Power Electronic Controlled Magnetic Gear (PECMAG)

WES Power Take Off Stage 3

Public Report

Oceaneering International Services Ltd

This project has been supported by Wave Energy Scotland

1. Project Introduction

The PECMAG PTO system is a modular all-electric system with magnetic gearing that is being developed to suit a variety of WEC devices, offering both rotary and linear actuator systems.

The PECMAG linear to rotary magnetic gearing system offers a wide speed range, long stroke length, high efficiency, overload survival and complex software control in a single compelling package.

A low-speed rotary to higher speed rotary system is also available, the advantages are similar to the linear version. The rotary version was not pursued in this project as the linear to rotary version seemed applicable to a wider range of WECs.

Medium scale prototypes of PECMAG systems have been manufactured and bench tested – with measurements confirming the high conversion efficiency performance figures expected from the contactless gear system.

The activities in this Stage 3 project included designing, manufacturing and testing a 10kW PECMAG, on a bench test rig and a wet testing platform, to acquire quantitative and qualitative data on the performance of a PTO system in a WEC that can achieve the long-term target LCOE of £120 per MWh.

The PECMAG prototypes have been developed with input from WEC developers, which has resulted in a thorough understanding and refinement of the PECMAG technology. Advanced studies and component testing have identified areas where performance and manufacturability improvements can be realised.

The PECMAG team will pursue opportunities to partner with WEC developers to undertake these commercial demonstration activities for utility scale wave farms and also pursue opportunities for PECMAG / WEC systems for niche markets identified to power the blue economy.

The consortium members of the PECMAG project are Oceaneering, Bathwick Electrical Design, Supply Design and Pure Marine Gen.

2. Description of Project Technology

The PECMAG system comprises a magnetic gear and permanent magnet generator coupled to an integrated electronic rectifier and control system. The PTO fits within a complete WEC system as shown in Figure 1.

The PECMAG prototype for this stage 3 project, shown as the front machine in Figure 2, is broadly cylindrical in shape and is mostly axisymmetric about the threaded bar. The magnetic gear and generator spin about the threaded bar. The threaded bar moves along the centre axis and is constrained from spinning by track wheels. The threaded iron bar acts as a linear to rotary converter causing the generator parts to spin. The rotor of the generator spins relative to the stator attached to the outer case and produces electricity in the usual way. The forces in the machine are controlled by bearings and guide wheels

The PECMAG is a contactless gear system and produces electro-mechanical conversion efficiencies greater than 80% across a wide range of speeds.

The PECMAG embodies a novel slip mechanism, which provides a failsafe to damage to the PTO system from overload conditions. The ability to overcome overload conditions, re-engage quickly and continue to operate

without long term degradation in performance provides advantages that are potentially game-changing in terms of meeting availability targets and mitigating key risks to survivability that have hampered the development of wave energy to date.

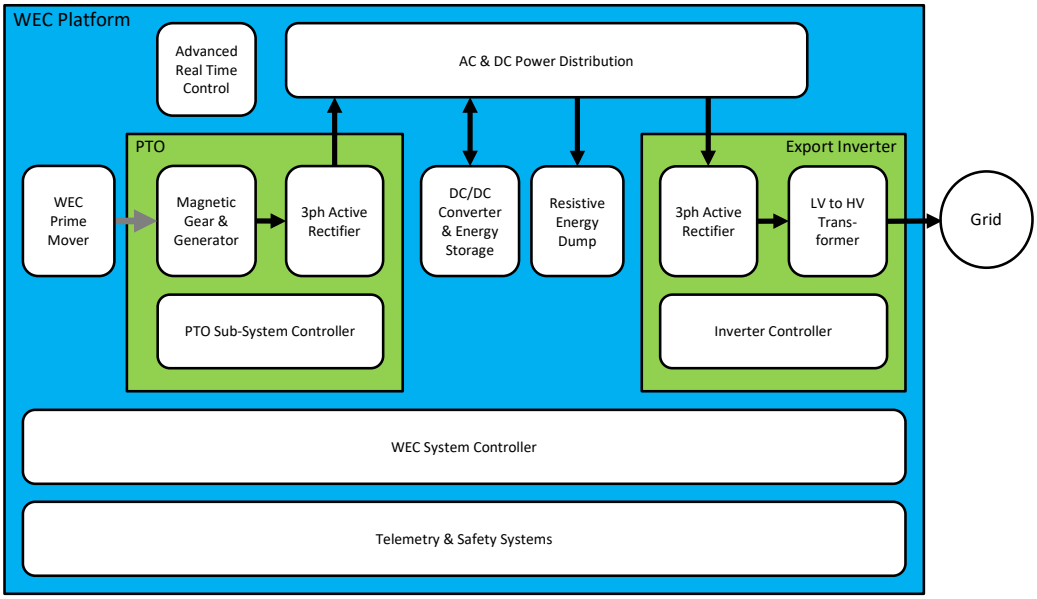

Figure 1 PECMAG System Overview

Figure 2

The PECMAG can be designed for a range of generation capacities and damping forces. It is controllable and is readily integrated into a WEC system as demonstrated by the in water testing shown in Figure 3.

Figure 3 PECMAG and IWTP under test at Montrose

Ultimately, the high efficiency of the PECMAG combined with the novel slip mechanism presents an opportunity to achieve an LCOE for wave energy less than £120 per MWh following a development pathway involving single device and small array demonstration projects.

3. Scope of Work

The Stage 3 activities were focused on achieving the following objectives:-

- Deliver a PECMAG machine to damping force in the region of 30kN and generate 10kW of electricity
- Demonstrate this capacity as well as the ability to slip / re-engage without damage.
- Wet testing an offshore PECMAG focused on WEC integration, marinisation and seagoing operability.

The goals for key performance metrics were:

- Demonstrate that “slipping” features avoid damage to system components and that the system re-engages and continues to operate without performance degradation.
- Measure power conversion efficiency, peak linear motion to DC link efficiency, that exceeded 85%.
- Design, manufacture and integrate a marinized PECMAG on a representative WEC system and operate in a real sea environment.

- Complete a FEED study, based on the scaling up of the PECMAG system, and associated techno-economic analysis to produce a benchmark for PTO systems on milestones for the roadmap towards delivering an LCOE of £150/MWh for wave energy farms.
- Complete advanced system studies on critical components of the PECMAG system to identify and quantify performance improvements that could be delivered in demonstration projects for the PECMAG in conjunction with WEC developers.

4. Project Achievements

The bench testing of the PECMAG provided measured data on performance and efficiency, which were independently certified, that enabled the system to be characterised across a wide range of forces, motions and control settings relevant to deployment in a WEC system.

The project successfully demonstrated the novel slip capability of the PECMAG in bench testing across a wide range of sinusoidal motions. Slip events occurred over one hundred times throughout the bench testing. The gear re-engaged and continued operating as expected, showing no signs of degradation. An example of results from testing slip events in shown in Figure 4.

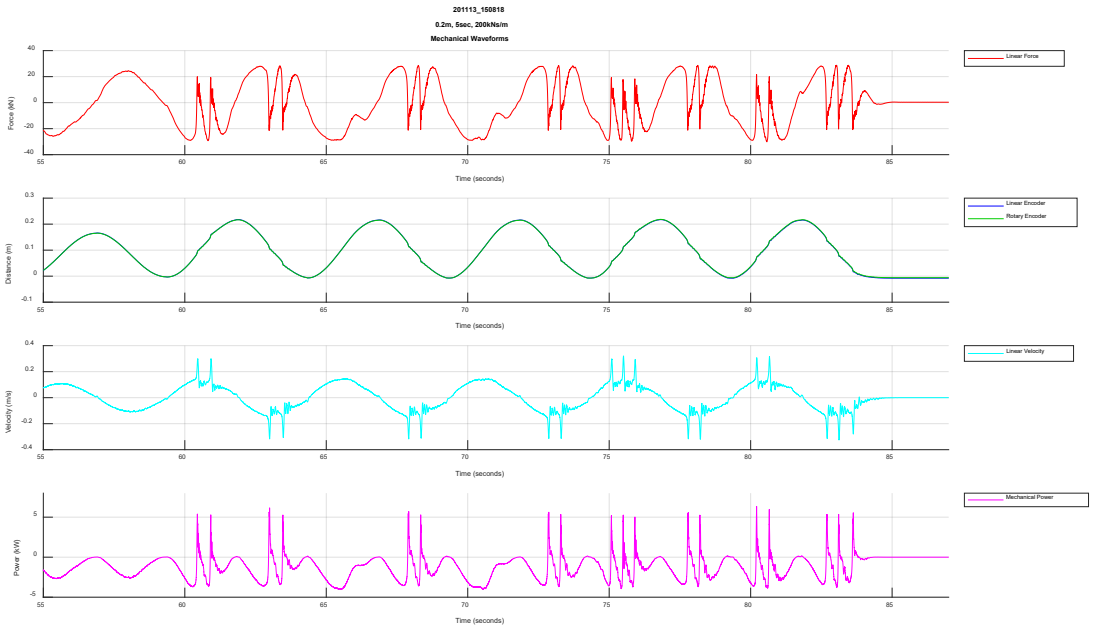

Figure 4

The peak electromechanical efficiency measured in the bench testing was 81%, and efficiencies that were greater than 70% were recorded over a wide range of wave periods and amplitudes, and controllable PTO damping settings, that matched the performance envelope the PECMAG would be required to deliver on a range of WEC systems. During the third-party verification of the results, a link between temperature and efficiency was discovered, which was subsequently linked to poor performance of the bearing selected for the prototype. The

project would have benefitted from having scope to replace the bearing and re-test to produce the higher efficiency figures that the PECMAG is capable of.

In laboratory testing the rectifier efficiency has been measured at greater than 95% when run at high constant velocity. At lower velocities the efficiency drops because the rectifier input AC voltage drops. During the sinusoidal load testing the system must travel through the less efficient lower velocities during every cycle. Despite this the rectifier efficiency for the higher velocity sinusoidal profiles was greater than 90%, peaking at 92%. At lower velocities associated with the lower wave periods and amplitudes the average rectifier efficiency dropped to below 70%. The opportunity to improve the bandwidth of the rectifier efficiency was investigated in advanced studies within the project scope. These found that further improvements in the architecture and design of the rectifier system could yield average rectifier efficiencies greater than 90% across the full speed range.

The combination of the average electromechanical efficiency and rectifier efficiency from the sinusoidal tests provided the overall system efficiency metric for the PECMAG. In the sinusoidal tests, the maximum value measured was 74%, with the system efficiency greater than 60% for most of the relevant wave periods for WEC systems. It was disappointing that an overall system conversion efficiency greater than 80% wasn't measured during the project, however, the improved bearing and modified rectifier architecture is expected to enable this key performance metric to be achieved.

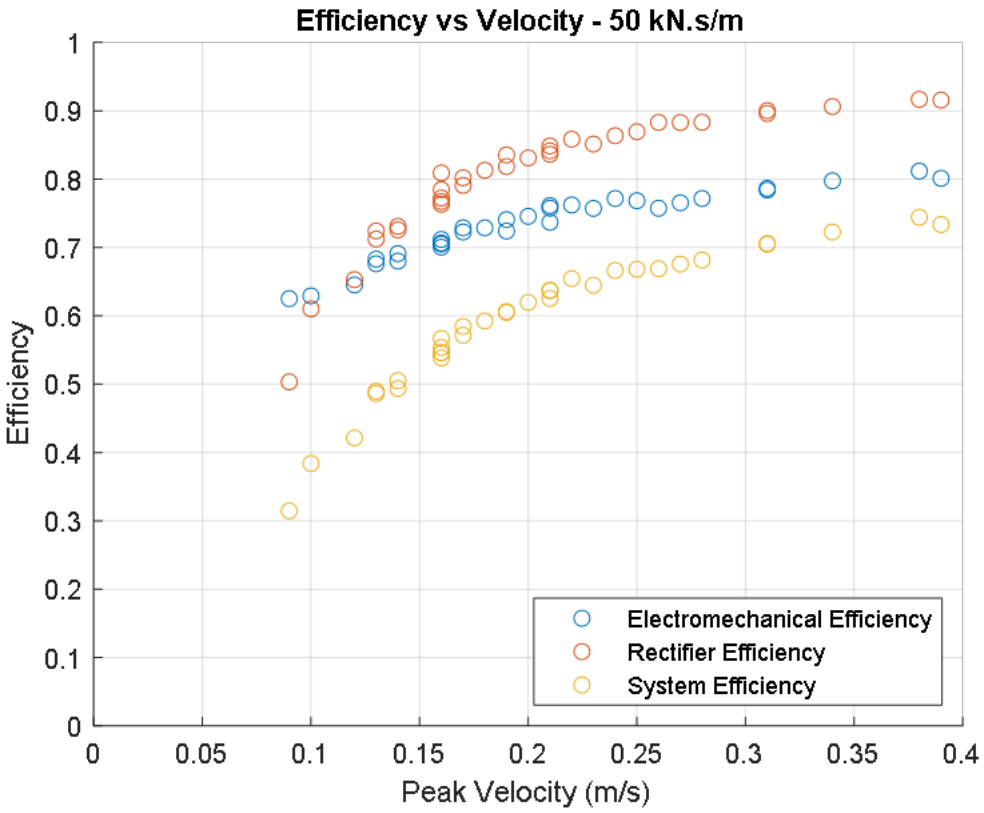

Figure 5 Results from bench testing of PECMAG

The objectives of the wet testing of the PECMAG were focused on WEC integration, marinisation and seagoing operability.

The wet testing was carried out at Montrose Port in Scotland with PECMAG and in water test platform (IWTP) deployed in the sea between 18th and 29th September 2020.

The overall layout for the In-Water testing in shown in Figure 6.

The in-water testing successfully demonstrated the integration, operation and control of the PECMAG in a WEC platform. Figure 7 shows that the rectifier successfully applied a damping torque to the generator which, when transmitted through the magnetic gear, produced a mechanical damping resistance on the IWTP, thereby extracting mechanical wave power from the sea to produce electricity.

The project would have benefitted from having a longer time window for sea testing and increased budget available to cover vessel support costs, which would have provided a greater opportunity to deploy at a more exposed test location and to exercise the PECMAG / WEC system in a larger range of wave heights.

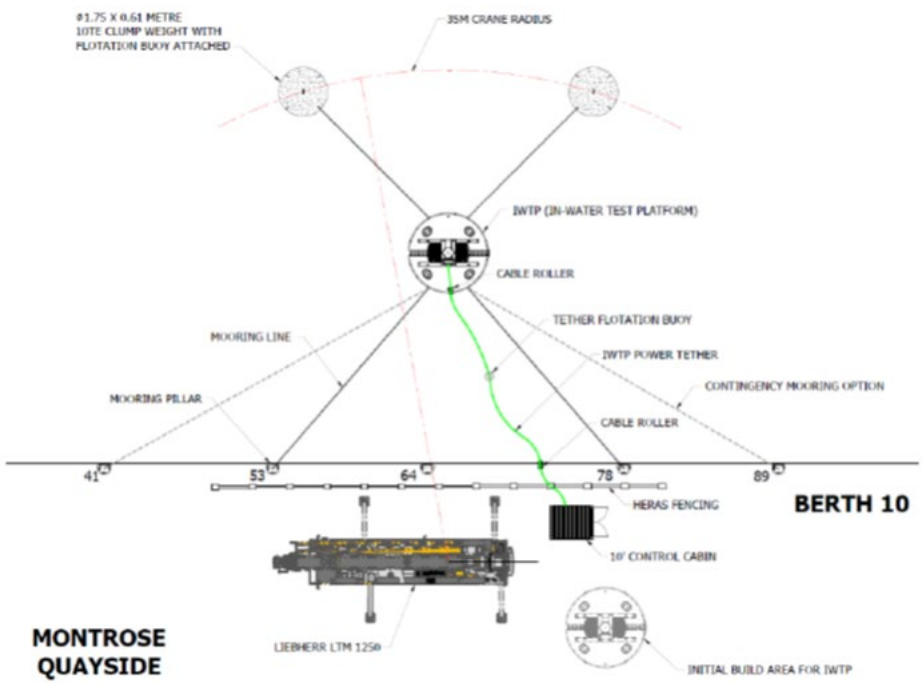

Figure 6 Mooring layout and device location for wet-testing

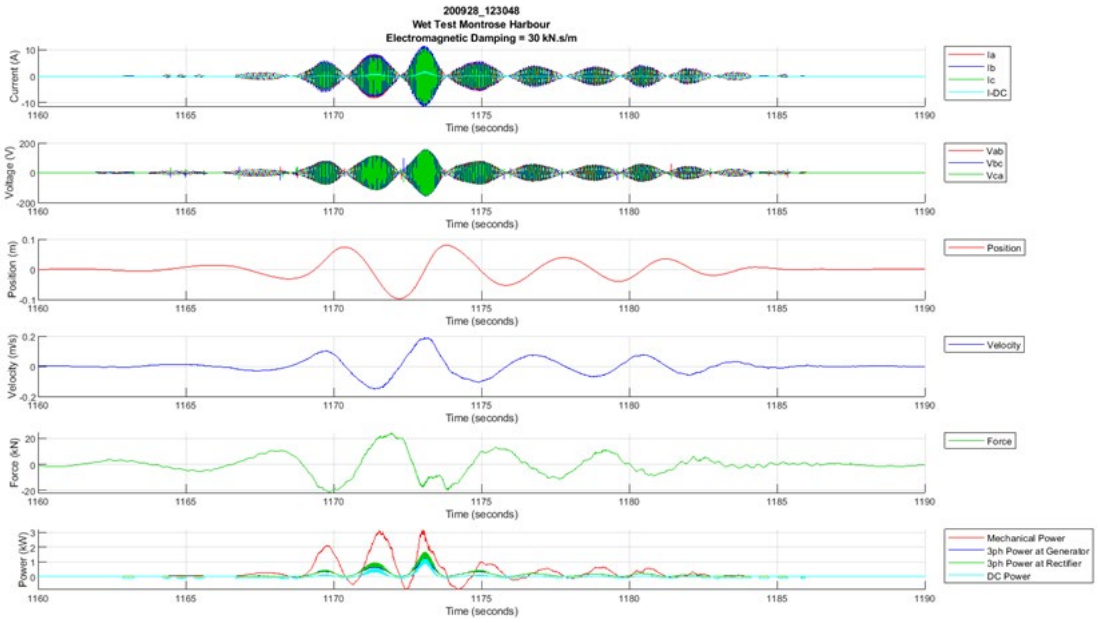

Figure 7 Example of outputs recorded during the wet-testing

5. Applicability to WEC Device Types

The weight and spatial requirements for the PECMAG compared to what was available on WECs were considered and the PECMAG was found to be compatible with all WEC types that require an electro-mechanical PTO system.

Detailed studies of the characteristics of a PECMAG needed for a point absorber, an attenuator and a multi-mode WEC were undertaken to inform a techno-economic analysis.

A FEED study developed costing for a 2MN / 500 kW gear / generator combination for a PECMAG that could be deployed in all three WEC systems analysed.

The comparisons with the FEED study costs and the targets from the reverse LCOE analysis for single WEC deployments, in Table 1, show that PECMAG is within the cost range contributing to all the WEC types analysed in the techno-economic study meeting intermediary targets on a roadmap to delivering an LCOE of less than £120 / MWh for a high resource site.

The higher AEP per required damping force for the multi-mode WEC means that a single device deployment at medium site resource levels is also within the roadmap targets.

	Resource level			FEED study costs
Device type	20kW/m	30kW/m	50kW/m	
Point absorber	£720,378	£970,329	£2,083,885	£2,280,000
Multimode WEC	£1,589,504	£2,096,327	£3,956,508	£2,050,000
Attenuator	£4,103,041	£5,558,508	£13,354,506	£7,570,000

Table 1

6. Summary of Performance against Target Outcome Metrics

Ultimately, the high efficiency of the PECMAG combined with the novel slip mechanism presents an opportunity to achieve an LCOE for wave energy less than £120 per MWh following a development pathway involving single device and small array demonstration projects.

Survivability and availability

The novel slip mechanism of the PECMAG, which provides a failsafe to prevent damage to the PTO system from overload conditions, was demonstrated. The ability to overcome overload conditions, re-engage quickly and continue to operate without long term degradation in performance sets the PECMAG apart from every other type of PTO system currently being developed. This feature provides advantages that are potentially game-changing in terms of meeting availability targets of 90% (assumed for the techno-economic analysis) and mitigating key risks to survivability that have hampered the development of wave energy to date.

Performance

The in-water testing demonstrated that the PECMAG could be integrated, operated and controlled when deployed as part of a WEC platform.

The extensive bench testing measured an overall system conversion efficiency of 74% and the efficiency metric was greater than 60% for most of the relevant wave periods for WEC systems. The peak electromechanical efficiency measured was 81% and the peak rectifier efficiency measured was 92%.

Advanced studies identified design improvements to the bearings and rectifier configuration that could be immediately implemented that would increase the electromechanical efficiency and rectifier efficiency across a wider range of speeds. The result is anticipated to be an increase in the system conversion efficiency to at least 80% across a wider range of speeds, which was the assumption used for the techno-economic analysis.

Affordability

The FEED study for the design and construction of a single PECMAG system, to provide a 2MN damping force and 500kW generator capacity, determined costs of £1,139,000 for a first of a kind system to be deployed in a single WEC device system as part of the next development step.

The techno-economic analysis showed that the costs for a PECMAG PTO system on single WEC are within the targets for a trajectory to achieving an LCOE of £120 per MWh for a large array.

7. Communications and Publicity Activity

- EWTEC conference – presentation at WES side event
- Poster & presentation at WES conference, December 2018 and December 2019
- Press release and article in 'Offshore Energy' – "PECMAG PTO system on trials at Port of Montrose", September 2020.
- PECMAG features in the new OES document "An international Evaluation and Guidance Framework for Ocean Energy Technology".

8. Recommendations for Further Work

The 10kW PECMAG has been extensively tested in bench testing. The initial deployment on the wet-testing platform demonstrated that the PECMAG can integrate, operate and be controlled in a WEC system.

The survivability and efficiency metrics proven for the PECMAG in this project position the PTO technology as one of the leading contenders to enable the delivery of LCOE for wave energy less than £120 / MWh.

A two-pronged strategy is proposed to fast-track the development and deployment of PECMAG systems and ultimately commercially attractive wave energy systems, namely

1) Scaling up the system and deploying on a single WEC in a demonstration project

- Focused on refining the engineering and manufacturing activities involved in the construction and integration of a PECMAG
- Maintaining and improving the efficiency of the PECMAG in larger systems
- Establishing maintainability metrics for longer term deployments

2) Increasing the number of PECMAG systems deployed in small-scale systems for R&D activities or off-grid applications

- Focused on increasing the operational time and performance data for existing PECMAG designs
- Implementing efficiency and design improvements identified in WES Stage 3 project
- Generate market opportunities linked to "Powering the Blue Economy", such as for ocean observation systems.

If funding was available, the PECMAG and wet-testing platform could be deployed at the sheltered test site at EMEC. This would achieve one of the immediate priorities identified, namely increasing the operational time and performance data when operating in a WEC system in real wave conditions.