be run, aimed at assessing the effectiveness of such procedures. Moreover, appropriate formulations should be pursued which aim at guaranteeing high working efficiency of the power converter besides guaranteeing good tracking of the reference DEG voltage trajectories. Functional features of such controls (robustness, stability) should be investigated.
- A general schematic of a control system architecture for a farm of DEG-based WECs was provided (see Figure 2). Such an architecture includes several delocalised logical and physical nodes, ranging from supervisory nodes, farm area nodes, and local nodes at the WEC, DEG and power converter level. Higher level nodes are quite generalist, and hold for different technologies, while local nodes are device specific. For DEG PTO control deployment, the logics within such specific local nodes should be investigated further. In particular, software implementation of the control logics within such nodes should be pursued, using a structure capable of implementing the hierarchical architecture of the proposed control system. Afterwards, the developed code should be tested in simulation environment, in combination with a representative set of models of the WEC interface, the DEG modules, and the power converter.
- Physical demonstration of the proposed control methodology should be provided via hardware-in-the-loop (HIL) experiments, combining simulated hydrodynamics of the primary interface (OWC or PD WEC) with physical DEG PTO and power electronics. In this regard, design of the following physical sub-components should be pursued
    - Test-bench for HIL experiments. A test-bench for HIL testing of inflating DEG samples, up to a scale of 1:20-1:30 has been developed in the framework of WES PTO Programme [5]. Such a test bench is capable of mechanically driving the deformation of inflating DEG prototypes, and it can be used to

emulate the DEG operation in combination with OWC or PD WEC devices, whose hydrodynamics are simulated via software and used to pilot the DEG deformation through the hardware test-bench. With the aim of performing functional tests on the control system, the set-up should be adapted, e.g., by integrating hardware components capable of simulating active security systems, and it should be equipped with further sensing equipment. In alternative, a larger scale (1:5/1:10) set-up might be considered for HIL testing, depending on the outcome of a pending project proposal to WES for a Stage 3 project by some of the present team members. That project will possibly lead to the development of a pneumatic driving system for large DEG samples

- DEG modules. Functional DEG PTO manufacturing has been preliminary demonstrated at laboratory prototyping level. With the aim of achieving significant demonstration of the proposed control methodologies, manufacturing of optimised DEG units should be pursued, with the aim of delivering an appropriate set of DEG samples with the required features of stability, durability and repeatable response. DEG prototypes at a scale compatible with the target scale of the HIL setup are expected to have diameter in the order of 30-50 cm, total thickness in the order of 0.1-0.5 mm, and capacitance in the range 50-100 nF.
- DC-DC converter. Deployment of a single unit of a bidirectional DC-DC unit for DEG driving is currently ongoing. The DC-DC unit can be used to perform preliminary tests on low-level control logics. Nonetheless, to perform HIL tests on a complete DEG module, a modular version of the power converter based on a cascade of DC-DC units should be set up in order to drive DEG samples with the characteristics listed above
- Hardware control equipment. This includes control electronics for the implementation of the controllers and sensing equipment.

6 Communications and Publicity Activity

The activities and intermediate outcomes of this Project have been presented through a poster at WES Annual Conference, Edinburgh (UK), 28 November 2018.

7 Useful References and Additional Data

[1] F. Carpi, D. De Rossi, R. Kornbluh, R. Pelrine, and P. Sommer-Larsen, Dielectric Elastomers as Electromechanical Transducers: Fundamentals, Materials, Devices, Models and Applications of an Emerging Electroactive Polymer Technology. 2008.

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[3] R. Vertechy, G. P. Rosati Papini, and M. Fontana, "Reduced Model and Application of Inflating Circular Diaphragm Dielectric Elastomer Generators for Wave Energy Harvesting," J. Vib. Acoust., vol. 137, no. 1, 2014.

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