Final Project Report – February 2022

Supergen ORE Hub Award FF2020-1040: *Advanced, Modular Power Take-Off Design for Marine Energy Converters (MP-WAVE)*

Jonathan Shek, Michael Merlin, Joseph Burchell, and Nan Zhang, Institute for Energy Systems, School of Engineering, The University of Edinburgh,

At present, the generator and power converter are two separate units that make up a PTO system. Combining and modularising these two units could potentially lead to significant cost reductions over existing methods of build and maintenance. The challenge is to demonstrate a modular PTO that has been design and built specifically for a wave energy converter, operating under realistic conditions. This allows the performance of the modular PTO as part of a drive train to be investigated and enables the stated benefits to be verified. This project aims to verify and quantify, in terms of performance and reliability, the benefits of modular PTO for wave energy converters.

This will be achieved through the following project objectives:

- Produce an optimised design of a modular integrated power electronics and permanent magnet generator topology based on real world wave data inputs and wave energy converter specifications. The simulation of this design will be incorporated into the C-GEN core design and used to assess the benefits of proposed system to industrial partners.
- The design and fabrication of integrated modules will deepen the manufacturing knowledge of the engineering team. Specifically, how to best incorporate the power electronics to optimise manufacture while allowing the requirements for heat dissipation from both the core electronics and stator coils.
- The production data which will feed into an LCOE & O&M analysis of the fabricated system when compared with existing non-integrated modules.
- Employ modern materials and manufacturing processes to investigate the effectiveness of injection moulding as a protective coating method for offshore marine machine operation. Specifically, whether such a method can be utilised while enabling the integrated system to maintain required heat dissipation.

1. Generator Stator Module Design and Modelling

The generator design proposed follows the classical C-GEN multi-stage design using steel plates in the central stages to support magnets on either side. These central steel plates do not provide any magnetic enhancing function but are essential for structural rigidity of the generator. Simulation results are presented in Figures 1 and 2.

Figure 1 shows the flux distribution with central steel plates and a plot of airgap flux density is shown in Figure 2.

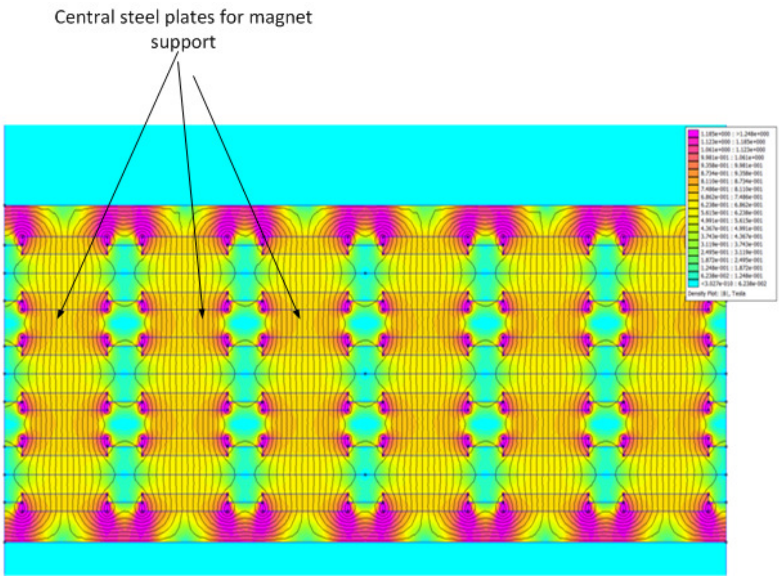

Figure 1: Flux density distribution with central steel plates.

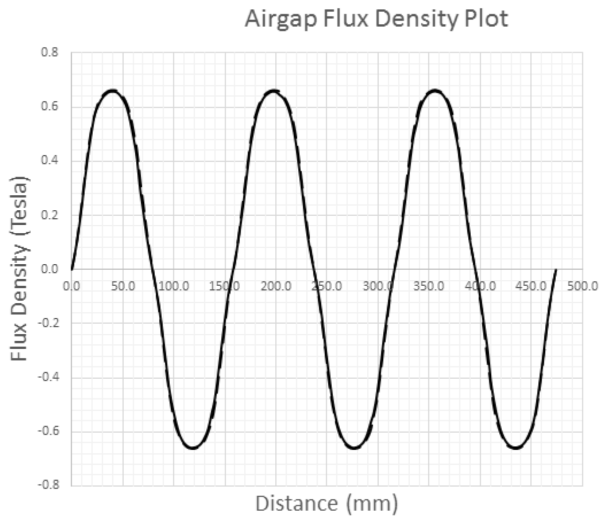

Figure 2: Airgap flux density distribution for generator with the central steel plates.

The main generator design parameters are given in Table 2.

Rated power	16 kW
Rated speed	80 rpm
Rated voltage	310 V
Rated Phase Current	17.2 A
Efficiency at rated power	90.2 %
Number of pole pairs	48
Generator active mass	234 kg
Mean diameter	0.8 m
Stator outer diameter	1.0 m

Table 2: Mark II generator design parameters

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In previous C-GEN generator designs, rotor deflection was observed during operation on load. This resulted in a change in air gap length during operation, which is undesired. Although the deflection does not affect the operation of the generator, it was felt that the rigidity needed to be increased for future generator designs. Three main measures were proposed to improve rotor rigidity in the MP-WAVE generator:

- Axial flux design with Internal rotor
- 2-stage stacked design with minimise rotor diameter
- Casted C-Core modules

No load test

The generator is operated over a range of fixed speeds from 0 to 80 rpm with no load connected to the generator terminals. The 3-phase voltages at the generator terminals are measured and plotted against the generator speed. The result should be a linear relationship between generator speed and output voltage. Figure 3 shows the no-load line voltage of the generator up to 70 rpm.

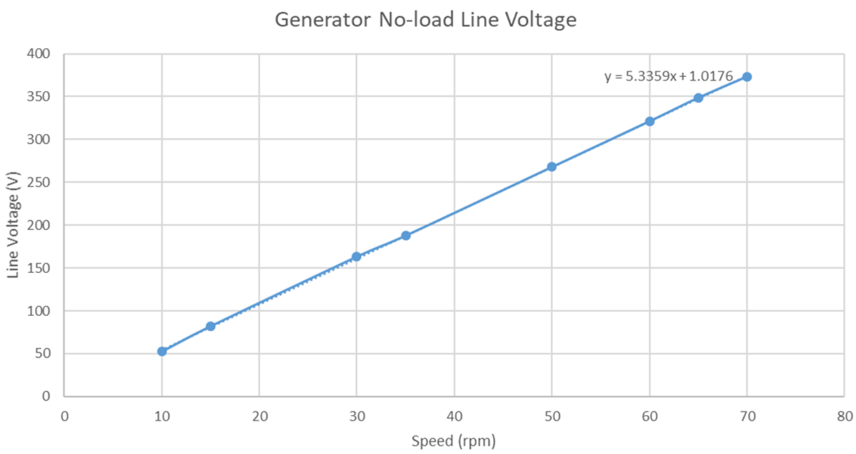

Figure 3: Generator no-load voltage vs. speed

Load test

The generator is operated over a range of fixed speeds from 0 to 80 rpm. For each speed setting, a resistive load is connected to the generator terminals and varied from no-load up to a load value that results in the maximum current being drawn from the generator. The generator voltage and current are measured to calculate the output power. The mechanical input power is calculated using torque and speed, measured by a torque transducer. The input and output power are used to calculate generator efficiency at different speeds over a power output range. Figure 4 shows the generator efficiency versus load for a range of different speeds.

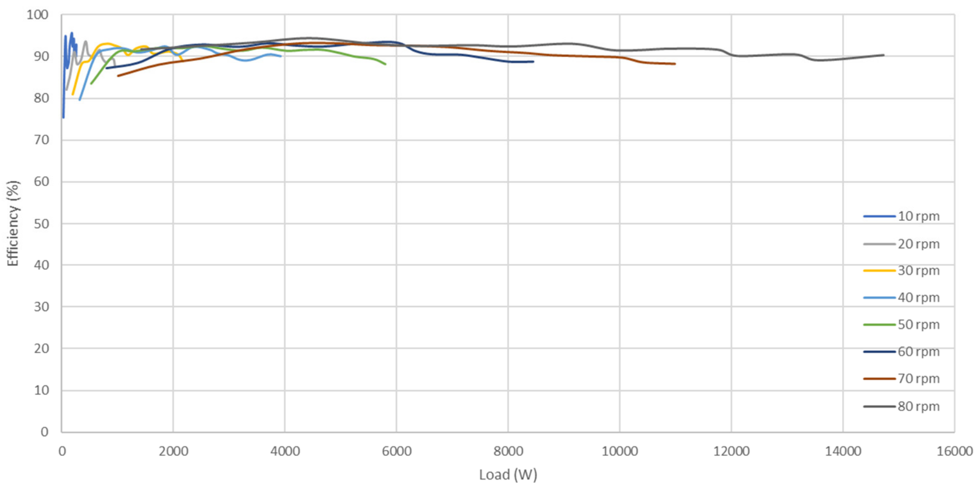

Figure 4: Efficiency vs. load at different generator speeds

2. Power Electronics Design and Modelling

Design and Model

A 16 kW C-GEN generator is studied in this project. The generator consists of 6 C-GEN modules per stage. Two C-GEN modules of the machine use the "modular power electronics technology" and the other four modules are connected to one single converter. Each C-GEN blade module has 6 coils, as shown in figure 1. In the simulation model, each module is divided into two 3-coils modules. One 3-coil module in one C-GEN module is connected in series with the 3-coil module in the other stage, and these two 3-coil modules are connected to one rectifier, which is a 3-phase half bridge converter. There are four rectifiers in total, shown in figure 5.

Three electric gears are placed between the rectifiers. Each electric gear consists of one switch, four diodes and one capacitor. The switch is controlled by the amplitude of the voltage at the machine side. A threshold value is set and compared with the control signal. When the machine operates in the low-speed region, the voltage at the machine side decreases and the switch of the electric gear is closed, thus the rectifiers' connection is changed from parallel to series. The DC voltage seen by the rectifier can be half or quarter of its nominal DC voltage. Therefore, the power factor of each rectifier can be increased.

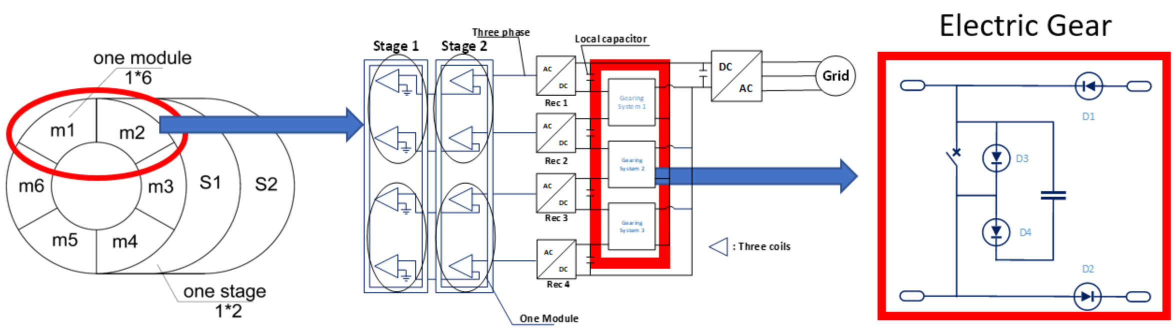

Figure 5: 16kW C-GEN machine and connection to rectifiers

The control algorithm of the control system is the zero d-axis current control and DQ control. The current at the DQ frame is transformed from 3-phase current via the park transformation. The current at the d-axis is kept as zero so that the stator current is equal to its q-axis component. Due to $\mathrm{T_e} = \frac{3\mathrm{p}}{2} * \lambda_\mathrm{m} * \mathrm{i_q}$, the electromagnetic torque is proportional to the stator current. The reference current at q-axis (I_q^*) is calculated from the electromagnetic torque reference (T_e^*), which is obtained from the speed controller. The speed controller is used to compare the rotational speed reference with the actual rotational speed and output the reference signal for the electromagnetic torque. The model of the modular power electronics and its control system is shown in Figure 6.

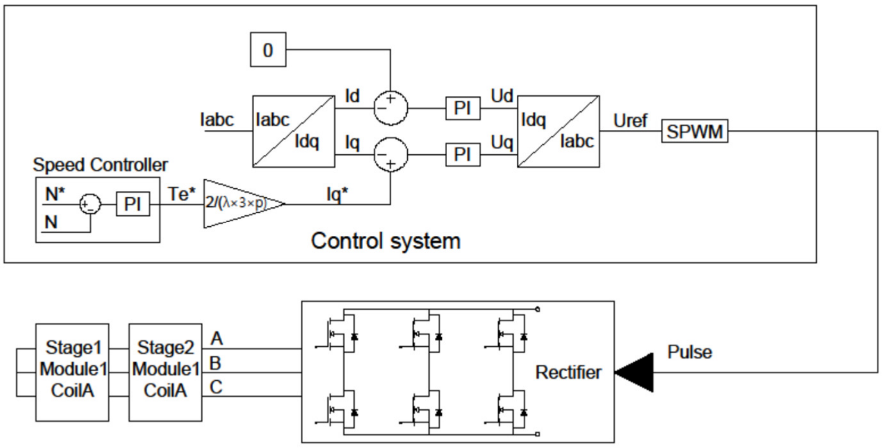

Figure 6: PWM speed controller for the three-phase rectifier

Simulation Results

Figure 7 and 8 compares the modulation index between the case that the modular power electronics is applied and the case that the machine is connected to a single converter. The modulation index of the converter is proportional to the amplitude of the AC voltage at the machine side ($\mathrm{m} \propto \frac{\hat{V}_{phase}}{V_{DC}}$). It can be seen the power factor in the low speed region is much improved. Since the modulation index is kept at a reasonable level, reduced power losses leading to higher efficiency and improved power quality can be obtained, as shown in figures 9 and 10.

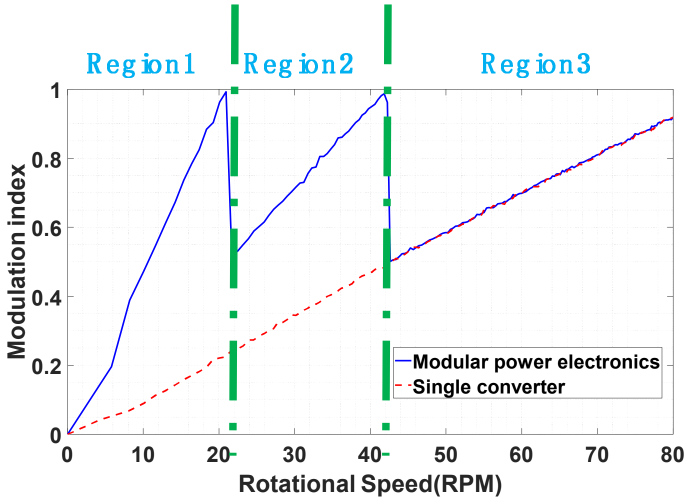

Figure 7: Modulation index comparison

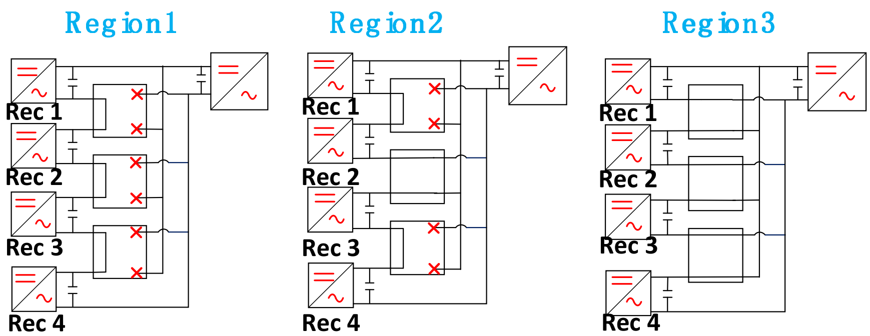

Figure 8: Connection of converters in different speed regions

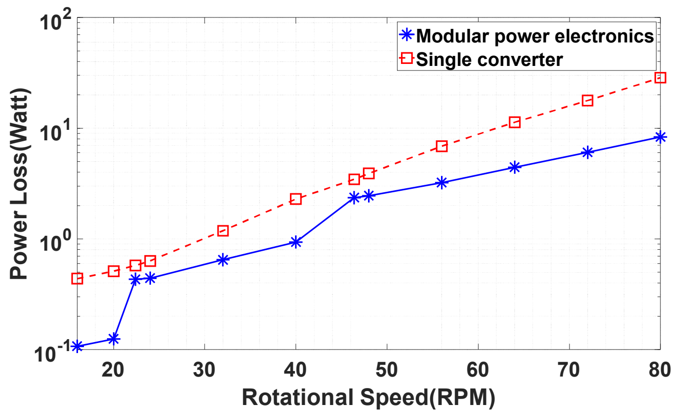

Figure 9: Power loss comparison

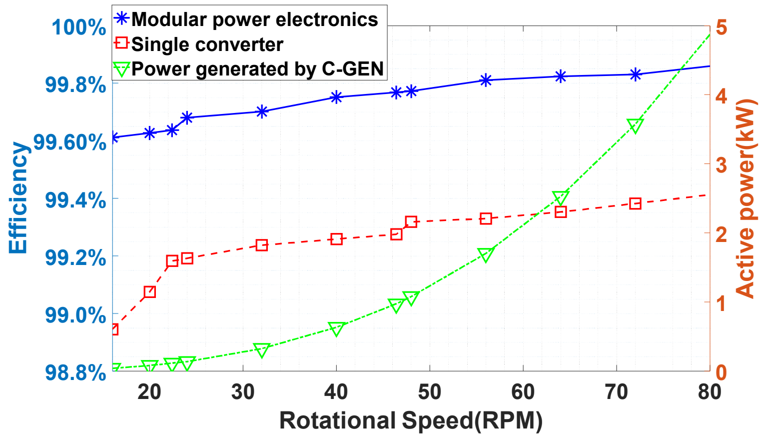

Figure 10: Efficiency of the converters and total power generated

The simulation results show, due to the electric gear, the modular power electronics applied to the C-GEN machine exercises a favourable influence in improving the modulation index and reducing the power loss of the generation system.

3. Hardware Build and Test

The MP-WAVE generator was manufactured by Fountain Design Ltd., who have many years of experience in building novel electrical machines. They are also able to utilise knowledge and experience gained from building previous electrical machines for The University of Edinburgh to optimise manufacturing technique, reduce build time and cost. Figure 11 shows a computer generated image of the stator modules with rotor section beneath. Six of these units would make up a complete generator. A single fabricated coil, which is used to form a 6-coil blade module is shown in figure 12.

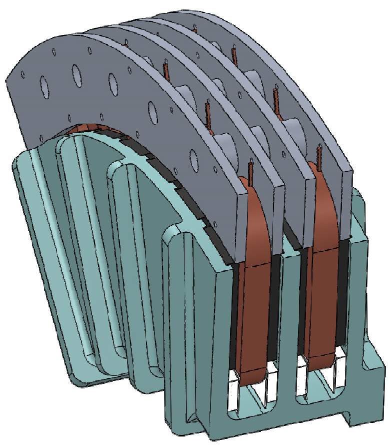

Figure 11: Computer generated design of two stator modules with rotor section beneath

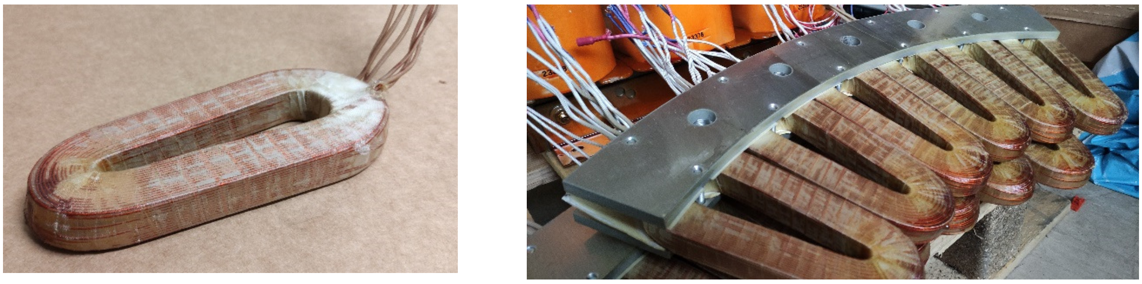

Figure 12: Fabricated single coil (left) and completed 6-coil stator module (right)

For the power electronics, the PCB design is shown in Figure 13. One rectifier and one electric gear are placed in one PCB, which is connected to the machine, the DC bus and other PCBs via connectors. The TI Launchpad F28379D is used as the microcontroller (MCU), which plug to the bottom of the PCB via four connectors. There are four slave MCUs in total, and they are communicated with one master MCU via SPI. The actual fabricated boards are shown in figure 14.

At present, the program work of the microcontroller is ongoing. The communication between the microcontrollers are expected to be realized. A mini C-GEN machine and a small PMSM motor are used for the PCB test and experiment at present stage prior to integration with the full-scale MP-WAVE generator.

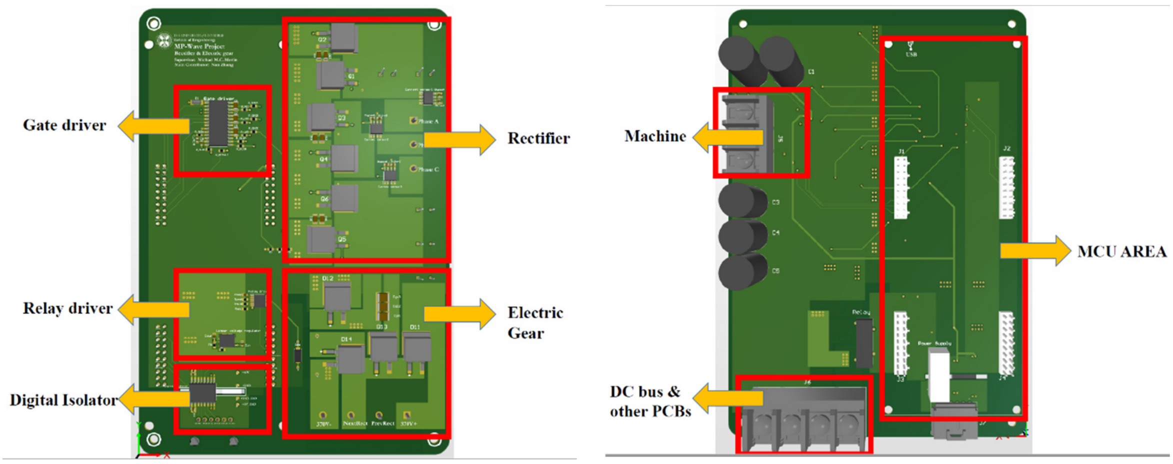

Figure 13. PCB design

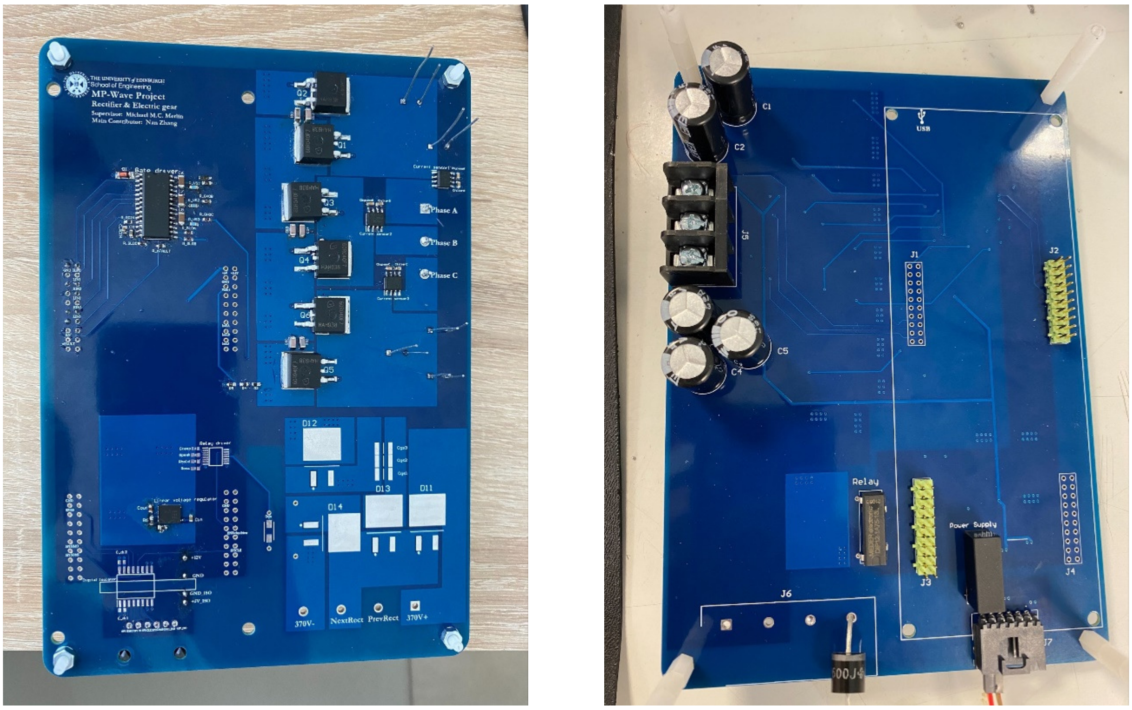

Figure 14: Actual fabricated PCBs with components partially populated

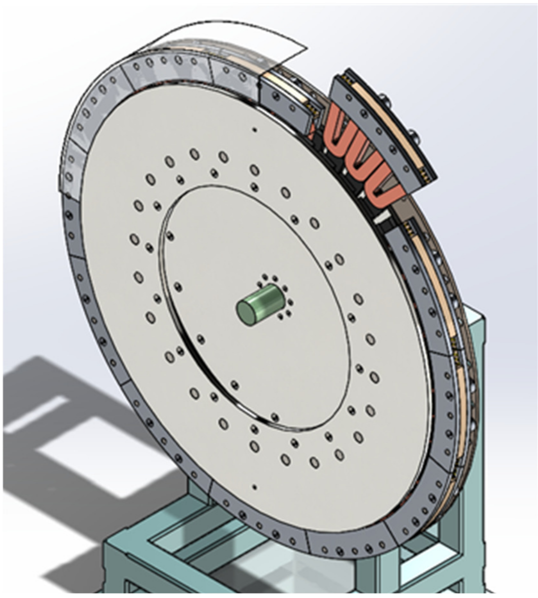

Figure 15: Integrated generator design

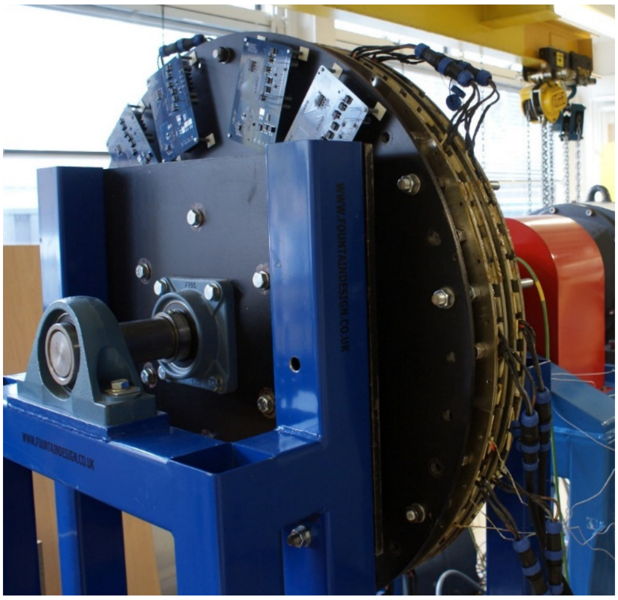

Figure 16: Assembled prototype

3. Materials and Manufacturing of Marinised Coils

Running in parallel with the main design and build of the modular PTO was the investigation of materials and their related manufacture processes for the commercialisation of marinised modular motor and generator systems. Through the assessment of an array of materials and their supply chains, associated manufacturing techniques, level of protection/structural integrity and implementation costs, the aim is to improve machine efficiencies, survivability and operation while installed within a marine environment.

From this study, a number of conclusions can be drawn:

Manufacturing Process Conclusions

- Injection moulding holds significant promise for this type of fabrication and build, but very high initial cost
- Transfer/compression moulding possible alternatives to injection moulding if tooling and mould preparation is achievable, although studies indicate a lower production speed
- Dip moulding could provide cheapest option, however, structural implications need to be reviewed as well as speed of process

Material Testing Conclusions

- Polypropylene – copper bonding is surprisingly good
- Compatibiliser helps to improve this bonding slightly
- Polybond 7200 is likely the best candidate given its improvement to strength, and its processability
- Sigma Aldrich MAPP degrades above 150°C, and has a very low viscosity compared to Polypropylene, making it more difficult to mix

Modelling Conclusions

- Indication that for a full blade, Polyphenylene Sulphide, Polypropylene and Polycarbonate provide comparable support to the blade
- Polyphenylene Sulphide performed best in all simulations
- Shot joint modules suffer from more than double the structural deflection than a solid blade

4. Further Work

Due to delays in coil manufacture as mentioned in the interim progress report, the integrated modular PTO was built within project period but much of the testing is ongoing. Publication of results with analysis is expected upon conclusion of the tests. In particular, this will include verification of lower losses across a wider speed range. For materials and manufacture, there is a need to carry out thermal and fatigue analysis of coil blades potted within the chosen medium, immersion studies on candidate materials, and coil blade aging test to assess the life span of materials when used in an offshore environment.