Power Electronic Controlled Magnetic Gear PECMAG

WES Power Take Off
Stage 1 Project
Public Report

Ecosse Subsea Systems

This project has been supported by Wave Energy Scotland

1 Project Outputs

1.1 Project Introduction

The project is part of the Wave Energy Scotland (WES) programme to explore new solutions to improve the performance of power take-off for a variety of Wave Energy Converters (WECs). This Stage 1 project explored the feasibility of a power electronics controlled power take-off (PTO) utilising a magnetic gearing and efficient power converter solution (referred to as PECMAG in this document) to deliver an outstanding technology solution capable of creating a new benchmark for PTO performance.

The PECMAG PTO system for wave energy converters is a modular all electric system with magnetic gearing, which has been developed by Ecosse Subsea Systems (ESS), working with Supply Design (SDL), Bathwick Electrical Design (BEDL) and Pure Marine Gen. (PMG). The project team covers a wide array of capabilities to enable them to design, construct, deploy and maintain PTO systems for wave energy converter systems through its proven experience in:

- Offshore Engineering & Deployment
- Design of High-Efficiency Power Electronics & Control Systems
- Design & Construction of Novel Magnetic Gear & Generator System
- Design of Wave Energy Systems.

The aim of this PTO project is to tackle well-known challenges using a high-performance magnetic gear empowered by highly configurable power electronics and control. A successful project will see our approach eradicate many of the problems and limitations of the predominantly standard approach, a hydraulic based PTO, and enable new performance benchmarks to be created.

1.2 Description of Project Technology

The PECMAG system consists of a magnetic gearing system coupled to and controlled by a permanent magnet generator and electronic rectifier. The magnetic gear is available in both rotary and linear forms, enabling its use across a variety of WEC applications.

Each modular PECMAG PTO consists of gear, generator, rectifier, voltage converter that connects via a system inverter to the grid and, depending on the configuration, this can be added in single or multiple modules that can be connected in a variety of configurations. The system installation flexibility enables blocks to be configured to suit the WEC applications. For example, part of the system can be on device, with other parts on a floating platform or back on-shore to optimise performance and reduce energy storage costs.

Features include:

- The gear can slip without damage should forces/torques above the rated values be applied to the machine.
- Use of digital control to provide precision system damping, regulation and smoothing. The high-resolution techniques enable multiple corrections throughout wave duration to enhance performance.
- A re-configurable micro-processor based control architecture that can accept signals from other sensors and systems to increase performance and safety.
- The magnetic gearing can be either slow-linear to fast-rotary, or slow-rotary to faster-rotary.

- Scalable power modules that can be connected in series and/or parallel to suit application power, reliability and efficiency requirements.
- The gearing can be high, ratios of 100 or 200:1 are readily possible.
- The gearing is non- contact, apart from bearings, so the system has a high resistance to wear.
- The machine may be readily controlled by varying the force/torque at the generator.
- The ability to connect one or more rotary electrical generators controlled by one or more electronic power converters.
- The power converters and gear can electrically disconnect under fault conditions.

Enabling the PECMAG PTO to:

- Provide robust protection against primary failure modes within the PTO system that could impact on the survivability of the entire WEC system.
- Operate with partial failure to increase availability and reduce overall system maintenance costs.
- Provide a range of forces and speeds for a variety of WECs, including point absorbers and attenuators, for their primary absorption step.
- Convert the power absorbed to electricity at efficiencies that exceed 80% across the full range of operating wave conditions for sea-states at prospective sites for WEC deployment. Base construction >80%, and >85% with a series-parallel combination.
- Meet CAPEX and OPEX targets for the PTO system component to enable WEC systems to achieve lower LCOE. Further price reduction is possible with modular construction and multi-industry purchasing power.
- Reduce environmental impact as there are no hydraulic fluids, or potential environmental contaminants, that would result from a system failure. From a legal, regulatory and certification perspective the PECMAG system should be readily accommodated by extending existing processes in this area from related industries like offshore oil & gas.

1.3 Scope of Work

The study aimed to prove that the PECMAG solution could solve some of the critical challenges associated with wave energy capture, and then evaluate the performance potential using hydrodynamic, system and LCOE modelling.

The study focuses on the key technology at the heart of the PTO, the magnetic gear, generator, and AC-DC converter, where innovation would make the highest impact on performance and cost. Each sub-system element is characterised as part of the overall PECMAG system with the specifications & trade-offs outlined.

A breakdown of the main activities includes:

- Outline electrical plus mechanical design & cost study of a linear to rotary magnetic gear and integrated generator.
- In-house BEDL finite element code EFFE™, to be used to carry out electromagnetic analysis and mechanical stress analysis.
- Design & cost study of power electronics solutions.
- Development of integrated system models and estimated conversion efficiencies.
- Development of Simulink models.
- First pass coupled analysis modelling, using Flexcom™, to determine the energy production associated with PTO capabilities.
- Using calculated energy production figures for LCOE modelling of the PTO within an overall WEC device.

1.4 Project Achievements

The feasibility study outputs from the design, analysis, numerical modelling and bench testing of vital components, has helped to quantify and demonstrate the fundamental advantages of the PECMAG PTO system. These results highlight how the PECMAG system can help the industry improve upon critical performance metrics required to meet the LCOE targets set for wave energy.

The key findings, highlighted in section 1.6, were generated from the result of modelling a variety of sea states, magnetic gear & power converter designs & configurations. The work unearths a variety of design options, showcasing the PECMAG flexibility, which can be tailored to different systems and conditions to improve overall WEC performance.

A greater understanding of the complexity of wave energy was also significant achievement for the project team. Wave energy is very complex with a large number of trade-offs, challenges and unknowns; this project has accelerated the knowledge sharing and the education of new entrants into the industry, but further efforts would be appreciated to reduce the chance of the new entrants falling into the same traps as previous companies. We would encourage additional efforts to be carried out in this area to further disseminate and accelerate knowledge sharing. Overall, the optimum solution is highly dependent on the device type, single device or array deployment and the specific system architecture (multiple variables). The difficulty in trying to evaluate multiple options made the overall project very broad. For specific use cases more detailed analysis, trade-offs and system design will be required to determine the best solution.

In addition, the project brought together new partners and technologies that wouldn't have otherwise have happened. This has provided an opportunity for smaller companies to compete, and bring new business opportunities, as well as cross-industry and discipline knowledge sharing. The funding has kicked-off technical and business relationships that have the ability to tackle the wave energy challenge, among others.

1.5 Applicability to WEC Device Types

The PECMAG PTO is compatible with most WECs which feature a linear or rotary slow velocity, high force or torque primary drive. The PECMAG is not likely to be of interest for machines which employ high-speed mechanisms such as air turbines.

The PECMAG can be deployed on point absorber, attenuator, oscillating wave surge converter, internal moving mass and terminator systems that utilise a mechanical or hydraulic PTO as the primary power capture system. The PECMAG project has identified that there is currently an addressable market of about 10 wave energy converters that might demonstrate the ability to meet commercial performance metrics over the next 12-18 months that present an immediate customer base for a small scale (1-10kW) PECMAG. These devices represent the second generation of wave energy converters that are building on lessons learnt from pioneering projects and have been identified through their success in the US Department of Energy's "Wave Energy Prize" and the Wave Energy Scotland "Novel Wave Energy Converter Competition". There are nine WEC devices that have demonstrated the potential to meet commercial performance metrics as evidenced through selection as finalists for the US Department of Energy's Wave Energy Prize competition.

The PECMAG PTO system could potentially be integrated into multiple device types, namely:

- Multi-mode point absorber
- Terminator
- Differential point absorber
- Combined OWSC and Heaving Device
- Point absorber with latching/de-clutching control.

One of the PECMAG project team members, Pure Marine, is employed as WEC designers by the Sea Potential team developing the DUO for the Wave Energy Prize and has direct access to the decision making for subsequent development steps and technical details for this device. Additionally, it is likely that a number of the devices selected by the Wave Energy Scotland "Novel Wave Energy Converter Competition" will demonstrate performance metrics competitive with the Wave Energy prize finalists and of the eight devices there are five that the PECMAG could potentially be integrated with. Members of the project team have previous commercial links with, or have had preliminary discussions on cooperation and collaboration with WEC developers.

Other wave energy converter systems being tested at sea and at a larger scale offer opportunities for retro-fitting the PECMAG to replace the existing PTO systems being trialled. These companies can be approached to determine opportunities for collaboration on the development and testing of the larger scale 100kW – 1MW PECMAG.

1.6 Summary of Performance against Target Outcome Metrics

AFFORDABILITY:

The cost assessment of the magnetic gear and generator provided evidence that the PECMAG could meet the torque/force capacity requirements of the WEC system at a similar cost to a hydraulic system at this early stage. This is illustrated in the numerical modelling of the WEC system with the integrated PECMAG PTO (WES_WP3-DOC_Rev_A.0). However, beyond this, the potential to reduce costs per 'Watt delivered' is much greater with a PECMAG system.

The cost of a hydraulic PTO system comprising of the cylinders, accumulators, pump motors, control valves, pipework, reservoir and hydraulic fluid, is c.£43 per kN (at limited speeds, restricting power capture). This price factors in components from an established sector making significant cost reductions unlikely.

The new technology PECMAG, pricing should be similar to that of the hydraulic system at higher volumes. Since the rated speed of the PECMAG can be much higher (>10x), than that of a system based on hydraulic rams, the potential to produce more power for the same cost is much greater. Furthermore, the PECMAG cost will reduce with increased quantities (potentially wave and other renewable sectors), and technical and manufacturing maturity improvements over time.

PERFORMANCE AND ENERGY CONVERSION EFFICIENCY:

The energy conversion efficiency was investigated by developing designs for the magnetic gear and the rectifier system that could meet the PTO control requirements and that could be integrated within a WEC.

The conversion efficiency characteristics of the gear and rectifier system were determined from simulation and bench testing of key components and concluded that a magnetic gear input to rectifier DC output efficiency of over 85% is achievable.

The characteristics of the PECMAG, incorporating torque and speed limits, were modelled in a WEC system using coupled analysis, time-domain software to calculate the resulting power capture of the WEC system. The results of the numerical modelling showed that the PECMAG PTO system can provide the force / torque and speed characteristics needed to optimise the power capture of a WEC from potential sites for commercial scale wave farms.

AVAILABILITY:

The assessment of the reliability and maintainability of the PECMAG system indicated that it is likely to contribute to an overall availability of a WEC system of over 90%.

The low number of component parts of the PECMAG, compared to other options like hydraulic systems, means that the probability of unplanned failures is significantly reduced. The absence of control valves, dynamic seals, pipework and hydraulic fluids is particularly relevant to this as lessons learnt from sea trials of wave energy converter systems indicates that these components have struggled to demonstrate adequate reliability to date.

SURVIVABILITY:

The PECMAG PTO system provides robust protection against primary failure modes in the PTO system that could impact on the survivability of the entire WEC system.

The bench testing of the magnetic gear demonstrated that any excessive torque results in the magnetic “teeth” slipping without any mechanical damage or heat transfer that would result in a system failure and require replacement. This characteristic of the magnetic gear system provides passive protection against the failure mechanism for an electronic PTO due to over voltage at the rectifier input. Preliminary system design studies show that the rectifier solution for PECMAG can apply an excessive torque in order to make the gear jump “teeth” to protect against over-speed and thus over-voltage events. This property enhances survivability by removing an intrinsic weakness in a geared solution.

1.7 Communications and Publicity Activity

A paper describing the magnetic gear technology with particular application to wind turbines is of relevance to the WEC PTO problem as the main challenges are similar, eg harsh environment, high torque low speed input, random and widely fluctuating input. UK Magnetic Society seminar on Novel Machines Feb 2015: *A Novel Lightweight Wind Turbine Generator D Rodger HC Lai, J Outram*

A paper describing some of the findings of this feasibility study was accepted for the International Conference on Offshore Renewable Energy CORE 2016. 12-14 Sept 2016 Glasgow: *ALL ELECTRIC PTO WITH MAGNETIC GEARING FOR WAVE ENERGY CONVERTERS M. Cowie, M. Wilson, D. Rodger, H.C. Lai, C. Britton, M. Brand and P. Brewster*

A poster was presented at the WES NWEC workshop 18th /19th April 2016 : *MODULAR ALL-ELECTRIC PTO WITH MAGNETIC GEARING - Scalable high performance PTO for a variety of Wave Energy Converters types*

1.8 Recommendations for Further Work

The magnetic gearing system can be implemented in a rotary or linear format. The electrical generator could in principle be any type of electrical machine - permanent magnet (PM), switched reluctance (SR) or induction. These permutations give rise to many possible projects, however we believe that a linear to rotary gear cooperating with an integrated PM generator would be the choice that would be compatible with most WECs. The reasons for this choice are fairly simple, many WECs have a naturally reciprocating action, and PM generators are generally efficient even at relatively low speeds.

A back to back arrangement of two machines can potentially allow testing to take place where one machine acts as the input force to the other machine which acts as a generator. This means that a specialised input machine would not have to be designed and built separately.