Progress update on the development and testing of an advanced power take-off for marine energy applications

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Progress update on the development and testing of an advanced power take-off for marine energy applications

Simon Robertson, Donald R. Noble, Henry Jeffrey, Luca Castellini, and Michele Martini

***Abstract*—The Electro-Mechanical Generator (EMG) consists of a recirculating ball screw integrated with a rotational permanent magnet generator and is able to convert reciprocating linear motion, typical of many marine energy devices, into electricity. The EMG is based upon technology from mature industrial and aerospace sectors and is undergoing adaptation, development and testing for application to marine energy. The proving of this technology has progressed through several projects for a range of mechanical and electrical configurations to reach TRL6/7. The results of the performance, hardware in the loop and offshore tests being undertaken will describe the performance of the EMG including efficiency, reliability and peak load ratios. This will draw upon up-to-date data from Wave Energy Scotland projects and the ongoing Horizon 2020 funded IMAGINE project. Italian manufacturer UMBRAGROUP leads the development of the EMG and is supported by a range of industrial and academic partners including the University of Edinburgh.**

***Index Terms*—Electro-Mechanical Actuator, Electro-Mechanical Generator, Power Take-off, Wave Energy.**

I. Introduction

GLOBALLY, the theoretical wave power resource is extremely large, with estimates around 18 to 32 PWh/year [1], [2]. For comparison, Enerdata gives global electricity consumption for 2016 at 21 PWh [3]. Despite over two decades of intense activities, wave-generated electricity is far from being competitive and there are no commercial devices yet. The sector is characterised by a number of radically different early-stage technologies and concepts, moving slowly through technology readiness levels. Cost reduction and reliability are therefore key challenges for the wave energy sector [4]. The Power-Take-Off (PTO) is a major cost element of a typical Wave Energy Converter (WEC), accounting for around 22% [5] of average CAPEX and its performance also significantly affects a WEC's energy yield.

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This suggests the need for new PTO technologies within the sector. The Italian industrial manufacturer UMBRAGROUP SpA are currently developing a new PTO solution, the Electro-Mechanical Generator (EMG), building on established technology from the mature aerospace industry. Testing and proving of this new application is discussed in the sections below.

The rest of this paper is structured as follows: Background on the operation and history of the EMG is given in Section II. Section III then outlines the prototype testing and proving conducted in a series of technology development projects. The future development and path to commercialisation are then discussed in Section IV, followed by conclusions in Section V.

II. The Electro-Mechanical Generator

The EMG is an innovative type of PTO, based on the established Electro-Mechanical Actuator (EMA) widely used in the aerospace industry. The EMG PTO can be applied to many of the WEC types currently being developed, which convert the slow reciprocating motion of the waves into electricity, typically through an intermediate mechanical system connected to a rotary generator.

The core element of the EMA/EMG is a ballscrew. This is based around a screw, a mechanical component that can convert rotary motion into linear motion and vice-versa. A cutaway schematic of the ballscrew system is shown in Fig. 1 with the energy conversion chain in Fig. 2.

The ballscrew is a mechanical device in which the balls, acting as low friction load-carriers, efficiently convert the low-speed linear motion of the screw into a high-speed rotary motion of the nut. The rotational speed of the nut is a function of the screw linear speed and the screw pitch (i.e. the axial distance between adjacent threads on the screw).

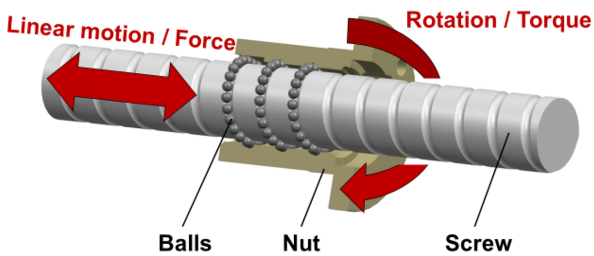

Fig. 1. Schematic representation of a ballscrew system.

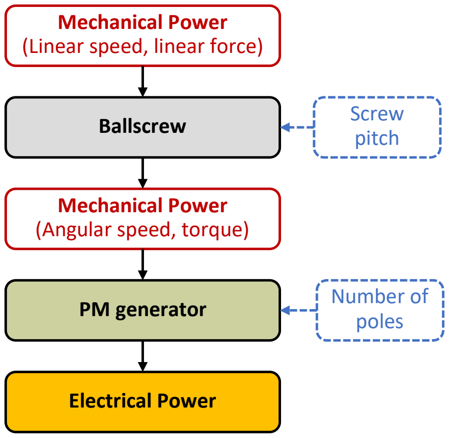

Fig. 2. Schematic representation of a ballscrew system.

TABLE I
EMG TECHNICAL SPECIFICATIONS FOR THE EMERGE AND IMAGINE PROJECTS

Specifications	EMERGE EMG	IMAGINE EMG*
Peak Axial load (kN)	100	330
Peak axial speed (m/s)	1	2.7
Stroke (m)	1.06	4.00
Peak Mech. Power (kW_p)	100	500
Rated electrical power (continuous – air cooled) (kW_{av})	10	—
Rated electrical power (continuous – water cooled) (kW_{av})	<30	125
Length (m)	2.1	6
Diameter (mm)	235–317	503–516

* IMAGINE EMG specifications preliminary

Permanent magnets are integrated in the nut, which thus acts as rotor of the electrical generator. The rotor, spinning inside a bespoke-designed stator, induces a voltage on the stator windings thanks to the principle of electromagnetic induction. The frequency of the induced voltage is proportional to the number of poles of the generator. The high rotational speed of the nut and generator rotor increases the induction rate and thus the overall system compactness.

By removing the need for a gearbox or hydraulic systems, thus reducing complexity, the EMG should also increase reliability of the overall PTO solution. Reliability is critical for ocean energy technologies that are subjected to the harsh marine environment, and where it is both costly and time-consuming to address faults.

Particularly in wave energy applications, the peak power determines the loading that the PTO can withstand. These prototypes are therefore rated based on the peak electrical power output (kW_p). The average power output (kW_{av}) that can be sustained over a long period is then a function of the cooling and control. The ratings defined are in accordance with the S1 (continuous) and S6 (peak) ratings as defined in BS EN 60034-1 [6].

A. Historical development

UMBRAGROUP identified an opportunity to adapt their existing EMAs to a linear generator application in 2012. The ball-screw technology architecture is reversible and can be readily adapted to serve as a linear generator and this was demonstrated in initial small-scale lab tests. Having identified the opportunity and undertaken a simple bench demonstration in 2012, a technology development programme was launched to understand and then address the specific requirements of the ocean energy sector.

Although the EMA is a commercial product in the mature aerospace industry, transferring this for application in the ocean energy sector leads to a reduction in TRL. Further development is therefore required, testing and proving this in a new environment for the wave energy industry. A development roadmap was prepared that sets out the steps that the technology would progress through as it increases in scale and TRL.

The EMG PTO is being advanced in a series of technology development projects, increasing both TRL and commercial readiness. Following design development and bench tests in 2013-15 a significant step was made in 2016 with a small-scale prototype (12.5 kW_p) being subjected to both dry testing on the bench to characterise the performance, and to wet testing integrated within a WEC in a flume and at sea [7], [8]. A further test incorporated an EMG (5 kW_p) into a tidal device that was tested in a flume in fully submerged operation. The development and testing activity ongoing since 2017 are the subject of detailed description in Section III of this paper. A summary of the progress to date is shown in Fig. 3.

This technology development programme has been supported by funding from Italian regional and national funders, Wave Energy Scotland, and the EC Horizon 2020 programme. Delivery of the projects has been supported by a range of industrial and academic partners across Europe.

III. EMG PROTOTYPE TESTING AND PROVING

The development, testing and validation of the EMG as part of the development roadmap is the subject of two major research projects underway since 2017:

- The Wave Energy Scotland funded EMERGE (Electro-MEchanical Reciprocating GEnerator) project, has the aim of validating a 100 kW_p EMG in the lab and demonstrating application in real sea conditions. This project is running from 2017–2019.
- The EU H2020 funded IMAGINE (Innovative Method for Affordable Generation IN ocean Energy) project will develop a larger 265 kW_p rated prototype that will be subjected to Hardware In the Loop (HWIL) tests. This project is running from 2018–2020.

In each of these projects, the EMG PTO is demonstrated at larger (physical) scale and higher output and under realistic operating loads and conditions. This will require design, development, fabrication and testing of the EMG to verify key metrics including cost,

Fig. 3. Major technology steps on the development pathway of the EMG PTO.

efficiency and reliability. A technical specification of the EMGs to be tested in each of these projects is given in Table I.

The EMERGE EMG was designed to the above specification and fabricated at UMBRAs Italian factory in 2018 and is shown in Fig. 4. The laboratory testing that has taken place and the at sea testing that is planned to take place in 2019 is described in Section III-A and Section III-B respectively.

The IMAGINE EMG is in design based on functional and technical specifications being developed in early 2019 in preparation for manufacture in mid-2019.

A. Validate technology in the lab

For the EMERGE project, a 100 kW_p EMG PTO prototype was designed, fabricated and tested in 2017–2019. The first part of this project was to characterise the machine and its performance in a controlled environment.

1) Test objectives: The EMERGE project objectives are framed around the EMG demonstrating ability to achieve a set of target outcomes metrics associated with efficiency, reliability and survivability. These target outcomes were defined by UMBRAGROUP and include outcomes to be achieved during the project that provide validation to longer-term industrial goals, see Table II.

The goal of the laboratory testing of the EMG is to characterise and validate the machine and performance in a controlled environment against the project target outcomes. To achieve this after assembly the EMG was subjected to a hierarchy of testing:

1) Factory acceptance tests at UMBRAGROUPSs in house R&D department to check basic operation and functions including sealing and pressure tests.
2) Performance tests to confirm load handling, efficiencies, cooling, control, sensor systems etc. across the range of input conditions.
3) Longer duration endurance tests in a HWIL configuration will apply realistic WEC like input conditions, derived from real sea states, to measure performance and reliability . This allows performance assessment of the successive sea trials, described in Section III-B to be completed in the lab before they are undertaken offshore.

Fig. 4. Factory Acceptance Testing of the 100 kW_p EMG

2) Test set-up: The main performance and HWIL tests require the development of a bespoke test rig, with key specifications given in Table III. Engineering specialists Doosan Babcock were appointed to design, supply, and operate a test rig to actuate the EMG. A test bench was constructed and operated at the Doosan Babcock facilities in Glasgow, UK.

The test bench can be described based on two main sections: the actuation system and the PTO/HWiL system. The actuation system is hydraulic comprising of actuator and servo-valve and a pair of hydraulic power packs (HPP), it was designed to supply representative

TABLE II
EMERGE PROJECT TECHNICAL TARGET OUTCOME METRICS PROJECT AND LONG-TERM

	Project target outcome	Industrial long-term target outcome (200–300 kW units)
Efficiency (Mechanical-Electrical (DC Bus))	65–80%	70-80%
Reliability (Mean time between failures)	Zero failures	20 years for ballscrew assembly
Survivability – Peak to average load ratios	Up to 10 times	Up to 15 times

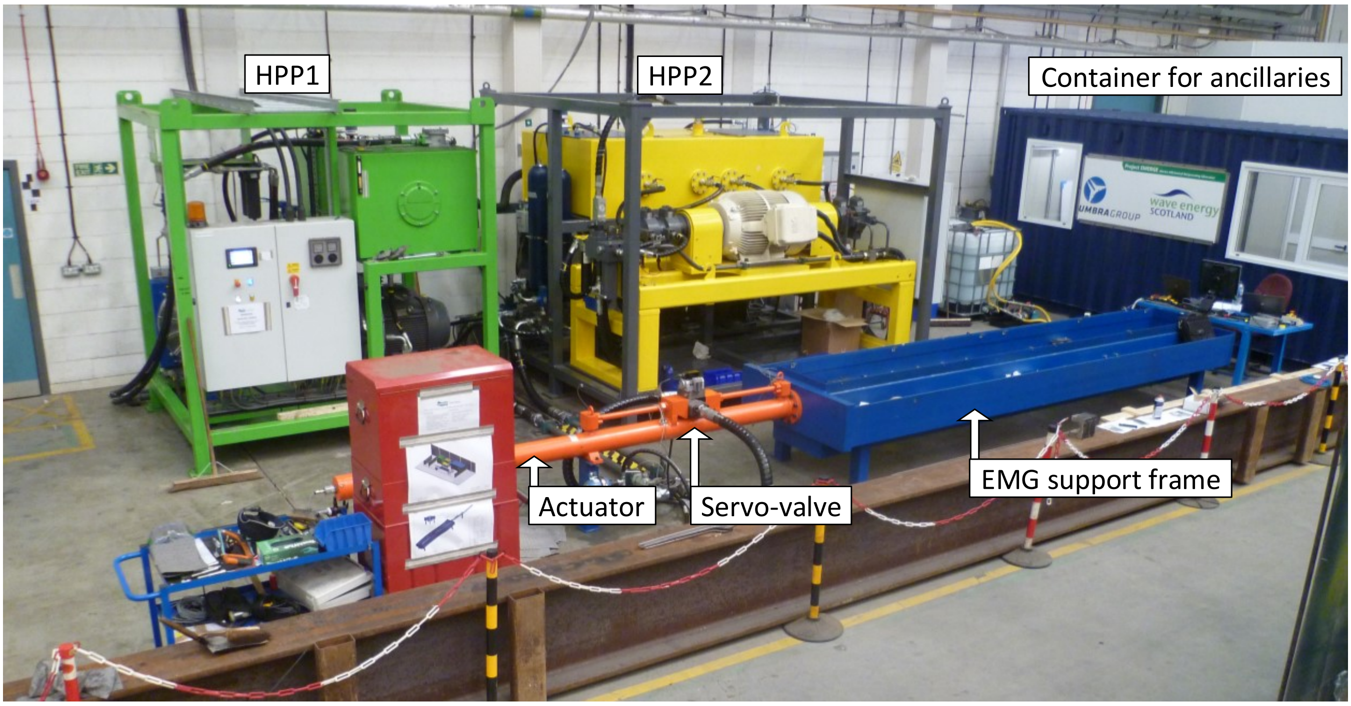

Fig. 5. Test rig set-up at Doosan Babcock showing hydraulic power packs (green & yellow), linear actuator (orange) and EMG support frame (blue). Note: EMG not installed.

TABLE III
TEST RIG SPECIFICATION

Actuator max.force (kN)	300
Actuator max. speed (m/s)	1.5
Actuator stroke (m)	1.5

load, speed, and stroke inputs to the EMG. Figure 5 shows the general arrangement prior to installation of the EMG, with HPP, actuator, and container with the ancillary systems. The EMG support frame, in blue, was designed to house both the EMG and connection to the actuator. It can be operated in a dry configuration or flooded using synthetic sea water.

The PTO and control system integrates a real-time hardware, where typical WEC device inputs have been modelled to generate characteristic load profiles in SIMULINK, and the EMG and container containing the ancillary systems. The control system for the test rig applies displacement profiles to the controller of the test rig to deal the specified loads to the EMG which will react in real time applying its own fixed damping control strategy in response. Figure 6 shows the general arrangement and block diagram of the system.

The control system for the test rig uses a displacement/force/speed control as required by the specific test. For the HWIL tests, typical WEC device inputs have been modelled to generate characteristic load profiles in SIMULINK. These inputs are then applied to the controller of the test rig to apply the specified loads to the EMG which will react in real time applying its own fixed damping control strategy in response. Figure 7 shows that the position achieved by the HWIL test bench closely follows the irregular input set from SIMULINK, with only minor variations.

Ancillary equipment known as the Power, Control and Monitoring (PCM) system is required to operate the EMG. This is housed in the 20 foot shipping container and includes power converters, control system, autonomous power supply including battery storage (required for the at sea testing set-up), monitoring and data acquisition systems. The PCM system is integral to the operation and delivery of power from the EMG and its performance is therefore taken into account in the analysis below.

3) Initial performance results: The main results that the project investigates with this tests are efficiency, reliability and power production capability. The EMG average efficiency is between 67% and 73% in the speed range 150–700 mm/s (constant speed tests). This efficiency is measured from the mechanical input to the EMG through to the DC electrical output of the PTO.

An example irregular wave HWIL simulation is presented in Fig. 8, showing axial force and speed at the EMG axis. The test was run applying a constant electrical damping coefficient at the EMG axis. This demonstrates that the EMG:

- is able to provide a reaction force proportional to speed under irregular conditions,
- has reached a peak force of -80/+50 kN, and
- has reached a peak speed of -0.5/+0.38 m/s.

As part of the lab tests, the EMG has run approximately 10k cycles during performance tests and >50k cycles in endurance tests. No early failures have been detected in this time.

In terms of peak-load handling capability, the EMG reached and survived 215 kN in high-load trials, more than double the specification in Table I.

Further analysis of the results is currently ongoing, however the achievement of these project target

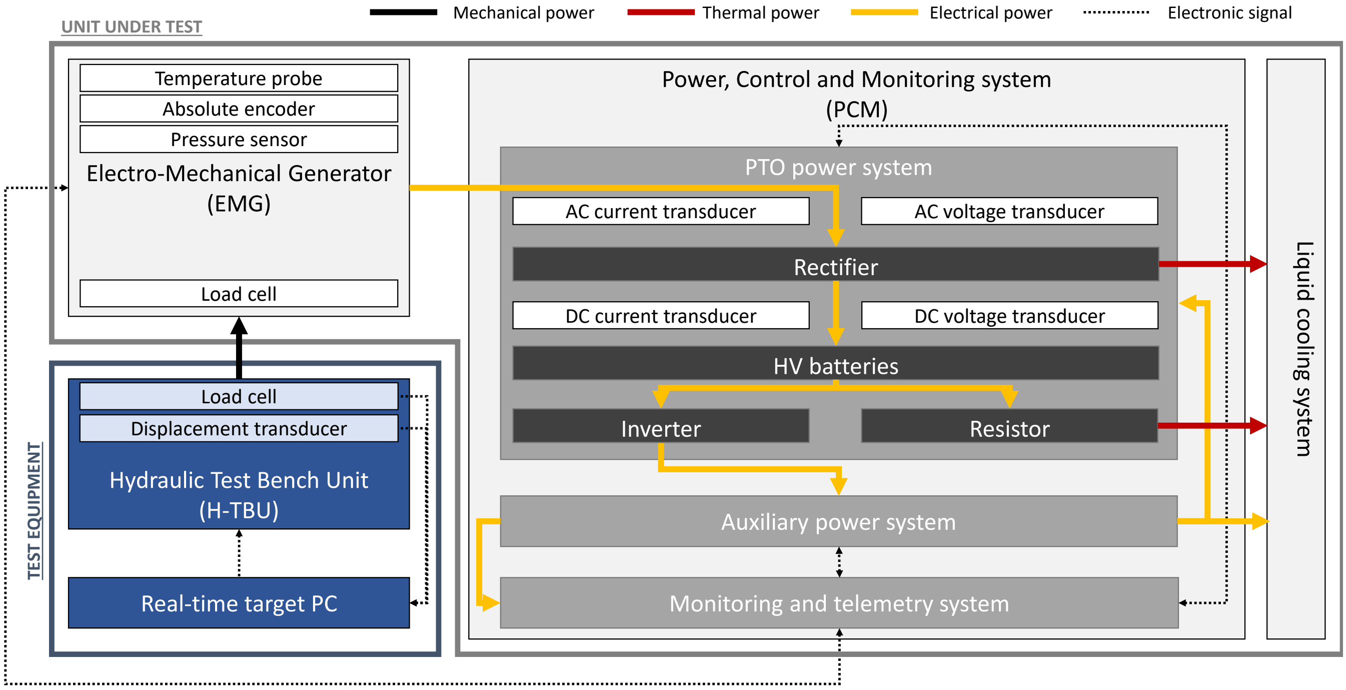

Fig. 6. General arrangement and block diagram of the system tested, with EMG PTO and test-bench on the left, and PCM on the right.

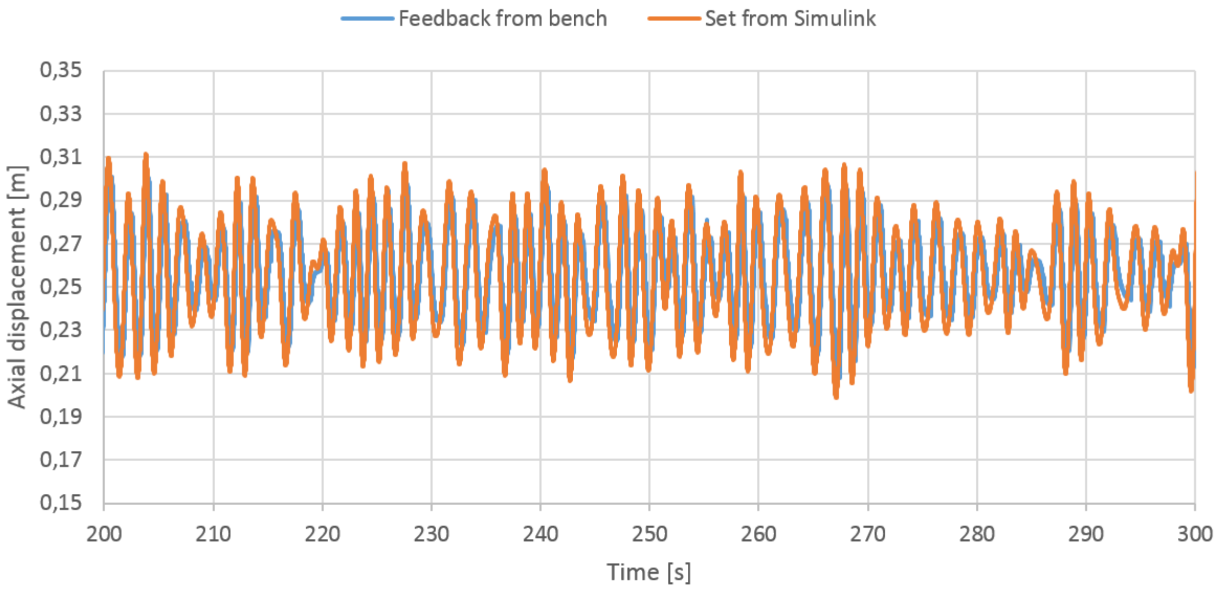

Fig. 7. Example time series showing the HWIL test bench actuator (blue line) following the position signal imposed by the Real-Time controller (orange line). 100 s extract from a 600 s irregular wave simulation.

outcomes gives validation to the long-term industrial target outcomes being realistic and achievable. The measured data are the output of the test plan and procedure applied by UMBRAGROUP and were certified by the quality system of the company.

B. Demonstrate in real-sea conditions at Scapa Flow

The second part of the EMERGE project is to demonstrate the technology in a real sea environment at Scapa Flow, Orkney, UK. The EMG PTO will be mounted on a barge integrated into a point-pivoted WEC. Note that this testing will commence in Spring 2019 so no results are available yet but the test objectives and test set-up will be described.

1) Test objectives: The primary objective of the sea trials is, in combination with the laboratory tests described in Section III.A, to ensure that appropriate wet testing in a relevant environment takes place to progress the EMG to TRL 7. The execution of sea trials in conjunction with a WEC is considered of primary importance, as the dynamic response of the prime mover provides invaluable information and improves confidence in laboratory based results.

Testing the EMG materials in real ocean environment will also demonstrate the marinisation aspects such

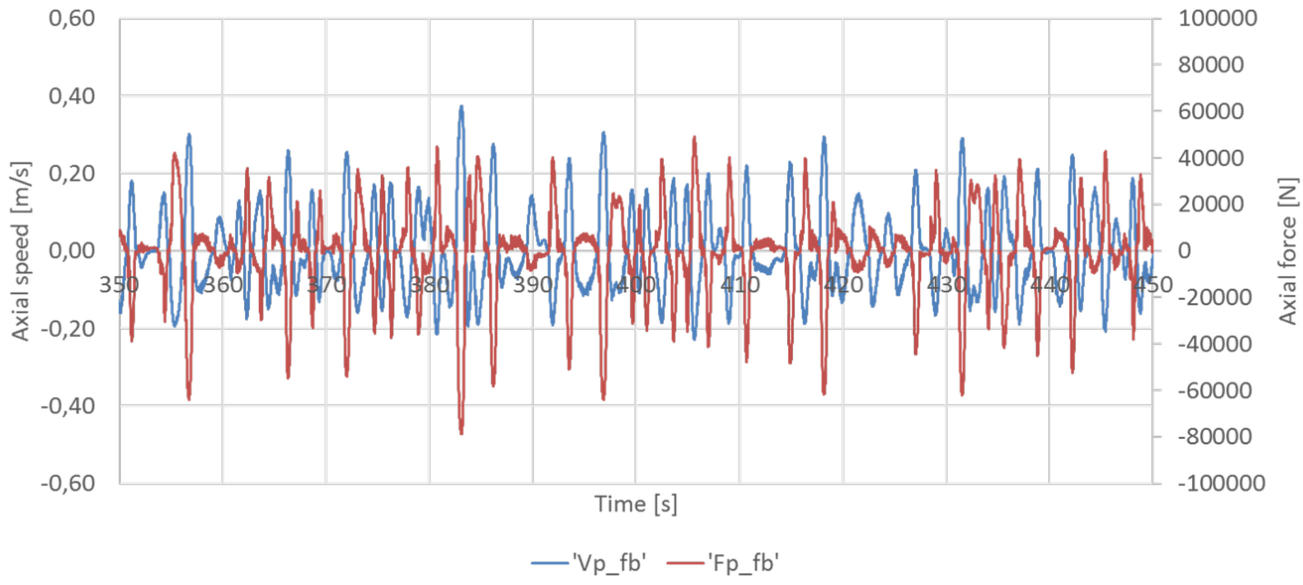

Fig. 8. Example time series measurements of force (red, right axis) and speed (blue, left axis) at the EMG axis, as measured on the test bench during one of the HWIL trials. 100 s extract from a 600 s irregular wave simulation.

as seals, biofouling and corrosion protection, that are vital for wave energy systems and present a different challenge to where UMBRAGROUP products are normally applied. The experience gained from designing and integrating with a WEC will also support the onward development and application of the EMG to meet specific WEC user requirements.

2) Test set-up: To actuate the EMG, a WEC solution was selected based on the experience gained from tank tests undertaken in 2016 using a point-pivoted WEC with integrated EMG. The point-pivoted WEC has already been extensively and successfully studied and analysed, see Fig. 9, and is based on a design by Seapower Scrl of Italy.

For the sea trials the EMG will be connected to a new version of the point-pivoted WEC tested previously. The EMG will be attached above water level to the WEC and the entire assembled support structure will be mounted to a floating gantry barge. This arrangement will facilitate the execution of a versatile range of sea trials, as the barge can be towed to and moored at different locations to expose the EMG and prime mover to different marine climates consisting of wind sea and swell based environments. This is illustrated in Fig. 10.

Having selected the Scapa Flow basin with the Orkney Islands archipelago, UK as an appropriate testing location, design work supported by 3D finite element analysis modelling of the buoy shape suitable to local site conditions and was completed in 2018. A robust support structure also designed to integrate the WEC, EMG and ensure it can be mounted securely on the barge for transit and operations. Fabrication of the buoy structure (Fig. 10b.) and the support structure was completed in early 2019.

This test set-up has required a range of ancillary systems and processes to be developed to allow the tests to occur so that the primary test objectives can

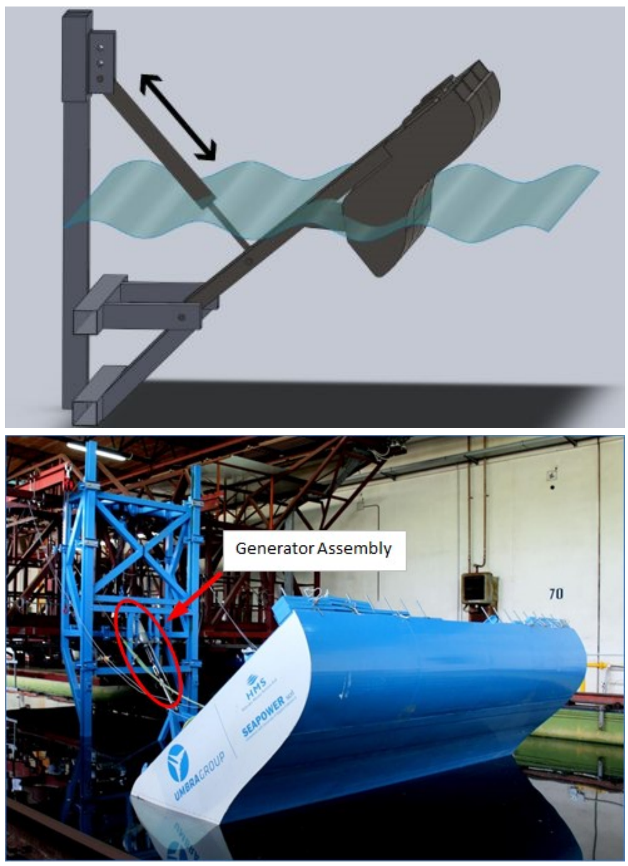

Fig. 9. a. Point-pivoted WEC CAD model indicating PTO motion; and b. 2016 tank testing of the EMG integrated into the point-pivoted WEC.

be achieved with minimal risk. These aspects, beyond the scope of the EMG development, have been project necessitates in areas of engineering interest including:

- Winch systems to raise and lower the flap for transit or in storm conditions.
- Autonomous power system (solar, micro wind, and batteries) to provide auxiliary power for the

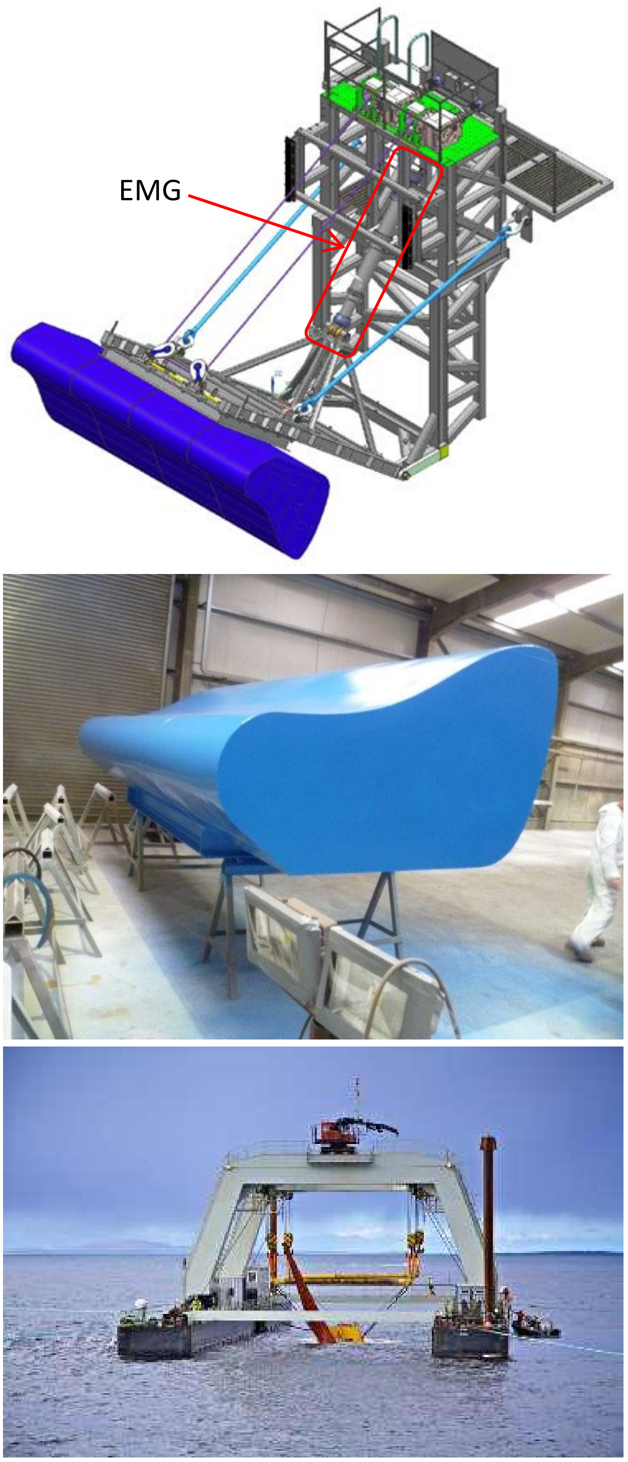

Fig. 10. a. Point-pivoted buoy CAD model with integrated EMG; b. WEC floater following fabrication; and c. gantry barge to be used for deployment.

operation of the off-grid system.

- Marine operating procedures and safety planning to ensure operations are safely planned and executed to project health and equipment.
- Communication systems to be able to record data and remotely monitor and operate the unmanned barge.
- Corrosion protection for the EMG, support structure an all ancillary systems, including the sensitive electronics housed in the container.
- A wave rider buoy deployed up-wave from the barge so that the input conditions can be accurately measured.

TABLE IV
SUMMARY OF RECOMMENDED ENVIRONMENTAL DESIGN PARAMETERS FOR EMERGE SITE IN SCAPA FLOW. [9]

Parameter	Value
Average wind speed (m/s)	4 - 7
H_{max} (m)	5.5
Average H_{m0} (m)	0.25 - 0.5
Max H_{m0} (m)	2.5
T_z (s)	1.7 - 2.3
T_E (s)	2.2 - 2.9
Directional spread	Around 40° at peak frequency
Spectral shape	Broad

The barge can be flexibly deployed to capture the most suitable sea conditions available to enable testing. The sea conditions expected within Scapa Flow have been assessed for a range of locations using available resource data sets and a preferred test location identified, see Fig. 11.

The key environmental design parameters for the preferred test site are summarised in Table IV. Records show that the lowest wave conditions occur in June and the highest in December. With testing planned in spring 2019, moderate conditions for this site should be experienced, enough to provide valuable testing inputs but avoiding the risk of extreme conditions that would prevent testing.

Depending upon the prevailing conditions the barge can be relocated to capture the best conditions available at the time to enable the testing to happen with the limited testing period. For short period energetic weather events the flap can be recovered to a vertical position using a winch system and locked down, also used during transport of the system. Equally, should any extreme conditions occur the barge can be safely recovered back to port. These measures will maximise testing time available as well as avoiding any conditions that may pose a risk.

C. *Advanced HWIL testing of larger scale prototype performance*

While the 100 kW$_p$ EMG developed in the EMERGE project is of a scale already appropriate for some WECs, many developers in the sector are working towards MW scale devices that would require a larger PTO unit, and/or multiple units in parallel. A larger EMG is therefore being developed and tested in the IMAGINE project, with key specifications shown in Table I.

Although this larger EMG is closer to commercialisation in MW scale devices, it is significantly bigger than any EMG previously tested, and thus initially is at a lower TRL. The IMAGINE project aims to demonstrate and characterise the technology at a larger scale using an advanced HWIL test bench. The HWIL test bench will be able to simulate more realistic loading for the EMG PTO over an increased range of environmental conditions. This will also allow testing of more advanced and realistic control algorithms.

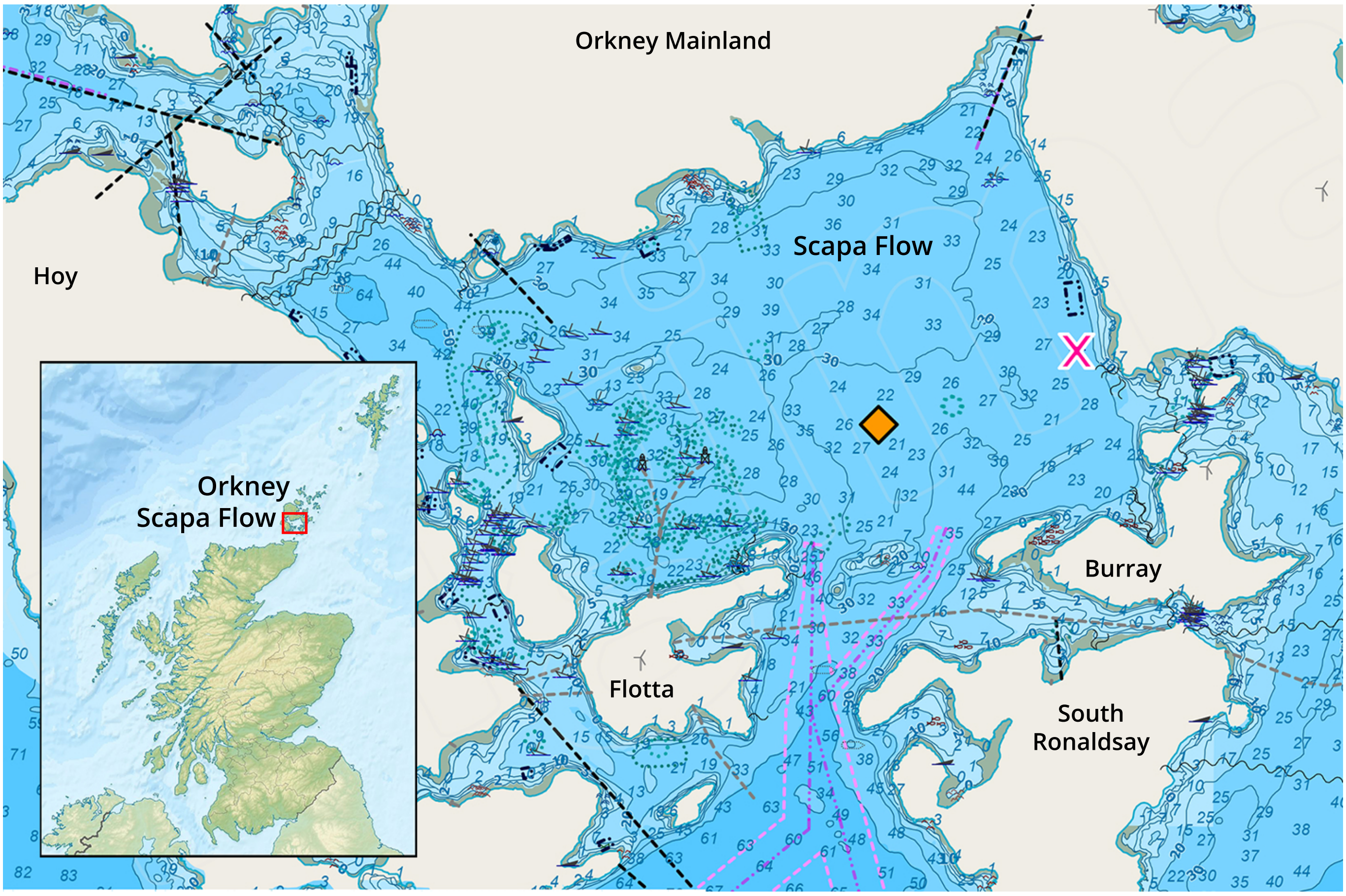

Fig. 11. EMERGE test locations in Scapa Flow – Orange diamond: EMERGE preferred test site; Red cross: European Marine Energy Centre nursery test site. [© British Crown and OceanWise, 2018. All rights reserved. Licence No. EK001-20180802. Not to be used for Navigation.]

As well as developing a HWIL test-bench for this specific application, there is an aspiration to provide a strategic test platform, and to work towards consolidating HWIL testing for the wave-energy sector. To achieve this, the IMAGINE project includes a Technical Advisory Board (TAB) of leading WEC developers including those with HWIL experience.

To investigate typical loading conditions for the EMG PTO, three generic WEC types requiring linear PTOs will be the basis for the EMG design for consideration at three typical European deployment location. The WEC designs identified cover a range of common WEC types, namely a two-body point absorber, a pressure-differential point absorber and an oscillating wave-surge converter (OWSC). To match the 250 kW$_p$ rating of the EMG PTO for this project required a scaling exercise [10] to be applied to reference cases of each of these WEC designs.

Deployment locations for WECs can be categorised into different energy classes, following [11], [12]. Medium energy (Class II) sites were considered most appropriate for the 250 kW WEC size for this project, with three different locations in western European waters selected. For each site, both normal and extreme sea-state conditions were characterised using scatter diagrams and wave roses, or exceedance plots and long-term environmental contours as appropriate [13].

The HWIL test-bench set-up will be similar to that used in the EMERGE project (described in Section III-A2), but will be at a larger scale and with the potential for more complex control algorithms.

IV. Path to Commercialisation

The development and testing programme of the EMG that has been underway since 2012 and has followed a logical development process with the EMG increasing in scale and performance in a stepwise manner as it proceeds through the TRL levels. The overall objective of this research and development activity is to bring to market a new PTO system that can be applied in the marine energy sector. How this future commercialisation is achieved is a key consideration within the commercial aspects of the EMERGE and IMAGINE projects.

All indicators and results to date, as well as future forecasts, indicate that technically the EMG can be integrated into a range of devices as it has the capability to meet the force, speed and stroke required by developers. As well as meeting these fundamental requirements, the EMG offers a unique set of capabilities to any user including efficiency, controllability, reliability, air or submerged operation and peak load handling. These capabilities can offer significant benefits to the wider WEC system but are not accounted for in simplistic integration studies where the EMG is retro-fitted into an existing PTO solution.

A critical future step on the pathway to commercialisation will be to undertake a systems engineering approach to the integration of the EMG and WEC device. This will enable all of the EMG capabilities to be exploited to optimise the overall WEC device and ultimately reduce the cost of energy. This could be achieved in partnership with an existing developer who adapts their WEC device to fully exploit the capabilities of a bespoke EMG. Alternatively, the best suited generic device types being studied in the IMAGINE project could form the basis for developing a new WEC that is built around the characteristics of the EMG.

The onwards development and commercialisation planning will form a development roadmap and business plan. This benefits significantly from this being an adaptation of an existing mature produce line, UMBRAs EMA, and the experience UMBRAGROUP SpA have in bringing innovative solutions to market and industrialising these to reduce costs whilst increasing capability and quality.

V. Conclusions

Through the work discussed in this paper, a new PTO solution for the ocean-energy sector is being developed, tested, and validated. Transferring technology from the mature aerospace industry to novel application in wave energy can help with the commercialisation of this nascent sector.

The EMG solution builds on a mature product line of linear actuators, EMAs, but adaptation requires a staged development process starting from lower TRL activity. The engineering knowledge on developing robust technology and industrial manufacturing experience of UMBRAGROUP SpA is allowing this development to happen in a robust and assured way. This gives confidence that the results achieved in early tests are validating the forecasts for the long-term industrialised EMG product.

Testing and demonstration of the technology in realistic loading conditions has required bespoke test rigs, incorporating advanced control systems to simulate the full complexity of the ocean environment. The EMG performance and costs have been validated in this work, and are meeting expectations of how the EMG PTO can contribute to a cost effective long-term marine energy devices.

The further work being undertaken to develop larger scale and higher TRL EMG's is being complimented by more detailed EMG and device integration, with both necessary to fully commercialise the technology.

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