Power Electronic Controlled Magnetic Gear (PECMAG)

WES Power Take Off Stage 2 Public Report

Ecosse Subsea Systems Ltd

This project has been supported by Wave Energy Scotland

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 system offers a wide speed range, long stroke length, high efficiency, overload survival and complex software control in a single compelling package.

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

The PECMAG prototypes have been developed with input from WEC developers, which has resulted in a thorough understanding and refinement of the PECMAG technology. The testing and LCOE modelling undertaken in the Stage 2 project has identified areas where performance and manufacturability improvements can be realised.

The Stage 3 project will extend the bench testing and refinement to include the bearings and assembly / manufacture processes for the gear system culminating in wet testing in real sea waves on a WEC test platform.

The consortium members are Ecosse Subsea Systems, Bathwick Electrical Design, Pure Marine Gen, and Supply Design.

Description of Project Technology

The PECMAG system is comprised of 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.

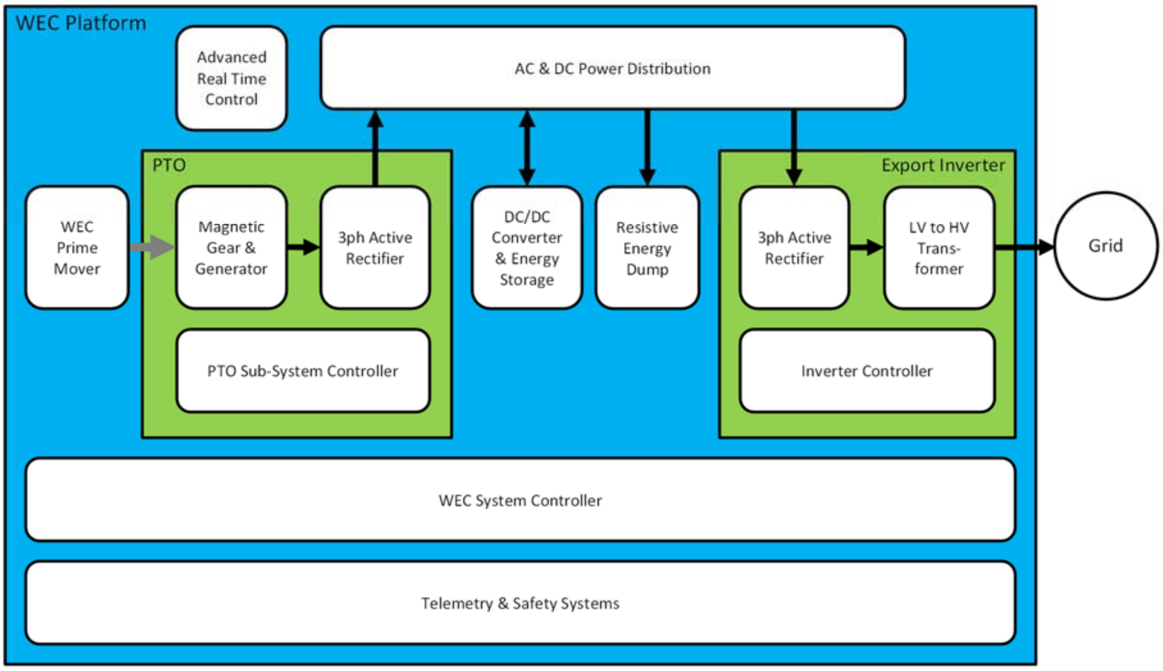

Figure 1 System Overview

The magnetic gear can be developed as a rotary or linear system as shown in Figure 2 & Figure 3.

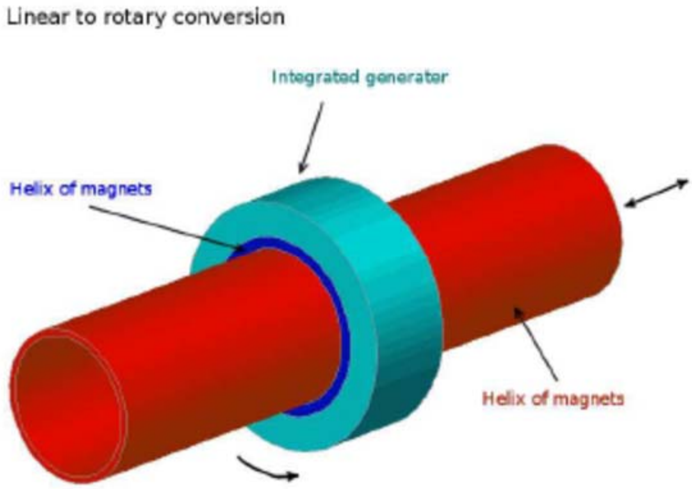

Figure 2 Linear gear schematic

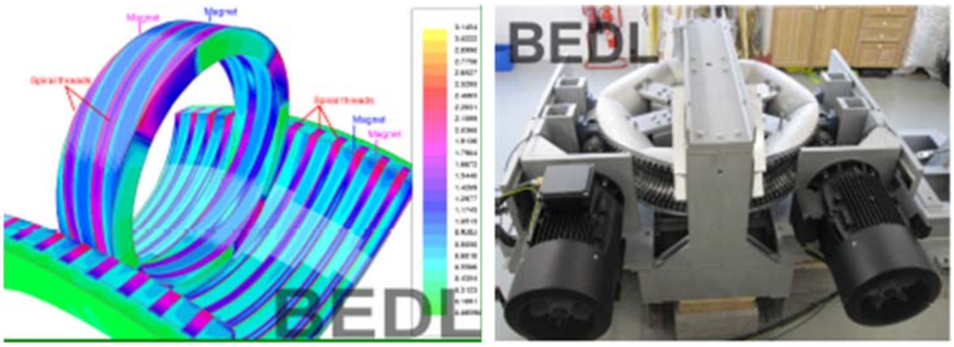

Figure 3 Existing rotary prototype

Scope of Work

The Stage 2 project involved the following activities:

- Assessment of the unit sizes and capacities that WECs would need for testing an intermediate scale and large-scale prototypes to inform the customer requirements that PECMAG units would be developed for.
- LCOE analysis employing the key performance metrics of the PECMAG on WEC systems that can achieve the £150 per MWh target.
- Design and construction of a 30kN / 10kW unit.
- Testing of the magnetic gear and rectifier systems to obtain efficiency and performance data.
- FEED Study on the integration of the PECMAG on a WEC.
- Plans for Stage 3.

The focus of this project was to design, build and test a prototype to confirm the efficiency and control features of the PECMAG and identify opportunities for cost reduction and performance improvements for subsequent integration and wet-testing on a WEC in a Stage 3 project.

Project Achievements

A rotary system with a torque capacity of 15kN was developed previously by BEDL. This Stage 2 project focuses on the design, construction and performance testing of a linear system with a force capacity of 30kN and a stroke of 0.5m.

The test rig consists of a motor driving a generator through a linear magnetic gear. The motor drives a magnetic gear which surrounds a threaded round iron bar. The generator is driven by its own magnetic gear which surrounds the same iron bar.

It is therefore possible to use the motor to rotate the magnetic gear so that the threaded bar moves. The moving bar in turn rotates the generator through its magnetic gear.

If required, it is possible to use both machines as motors so that the combined axial force results in a rig which could produce a force up to about 6.5-7 tonnes. This means that the existing test unit could be used for commissioning other PECMAG units develop for prototype sea trials in a Stage 3 project.

The 30kN prototype constructed for the Stage 2 project in shown in Figure 4. The space envelope is 1.2m diameter by 1.75m long. The large, open design is due to the back to back configuration, requirement for access, modularity and torque measurement. A real machine of the same rating would be the same length and about 0.5 to 0.6m diameter, as shown in Figure 5.

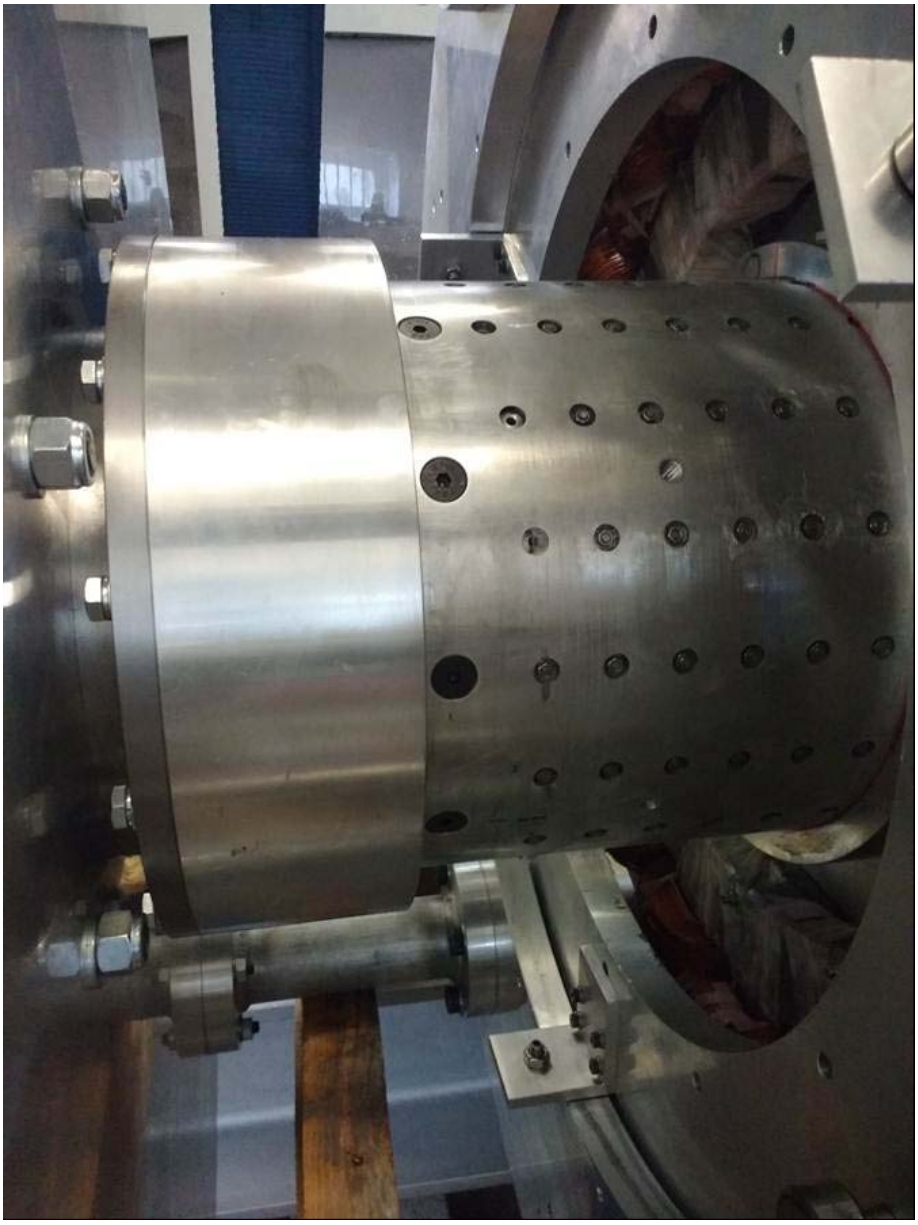

Figure 4 Test rig.

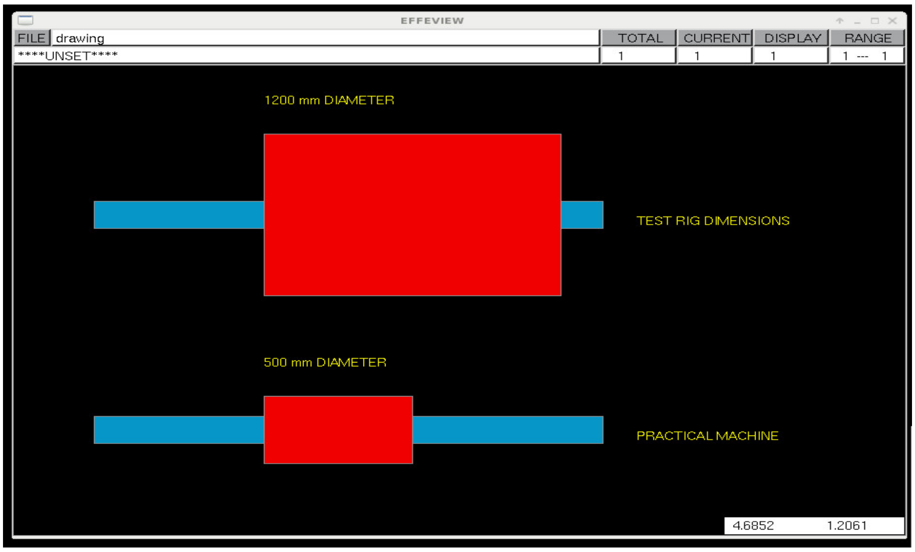

Figure 5 Relative dimensions of a practical machine

Design

BEDL designed and built two magnetic gears and two motor/generators for the rig.

Some key details are given below.

MAGNETIC GEARS

Ultimate loads

The load capacity of the gears is easily estimated by multiplying the overlap area by the shear stress of the configuration. In the present case of the magnets on one side facing an iron thread, the shear stress is about 200kN/m/m, which is 5-10 times that of a conventional electrical machine of the same force rating. It is in fact slightly more than the 180kN/m/m quoted for a superconducting wind turbine.

Failure modes

The magnetic gear is completely passive, so the failure modes are mostly restricted to bearings, fastener failure, bending under mechanical stress.

Bearings:-

The machine will fail if the supporting bearings fail, in common with most other machines which involve moving parts. The high thrust forces along the axis of the machine must be managed, either by mechanical bearings or by magnetic bearings.

Speed:-

There is no sensible fixed upper limit to the linear speed of the mover, for example, the high pressure moving seals that restrict the upper speed of a hydraulic ram. Since the gear magnets are on the inside of a spinning cylinder, centrifugal forces are not a problem.

An integrated permanent magnet (PM) generator could be of the exterior rotor or interior rotor variety. An external rotor machine would also have no magnet retention problem. In this case we designed a bespoke interior rotor generator.

Bending:-

The force between the magnets and bar are theoretically zero if the bar is perfectly centred inside the magnet carrier. This ideal is unlikely to be possible, so finite element models of the offset bar were run to find out if the forces were manageable.

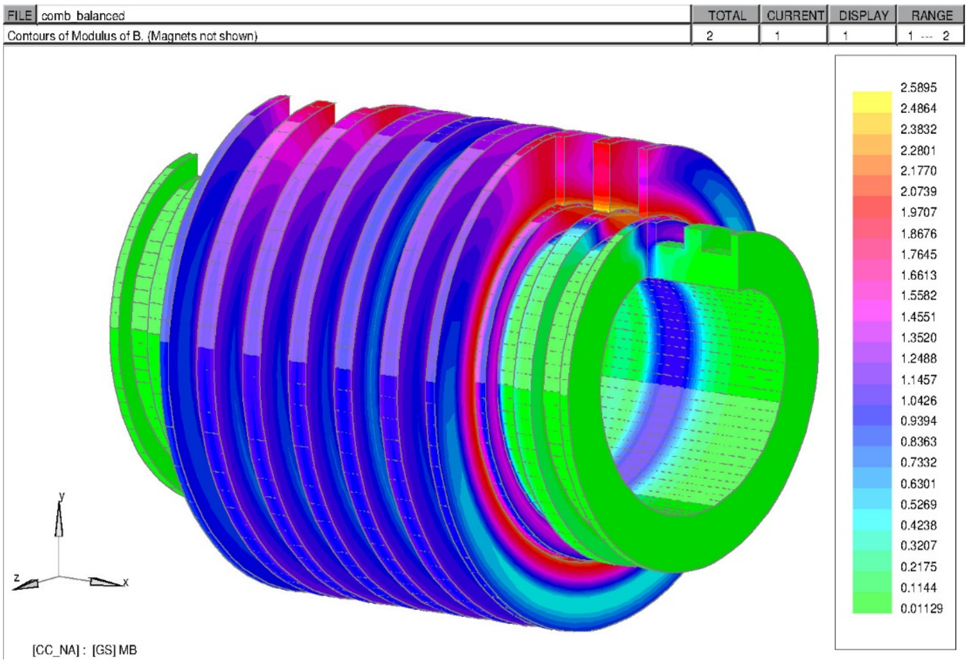

Figure 6 Finite element model of a section of the machine.

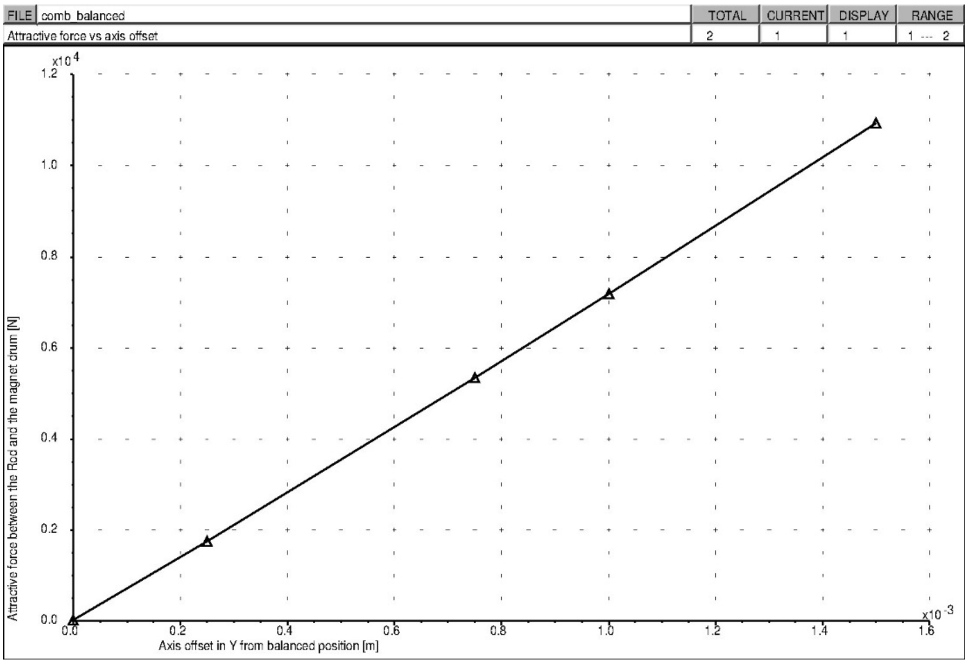

Figure 7 Unbalanced radial force versus displacement.

MOTOR/GENERATORS

Two bespoke motor/generators were designed for the rig. It was shown that generator efficiencies of over 95% with a simple construction not requiring expensive winding machines can be realised.

Performance

Efficiency:

The gear efficiency is a function of torque and to a lesser extent, speed.

Slip when force limit exceeded:

When the design force is exceeded, the gear will pole slip and immediately re-engage when the force falls below the limit.

Scaling to larger units

The test rig/technology demonstrator built in Stage 2 was built around a solid iron bar, 3m long by 200mm diameter. Larger capacity machines could be constructed in several ways, by using several smaller machines in parallel or by using a smaller number, perhaps one, of larger machines. Either way, a hollow pipe preferably based on a standard section could be used for larger machines.

Long strokes imply a long mover, in some cases significantly longer than the spinner part of the gear. Since the mover is made from relatively inexpensive material, this should not cause any undue increase in price.

The force produced by a magnetic gear is simply the product of the overlap area and the shear stress, so the cost of the active magnetic materials should increase fairly linearly with increasing size.

Rectifier

For Stage 2, Supply Design produced 2x 10kW lab prototype rectifiers and a 10kW back to back motor test rig with a 1:1 magnetic coupling as shown in Figure 8.

Design description of Rectifier test rig

The back to back 10kW motor test rig with magnetic coupling is shown in Figure 9.

The back to back rig allows us to simulate the rotational motion of the PECMAG generator in sympathy with incoming waves. The system contains a significant inertia on the input side, simulating the mass of the prime mover.

Design issues

The design, build and testing of the rectifier has been surprisingly smooth. The largest issue has been vibration within the 10kW back to back test rig's magnetic coupling. The outer section of the coupler can be moved left and right to increase or decrease the maximum sheer force. This mechanism would benefit from some reinforcement as it is prone to vibration at higher loads.

Performance

The rectifier's performance has shown to be very suitable for a wave energy application. The basic single rectifier has the performance profile shown in Figure 10.

Peak rectifier efficiency exceeded 95% during testing.

An electronic rectifier has the potential to be highly efficient right across the operating range of a WEC.

Scaling to higher power

Single six switch electronic rectifiers may be operated up to the MW level by using suitably sized IGBT switches. These topology is also capable of being operated in parallel. This allows large power capabilities to be constructed from an array of smaller devices. As with data centre applications, redundancy and automatic switch over solutions may be incorporated into a multi-unit architecture. This has the potential to greatly improve system reliability and availability.

As WECs are relatively inaccessible locations, it is likely that maintenance will be extremely costly. The PTO electronics hardware is inexpensive when compared to other systems. A relatively small increase in CAPEX costs is therefore likely to yield a significant benefit in LCOE if availability can be increased.

Future improvements & opportunities

The following areas for improvement were identified during the project.

- Paralleling, Super Caps & Battery Storage Architecture
- Alternate Overspeed Strategies
- Active Vibration and Oscillation Damping

Further work and collaboration with WEC developers will be required to fully quantify the benefits.

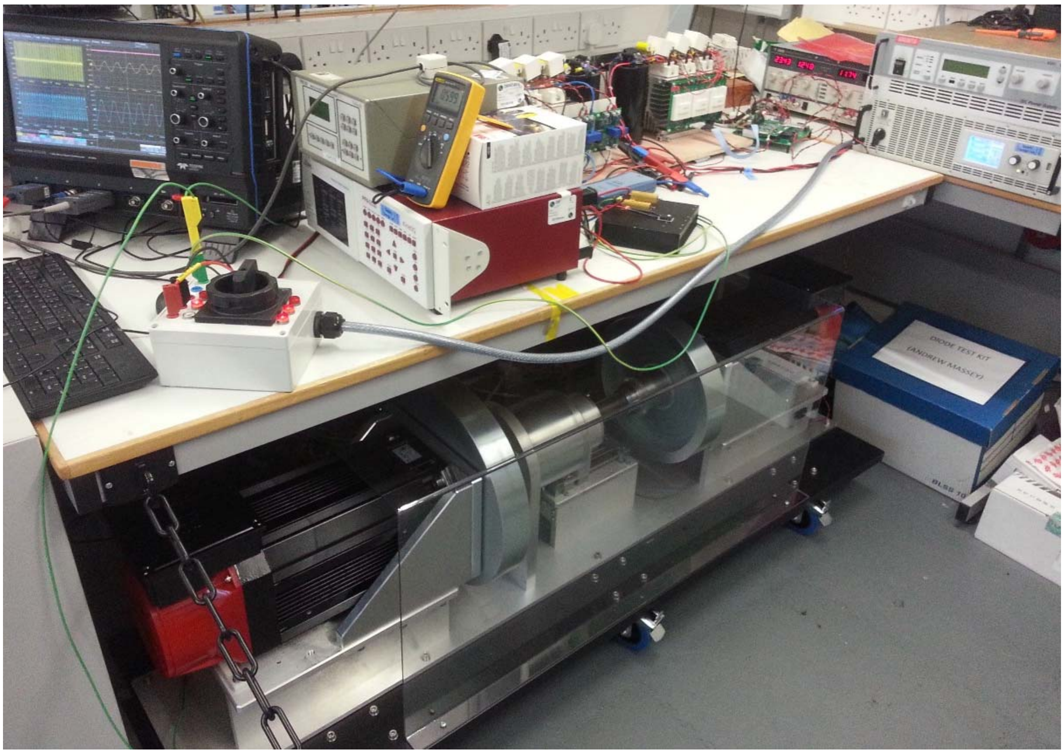

Figure 8 Rectifier test setup

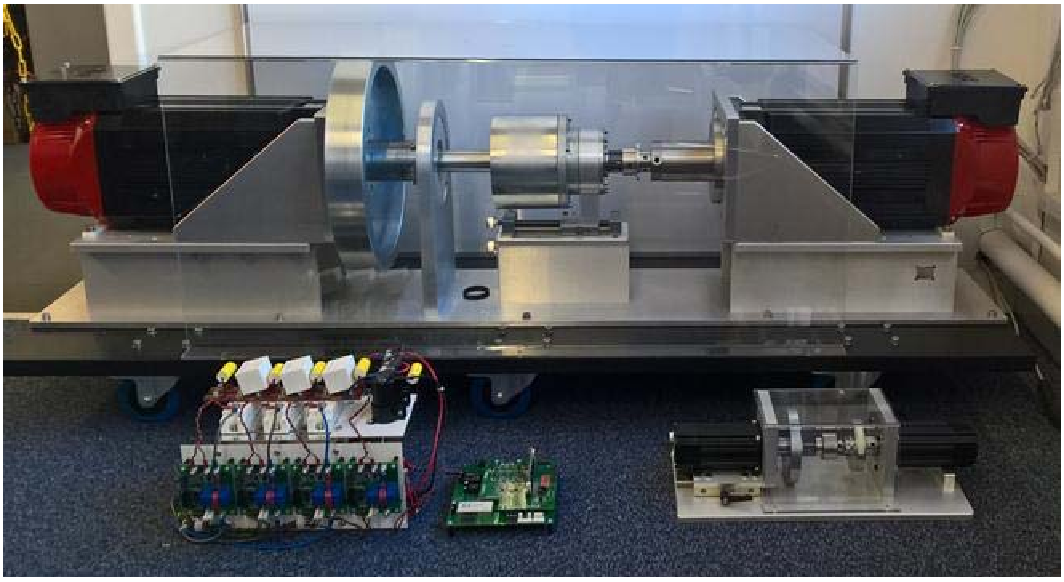

Figure 9 10kW rectifier test rig

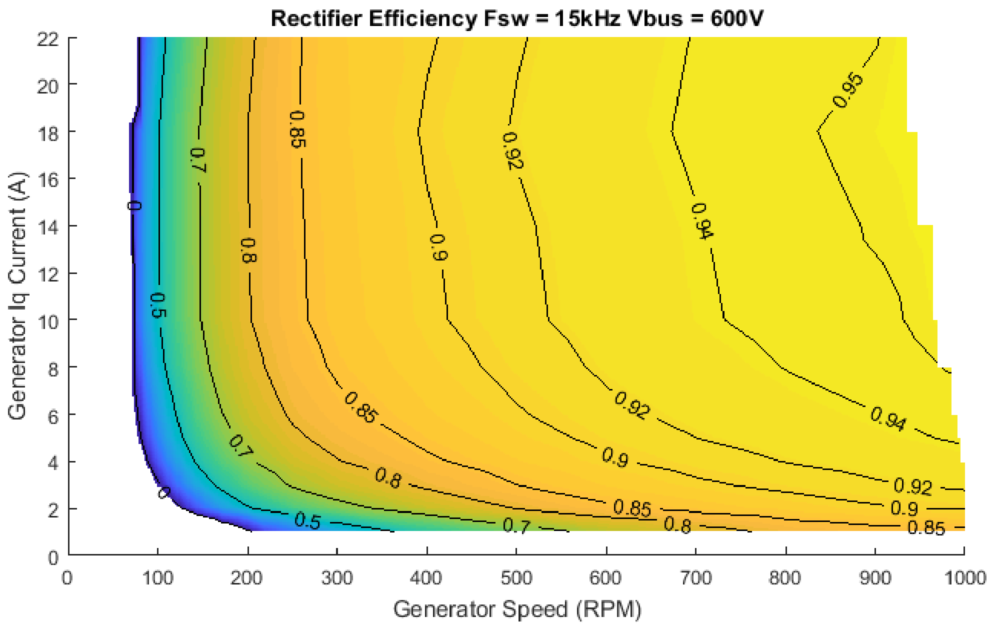

Figure 10 **600V DC link, 15kHz switching efficiency surface**

Integrated Rectifier & Control system

Electrical Compatibility

The primary purpose of our initial testing was to demonstrate compatibility between the rectifier and the magnetic gear's custom generator. The plot in Figure 11 shows the response of the rectifier to a burst of motion from the magnetic gear. In the plot, the system is configured to act in constant damping mode (iq current increases with AC frequency) up to a current of 10A. At this point the system transitions to constant torque (current) mode. Once the system velocity reduces, the system returns to constant damping mode.

It is clear from this plot that the electrical and mechanical aspects of the system are capable of operating in tandem.

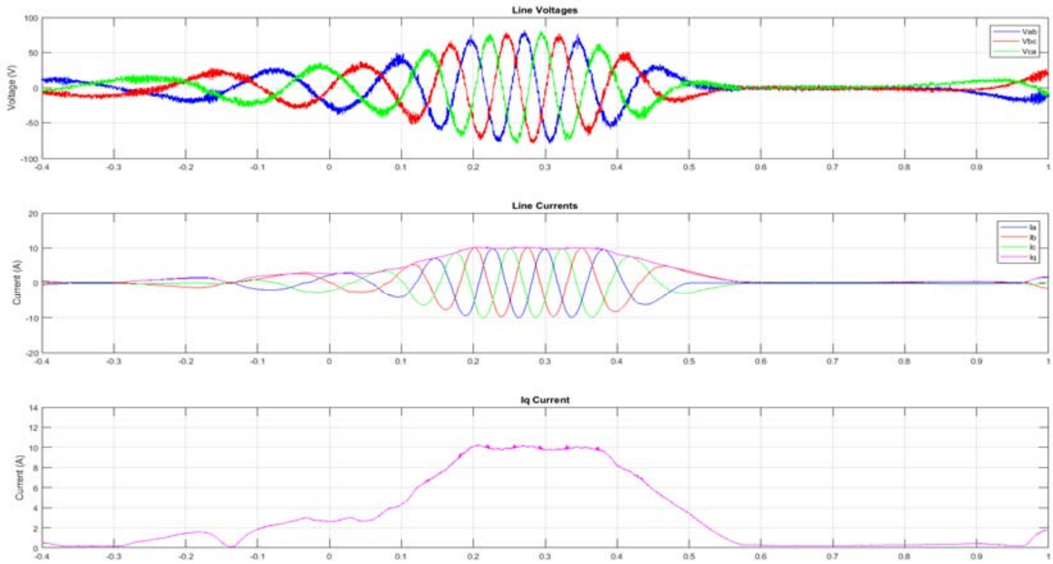

Figure 11 A burst of motion during initial testing

Force / Torque and Overload

In our second set of tests, the magnetic gear was driven at a constant velocity over the length of a stroke while a wide variety of loads were applied by the rectifier. Figure 12 shows a generator torque of 100Nm (equivalent to a 10kN linear rod force) being applied as the system cycles back and forth.

In Figure 13, the system output load torque was increased to around 220Nm (22kN linear force). This resulted in the system occasionally skipping a magnetic thread and then recovering. Skipping can be seen at around 38 and 45 seconds.

The rectifier has therefore been able to exercise the gear across its entire force range. Please note that bearing losses described earlier provide additional torque load.

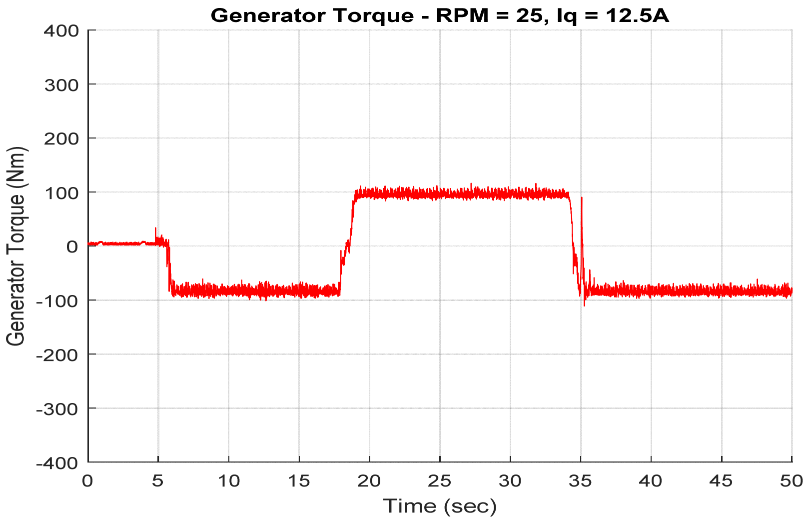

Figure 12 10kN linear force, 100Nm rotational torque operation

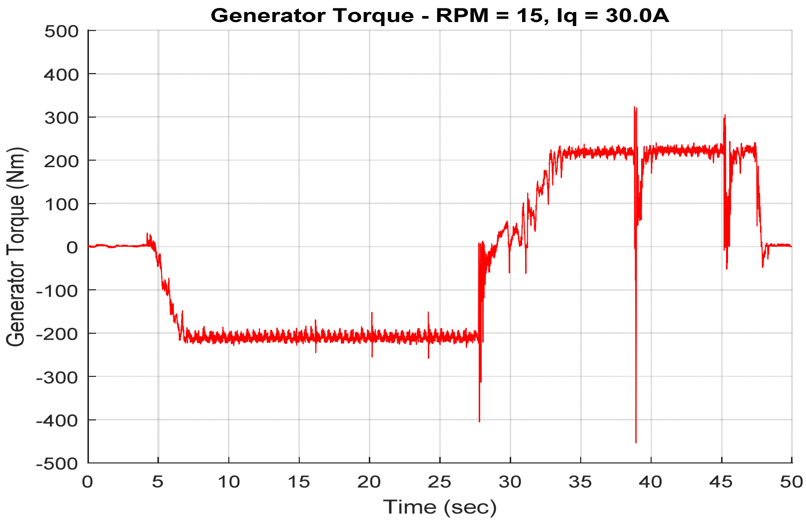

Figure 13 22kN linear force, 220Nm rotation torque operation

Low Velocity Rectifier Efficiency

For the results shown in Figure 14 the speed was kept at the lower end of the machine's capabilities – equivalent to very light seas. Conversely, torque was varied across the full capability of the machine. The maximum tested speed was 25 RPM versus the machine's rating of 250RPM. This means that we are operating at the low end of the rectifiers efficiency curve. To provide a reference, the results have therefore been compared to an equivalent data-set pulled from the back to back motor testing.

The efficiency of the rectifier was significantly higher when operated from the BEDL generator than from the off the shelf PM motor/generator. Efficiency is also rising rapidly with RPM, as anticipated from previous testing.

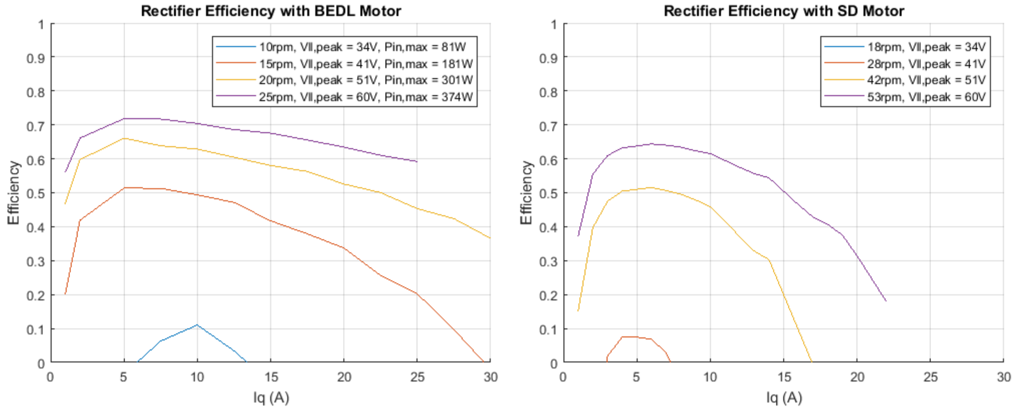

Figure 14 Rectifier efficiency with BEDL Gear/Generator and SD back to back rig

Applicability to WEC Device Types

The consultations with WEC developers and direct hydrodynamic analysis of a high-power capture WEC provided the technical requirements that the PTO system would have to meet in order to be part of a WEC system that can achieve the LCOE targets of £150/MWh.

The conclusions from the LCOE analysis were:

- The lowest LCOE for the overall WEC system, within which the PTO operates, is achieved from a device with a high power to structural cost metric when operating in a site with a high resource level (>50kW/m). This assumes that all other costs are based on the general WEC breakdown using the structural cost as a reference point.
- Within such WEC system the PTO units must have the capacity to provide a damping force of between 3MN to 4MN, to avoid limiting the hydrodynamic power capture of the WEC.

These results are summarised in Table 1.

WEC system	Description	PTO Capacity	Site: EMEC (20kW/m)	Site: Bernera (30/kW)	Site: IrelandWest (50kW/m)
PECMAG-3	power capture to cost metric of 3m / £million	Force = 3.5MN; Generator = 1500kW	£964 / MWh	£626 / MWh	£328 / MWh
PECMAG-6	power capture to cost metric of 7m / £million	Force = 3.5MN; Generator = 2300kW	£462 / MWh	£303 / MWh	**£188 / MWh**
PECMAG-2MN	metric of 7m / £million & PTO damping force cappeed at 2MN	Force = 2.0MN; Generator = 1200kW	£637 / MWh	£426 / MWh	£249 / MWh

Table 1 Summary of LCOE analysis

A sensitivity analysis identified cost and efficiency targets the PECMAG would have to meet in order to achieve the £150/MWh target, which are shown in Table 2.

Factor	Value
LCOE	£150/MWh
Site resource level	54kW/m
WEC power capture metric	7m / £million
Total cost per device [1]	£3,000,000
PTO unit cost	£510,000
PTO average conversion efficiency	83%
WEC availability	92%
Real discount rate	7.6%

(1) In a 100 device wave farm

Table 2 Summary of Target values to achieve LCOE of £150/MWh

Technical Requirements of the PTO

The technical and associated cost requirements of the PTO system linked to achieving the LCOE target of £150/MWh are as follows:

- Operate in a site resource level of >50kw/m – which provides the sea-states that the WEC & PTO system will have to operate in.
- The PTO must operate within an overall WEC system that produces a high-power capture metric in relation to average capture width to structural cost / size (greater than 7m / £million) – the power matrix from this WEC system in inextricably linked to the peak damping force, peak speed and peak power requirements for the PTO when operating in the high resource levels above.
- The target CAPEX cost for the PTO system is £510,000, representing 27% of the total device costs.
- An overall average PTO conversion efficiency greater than 83% across all operating conditions throughout the lifetime of the WEC operating within a wave farm array.
- An overall availability greater than 92% - which is for the whole WEC system and is strongly linked to the number of unplanned failures of components and the resulting loss on energy production.

The potential for the PECMAG to enable a WEC system to produce competitive LCOE figures results from:

- The PECMAG meeting technical requirements for high performing WEC devices operating on high resource sites through:
  - A novel slip mechanism to avoid overload
  - A low-cost construction for large strokes
- A higher conversion efficiency of the rectifier system using a modular “stacked” design instead of a single, cheaper rectifier unit
- High efficiency and reliability of the magnetic gear

The reliability of the PECMAG PTO contributes to availability in terms of providing high mean time between failures (MTBF) for components in conjunction with ability to maintain partial energy conversion and production until the repairs are completed and full functionality is restored. The ability of the PECMAG to be integrated with the WEC as a series of modular units also contributes to an ability to maintain partial energy conversion and production when one of the modules fails and needs repaired.

Summary of Performance against Target Outcome Metrics

The capacity and associated cost of the PTO units needed to meet the requirements of a WEC that can produce a performance metric of power capture to structural cost (size) greater than 7m average capture width / £million were determined. The key factors in this PTO and high power WEC combination, that can achieve the LCOE target of £150 / MWh, are the CAPEX and overall average efficiency of the PTO.

The efficiency target is achieving an average of 83% over all sea states at a site. This can be achieved by a combination of gear / generator average efficiency of over 88% and an average rectifier efficiency of over 94%.

The tests conducted on the rectifier system indicated that an average rectifier efficiency of greater than 94% can be achieved.

The peak gear / generator efficiencies measured on the 30kN test rig were in the 80-85% range, however, testing was limited to the lower speed range that would be experienced in the WEC system. When tested over the large speed range the efficiency would be expected to increase to over 90%. Improvements to the bearings was also identified as a key area where efficiency gains in the gear / generator units can be achieved.

The prototype testing in this Stage 2 project and the assessment of the integration requirements of the PECMAG with a high performance WEC system design provide confidence that the efficiency and cost targets from the PTO required to enable a LCOE of £150 / MWh can be achieved. Quantifying the OPEX costs associated with the expected high level of reliability expected from the PECMAG will further improve the competitiveness of the PECMAG as a PTO solution for an overall WEC system that can achieve an LCOE of £150 / MWh

The target outcomes for PECMAG in terms of the WES metrics are summarised in Table 3.

Metric	Qualitative	Quantitative
Performance	• High efficiency	• Gear Efficiency > 90% • System efficiency > 80%
Affordability	• High gearing ratio >> compact generator • High shear stress = low magnet content • Iron translator provides cheap long strokes	• CAPEX < £40 per kN & £25 per kW
Availability	• Non-contact prime mover • Parallelable, stackable, modular • Redundant electronics	
Survivability	• No damage on overload	• Peak speed >5m/s • Optimised for Force
Controllability	• Fast electronic control • Suitable for complex control	• Response time - milliseconds
Manufacture; Installation; Integration, Scalability	• Low speed, high force PTO • Wide speed range • Unlimited stroke length • Linear & rotary options	

Table 3 Target Outcomes for PECMAG

Communications and Publicity Activity

- EWTEC conference – presentation at WES side event
- Poster & presentation at WES conference

Recommendations for Further Work

The design for the PECMAG that has been developed draws heavily on existing and proven technologies from several sectors. However, the technology as a combination is new, and a number of challenges to overcome are anticipated.

The Stage 2 project identified the following areas on which to focus design and optimisation work to improve the affordability and performance of PECMAG:

- Bearings on mounting shafts in relation to dealing with any vibration loads when slip events occur and also to reduce contact friction that will directly improve the overall conversion efficiency of the PECMAG system.
- Design and marinisation of the iron rod actuator.
- Assembly of the system for improved manufacturability.
- Connecting to a WEC and testing in real sea waves to measure the efficiencies in this environment so that these can be compared with the performance figures from the bench tests.