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The design and build of a 75 kW linear C-Gen generator prototype for wave energy power conversion

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Abstract— **The simplification of drive trains and power take off systems for wave and tidal devices can reduce both construction and O&M costs as well as increase reliability and system efficiencies. Project Neptune is a Wave Energy Scotland Stage 3 Power Take Off (PTO) project, focusing on the development of the C-GEN medium to full scale direct drive generator topologies for the marine environment. The C-GEN direct drive generator is a modular multi-stage Permanent Magnet Generator (PMG) that is applicable to direct-drive, slow or medium speed PTO applications. A 75kW C-GEN linear generator has been designed and built for testing within the offshore marine environment. To aid the survivability and efficiency of the generator system, polymer linear bearings, flooded airgaps and protective marine coatings have been utilised to remove complex mechanical bearings, seals and improving cooling. In order to test the linear generator under realistic wave profiles and loads a linear motor generator back to back test rig has been built. The complete system will be installed and tested at Leith docks. The machine will be operated over a range of loads, speeds and conditions to ensure full scale viability.**

Keywords—**Linear Generator Prototype, Direct Drive, Wave Energy PTO.**

I. Introduction

THE C-GEN generator is a novel direct drive generator which is easy to manufacture and assemble, [1] [2], as well as being highly efficient over a wide range of loads, typically 85-90% for wave applications from part to full load [3]. Direct drive systems of this type involve the generator being directly coupled to the prime mover, which minimises the number of moving parts, leading to a high level of reliability, and hence availability. Several prototypes have been demonstrated to prove the concept, including a 1 MW rotary prototype for wind energy and a 50kW prototype for wave energy applications [4]. Since previous marinised C-GEN developments have taken place in the lab, this project will focus on understanding how generator windings and bearings may perform under real marine conditions, address the challenges of marinisation and ensure critical components remain reliable. Results from modelling and testing will feed into the design tool to be used for full scale designs of existing wave devices, to demonstrate total energy cost consistent with the WES target of £150/MWh. Additionally, work completed with partnered wave energy developers will indicate the installation and commercial viability of the C-GEN machine design for the wave energy industry.

The C-GEN generator is specifically designed to further address the problems that plague the reliability of machines based in remote offshore environments by maintaining a low number of O&M interventions and ensuring a low O&M cost. The differentiating design features of the patented C-GEN design include:

- An axial flux topology with C-shaped rotor/translator core
- Modular stator arrangement containing air cored coil assemblies
- Modular rotor or linear translator assemblies containing active magnetic material
- An axially stackable generator topology that can increase torque and power through the addition of C-GEN stages, Fig. 1

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The optimal design of the magnet and coil modules has been assessed for the water depth of the testing area and is fully described in Section II.

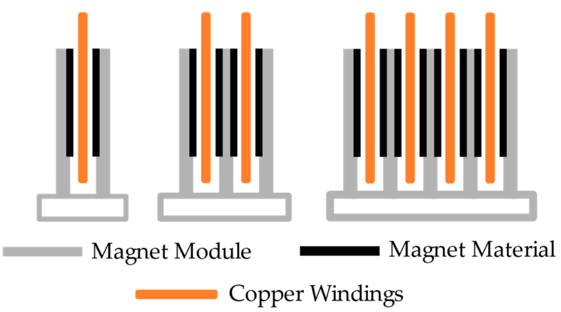

Fig. 1. Stacked C-GEN machines. (A) Single stage C-GEN. (B) Double stage C-GEN. (C) Four stage C-GEN

The modular aspect of C-GEN enhances maintainability, and this has been demonstrated on previous prototypes in which faulty stator modules have been replaced in-situ in minutes rather than days. There are no lubrication requirements, as polymeric bearings are being used. Survivability is key to the success of wave energy. Significant power in the waves can exist, resulting in very large forces. It is uneconomic to size the machine and power converter to meet the extreme forces, but the machines must survive such extreme events.

Based on thermal modelling and experimental results from Stage 2 WES of a flooded machine, [5], the machine is capable of withstanding more than 5 times overload, without concern over temperature rise in the windings. As stated earlier the nominal design spec for the machine is for a current density of 4-5 Amm^{-2}, but during overload conditions it is capable of greater than 20 Amm^{-2}.

Mechanical survivability was demonstrated by NGenTec on a 1MW stator blade, in which 5 times nominal torque was applied, with no deflection or mechanical failure. Therefore, a thrust force of 5 times rated is targeted in this project. Additional survival aspects are outlined below:

- Maximum/Average load ratio – electrically and mechanically a factor of 10 is targeted
- Load shedding capabilities – as a result of operating fully flooded C-GEN can operate on overload and thus extreme damping or electromagnetic braking could be used in the machine as part of load shedding – a target of up to 200% overload continuous and 500% short term rated.
- Fatigue loading - Tests completed by NGenTec on a 1MW stator blade – copper coils potted in epoxy – demonstrated excellent fatigue performance.
- Bio-fouling resistance – as C-GEN is operating fully flooded this is an important challenge and methods of protection for the translator and magnets will be noted.
- Life expectancy – in line with other offshore and energy sectors a lifetime of 20 years for the PTO is the target, but with the anticipation of scheduled maintenance and parts replacement every five/ten years.

II. DESIGN AND BUILD

The design of Project Neptune's 75 kW linear generator and associated test rig depended on the testing method. The machine requires testing in the salt water marine environment while being accessible for study and O&M investigations. Without a Wave Energy Convertor (WEC) the test rig design requires that the generator is attached to a device that can emulate wave motion in a controlled manner. Various linear actuator options were evaluated including hydraulic pumps, leadscrews, chain drives and beam assemblies, a preliminary design of which is provided in Fig. 2. However, after completing financial and structural studies it was decided that a combination of two C-GEN machines operating as linear motors back to back with two C-GEN generators would be designed and built. The motors and the associated motor drive are rated at 100 kW and use the converted electrical power from the generator sections to offset the draw from a three phase mains supply. In this way, the operation of the machine can be closely studied and easily controlled based on feedback from the motor drive. However, in order to counteract the additional power required from the motors to move the mass of the translator, counter balances were added to the test rig design. An isotopic view of the complete design is provided in Fig. 3 with a brief description of the major components provided in Table 1.

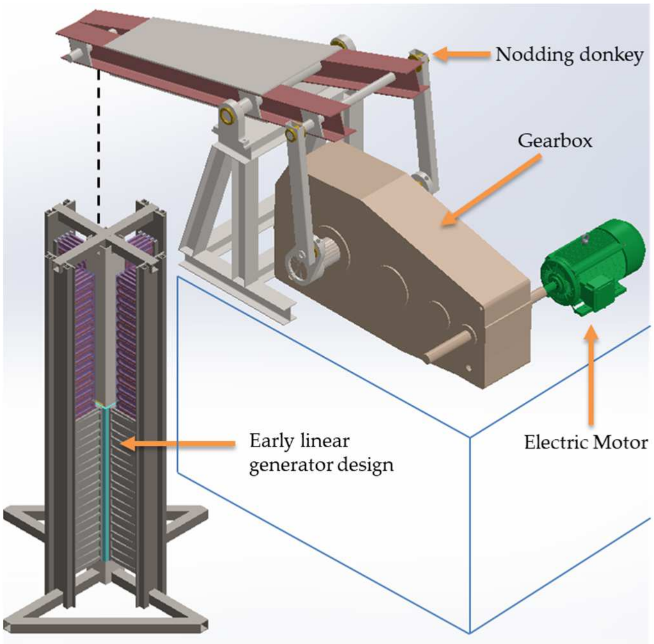

Fig. 2. Conceptual design of beam actuator with a four-sided, four stage C-GEN linear generator assembly

TABLE. 1.

PROJECT NEPTUNE TEST RIG ASSEMBLY DESCRIPTION

Notation	Component Description
A	Data acquisition and power boards
B	Translator/counterweight pulley system
C	Test rig support structure
D	Counter weight 1, counter weight 2 opposite
E	Generator coil modules
F	Motor coil modules
G	Translator 1
H	Translator 2
I	Test rig base plate

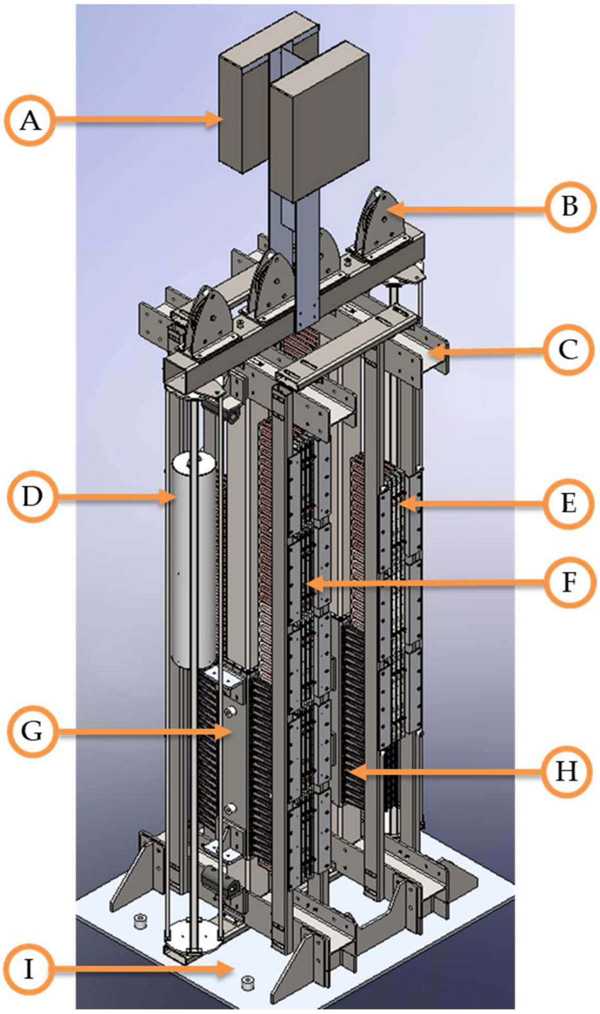

Fig. 3. Project Neptune test rig assembly

The operational specification for the Neptune test rig is as follows:

- Sinusoidal motion with a peak velocity range of 1-1.5ms^{-1}
- Voltage = 415 V (peak), and 339V (rms), per phase in star connection
- Current density: nominal 4-5 Amm^{-2}, but with > 20 Amm^{-2} overload capability
- Efficiency >60-80% for the peak velocity range of 1-1.5ms^{-1}
- CAPEX = £400k/MW
- Overload = 200% continuous, 500% short term rated

The test rig structure was designed based on these operational specifications and the forces calculated within the machine during operation, Fig. 4. Additionally, the design requires a structure that enables the removal of stator modules and bearing pad assemblies, support of the moving translator sections mass and counter weight assemblies' mass as well as transportable from QuartzElec, Rugby to Leith Docks, Edinburgh. Both the University of Edinburgh and QuartzElec investigated the structure of the test rig leading to a machine 9m in height and weighing 25 tons.

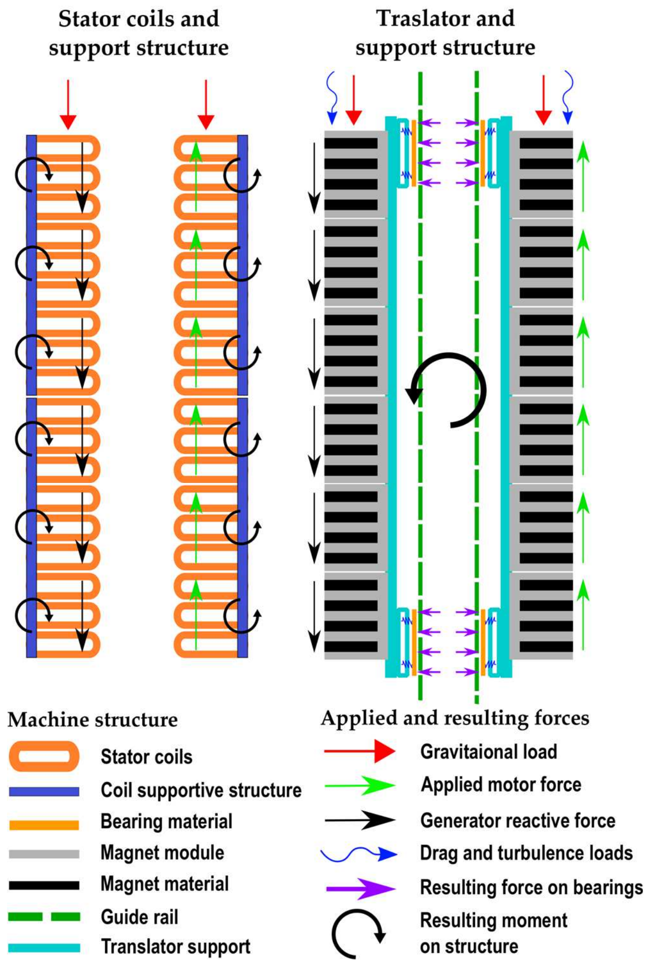

Fig. 4. Indicative diagram explaining the applied and resulting forces and moments experienced by the active elements of one side of the machine during upstroke

A. Translator and Bearing Assembly

The design of the translator consists of 24 cast iron magnet modules as shown in Fig. 5. Each magnet module consisting of a four-stage stacked C-GEN design, with each stage made from 4 poles created from 2 magnet sections per pole. A total of 64 neodymium magnet sections were used in the production of each module.

The magnet modules were separated into two groups of 12 for installation on to translators 1 and 2. Fig. 6 shows translators 1 and 2 joined together via two I beam sections. The magnets are coated with a nickel copper epoxy coating which was applied by the manufacturer's pre-insertion, and once all magnets were inserted into the modules an extra layer of sea water protection was provided by ELANTAS Elmotherm VA63 impregnating varnish.

Fig. 5. Magnet modules. Left: Cast magnet modules ready for magnet insertion. Right: Magnet module with magnet insertion underway

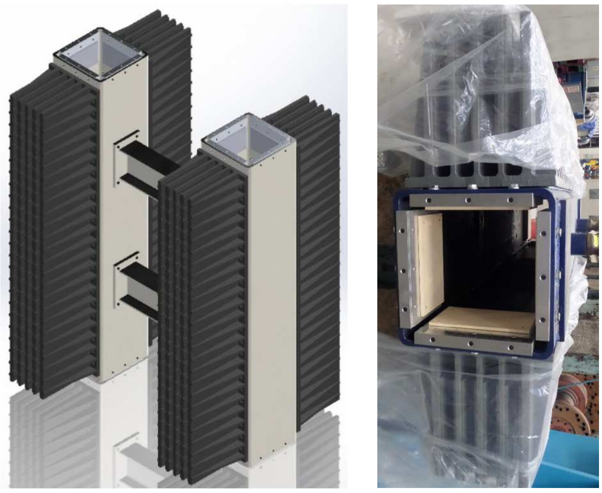

Fig. 6. Translator construction. Left: CAD drawing of two translators joined together. Right: Fabricated single translator viewed from below indicating magnet modules and bearing pad assemblies

Fig. 7. Translator central support structure pre-fabrication

Fig. 8. Single complete translator installed on a single generator/motor stator assembly in the horizontal position prior to being raised into the vertical position. Stator assembly indicated top and bottom of translator

The translator assembly includes 8 polymer surface contact bearing pads per translator. These are mounted on the inside of the translator's support structures, Fig. 7, and will maintain the airgap and fluid movement of the translators as they travel along the central guide rail, as indicated in Fig. 8. The bearing pad carriages were designed based on work carried out in the WES Stage 2 C-GEN project, [6] [7]. The bearing pads are bolted to an aluminium support structure with springs between, Fig. 9, to enable continuous contact between the pads and the guide rail, Fig. 10. The carriages have been designed to be removed for inspection and to investigate the bearing maintenance.

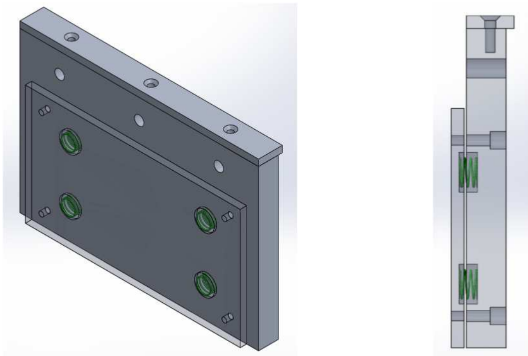

Fig. 9. Sprung bearing pad module indicating springs in green. Left: CAD iso view. Right: CAD profile transparent view

Fig. 10. Bearing pad module assemblies. Left: Bearing pad with temperature sensor insert. Right: Bearing pad modules installed on translator support

B. *Stator Manufacture and Assembly*

The design of the stator module is the same for both the motor and generator parts of the test rig. The module contains 4 coil blades stacked together with spacers to maintain the airgap as well as the distance to allow the traverse of the magnet modules, shown in Fig. 14. Each blade consists of 9 coils over the length of 1 m, thus one module contains 36 coils. Each 9-coil blade is wired internally, supported with fibre glass inserts and potted within an epoxy resin, Fig 11, Fig. 12. And Fig. 13. The resin provides structural support as well as water proof protection for the coils from the marine environment. Glands are potted into the blade to allow for water proof cabling connections and all blades in a single stage are connected in series, Fig. 12. In order to achieve speeds at which the generator produces an electrical output, the motor sections are made of 5 coil modules each, while the generator sections of the test rig contain 3 coil modules each.

Fig. 11. Assembly of nine coils for potting into an epoxy coil blade

Fig. 12. Coils wired in series ready for potting

Fig. 13. Completed epoxy potted coil blade

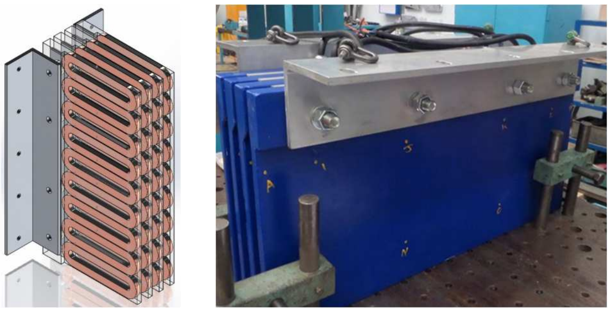

Fig. 14. Coil blade modules. Left: CAD illustration of the four-blade module. Right: Fabricated coil blade module ready for installation into test rig

C. *Assembly of Test Rig*

The test rig consists of two generator motor pairs, each of these assemblies were constructed and wired horizontally, Fig. 15. Being horizontal meant testing of each motor could be carried out without the need for counterbalance weights. It also enabled the bearing pads, coil modules and translators to be aligned and installed quickly. The two machines were then moved into the vertical position and connected to the test rig base plate. The translators were then joined via I beam sections and finally the counter balance weights were installed and connected to the translators. Both motor and generator stator assemblies were cabled back to the power board. Strain gauges, temperature sensors, air gap sensors, bearing wear sensors and search coils were installed and wired back to the data acquisition board.

Fig. 15. Wiring of motor coil modules in horizontal position

Fig. 16. C-GEN Project Neptune test rig, motors and generators in vertical position ready for counter balance installation

III. SIMULINK/MATLAB SIMULATION

A model has been developed using Simulink/Matlab and MagNet/Infolytica. The analytical model has been based on the design model previously developed at the University of Edinburgh. A more realistic version for the linear generator has been accomplished in this iteration.
Electromagnetic finite element calculations of the motor and generator are obtained from MagNet/Infolityca and added to the model. Additionally, the model presents a one degree of freedom to control position/velocity. The model is used to predict the performance of the linear motor-generator back to back test rig.

D. *Free body diagram*

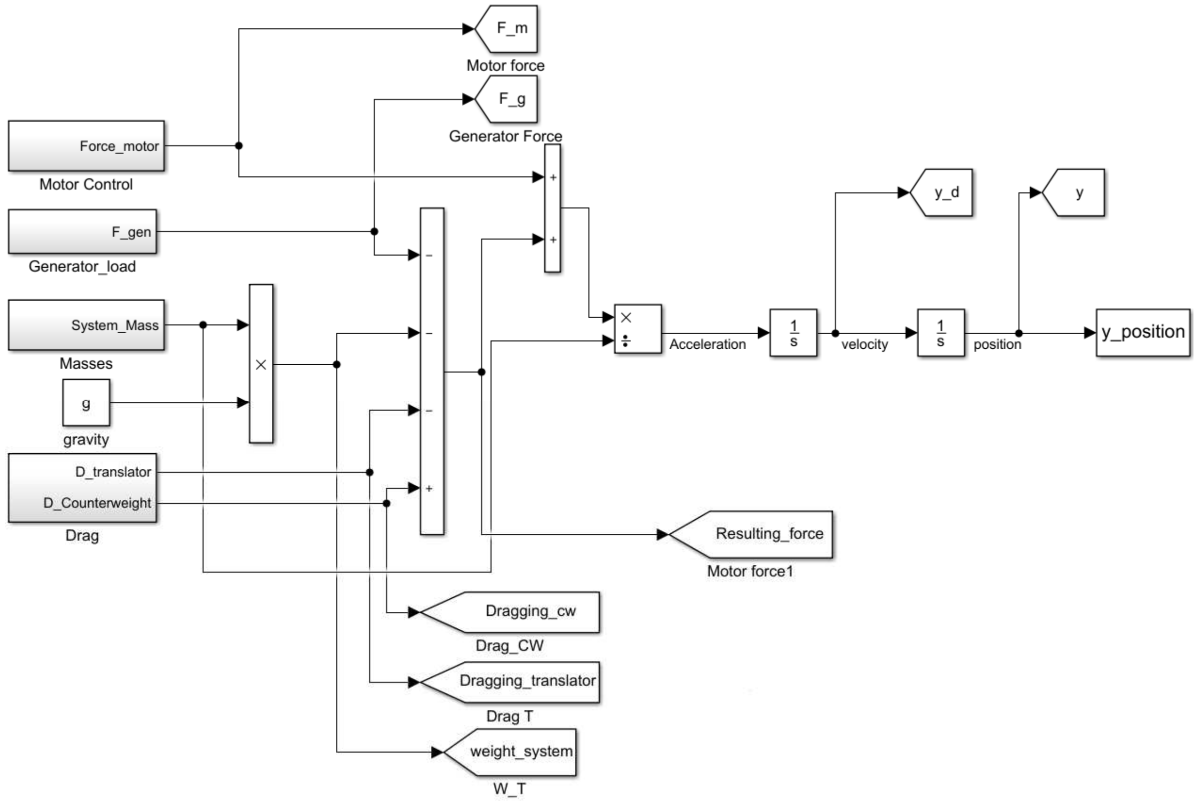

Fig. 17. Summation of forces on the "y" axis

The mechanical part of the model equalised the forces applied on the translator to the mass times acceleration of the system, as indicated in Fig. 18. The translator speed and position are obtained by integrating the acceleration signal as can be seen in the Simulink diagram Fig. 17.

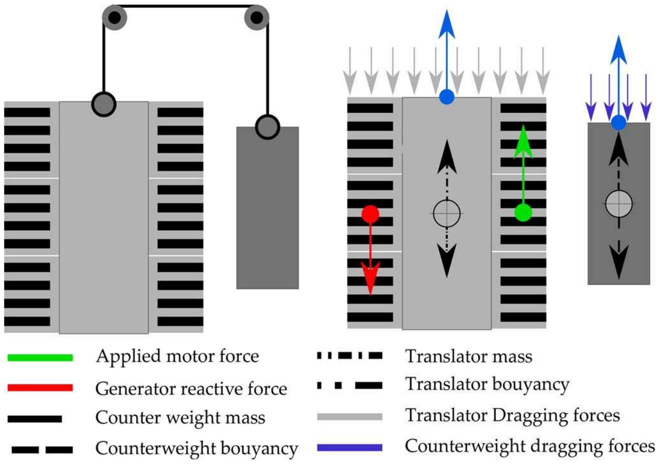

Fig. 18. Free body diagram of translator assembly

E. *MagNet modelling*

A current vs translator position simulation was run in MagNet, Fig. 19, and the forces obtained were used in a lookup table to create a 1 degree of freedom control loop for the moving part. The 2D MagNet model, provided in Fig. 19 produced indistinguishable results compared to the 3D MagNet model, therefore the system was simplified into a 2D environment to enable faster processing of results. Additionally, the drag force of the translator and counterweight were determined from CFD modelling [8] and incorporated into look up tables for use in the model. The derivation of the 3 phases voltages and currents were scripted in a *s-function* block in the Simulink model. Results are presented in the following sub section.

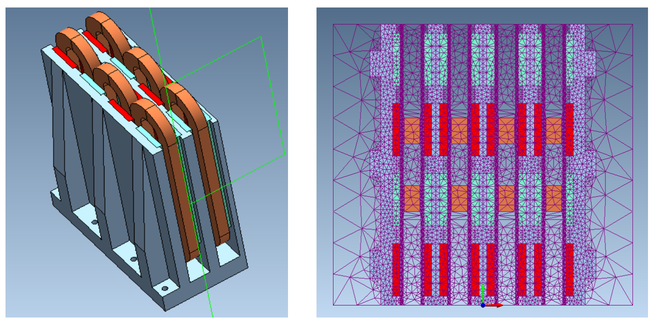

Fig. 19. Left: 3D MagNet Geometry. Right: 2D environment simplification and 2-D mesh

F. *Simulation and results.*

The translator follows a sinusoidal position setpoint with an amplitude of 3 metres (total length of the stroke) and a frequency of 1/6 π radsec^{-1} for half of a cycle (6 seconds) as shown in Fig. 20. The model was run so the translator will move due to the activation of the coils in the motor part. The model considers the relative position of the permanent magnets with respect to the coils and energises the coils accordingly to ensure the force is in the correct direction. The forces generated by each phase and the resulting total force are shown in Fig. 21.

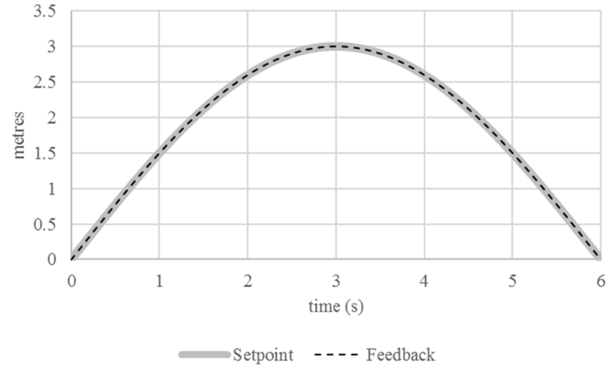

Fig. 20. Position control plot

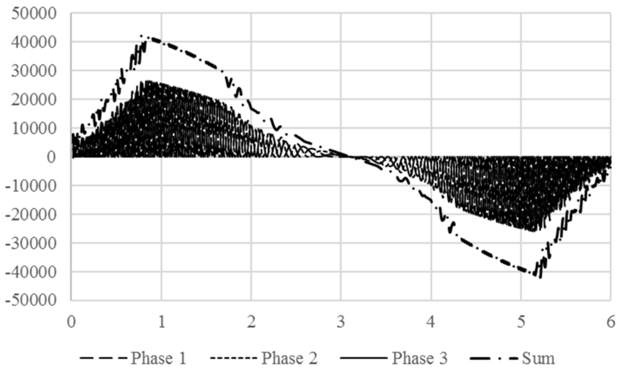

Fig. 21. Motor forces

The voltages and currents on the motor part are presented in Fig. 22 and Fig. 23.

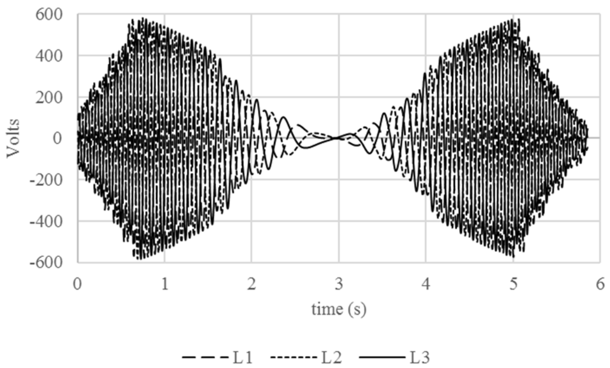

Fig. 22. Motor three phase voltage plot

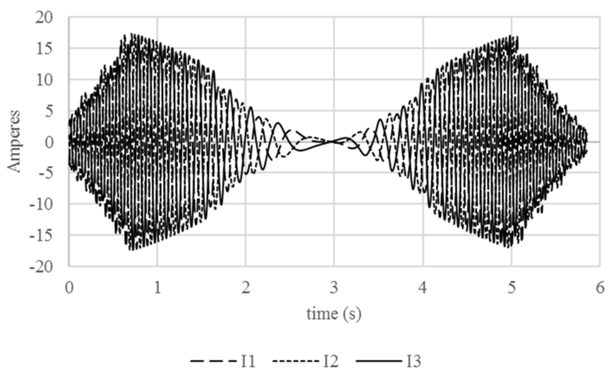

Fig. 23. Motor three phase current plot

Furthermore, the model was simulated with a resistive load of 13.24 Ω. The generator output is shown in Fig. 24 and Fig. 25.

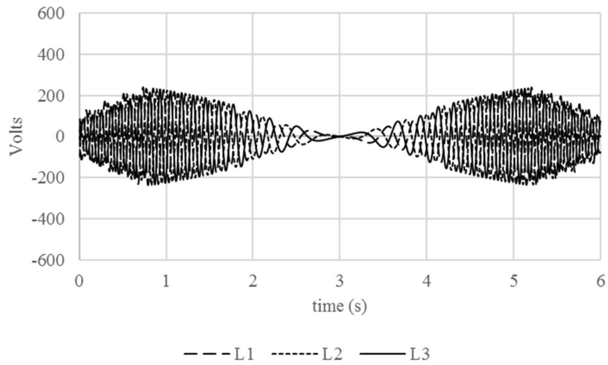

Fig. 24. Generator three phase voltage plot

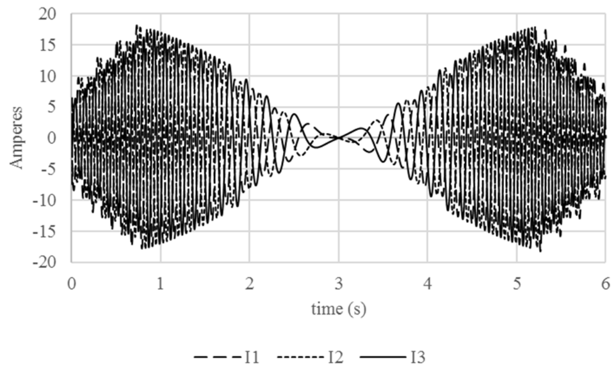

Fig. 25. Generator three phase current plot

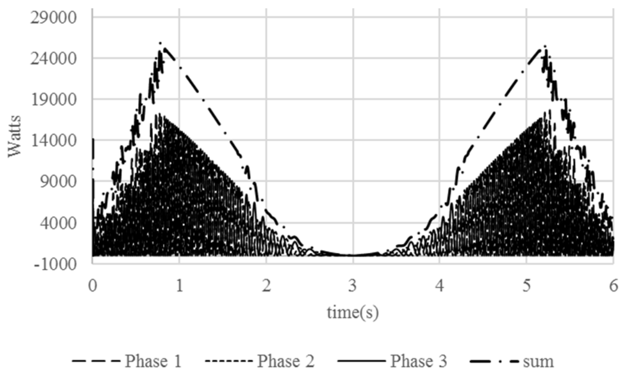

Fig. 26. Generator three phase power plot

The voltages, currents and forces in all the graphs are not completely uniform, because the translator is not covering the entire number of coils at all time on the generator part, as can be noted in Fig. 16. The results have been corroborated in MagNet with a high degree of similarity, examples of which are provided in Fig. 27 to Fig. 30. As noted previously in Fig. 19, the C-GEN geometry was simplified in Magnet. During simulation, both models operated with a peak velocity of 1 ms^{-1} and a resistive load of 13.24 Ω. Slight differences between models are believed to be the result of the geometry simplification.

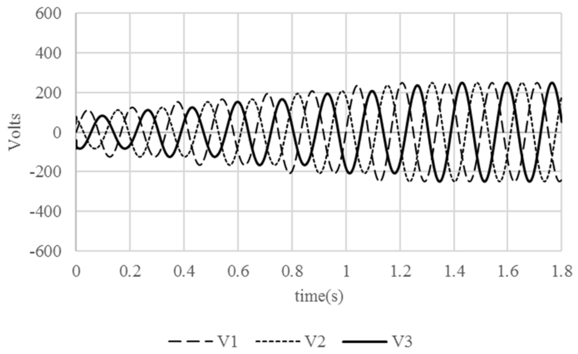

Fig. 27. Simulink three phase voltage plot

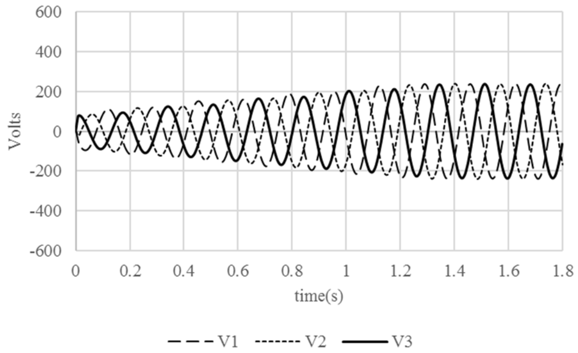

Fig. 28. MagNet three phase voltage plot

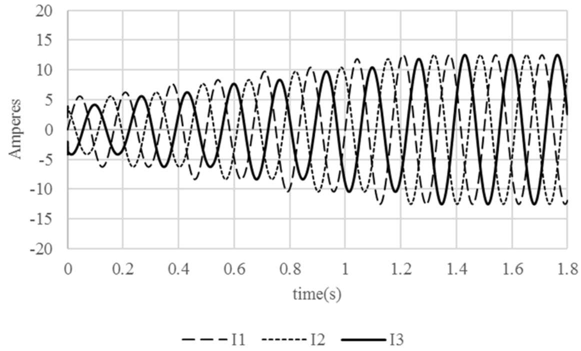

Fig. 29. Simulink three phase current plot

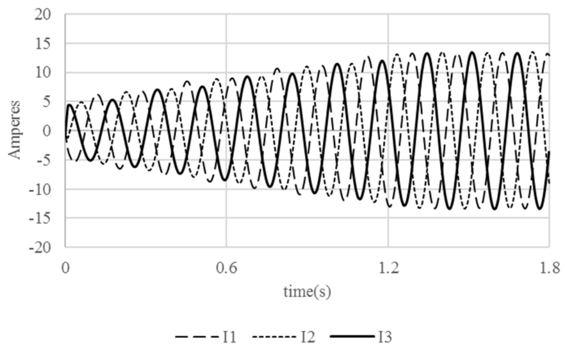

Fig. 30. MagNet three phase current plot

IV. Testing

The objectives for fully submerged salt water testing are to operate the Stage 3 C-GEN demonstrator in a real environment by considering typical load profiles and operating conditions in order to demonstrate the unique selling points of C-GEN for marine energy as portrayed in Fig. 31.

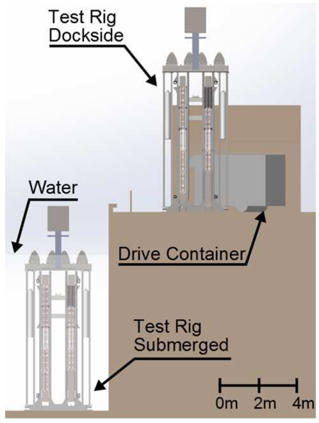

Fig. 31. Proposed test rig installation at Leith Docks for wet and dry testing

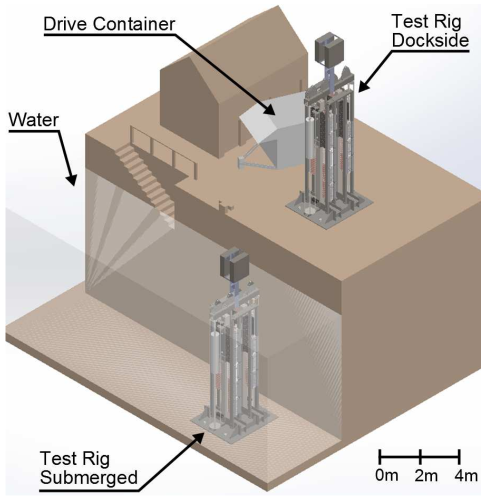

Fig. 32. Proposed test rig installation at Leith Docks for wet and dry testing

The wet test program to be completed at Leith Docks includes:

- No load test at varying frequency of operation in order to verify voltage output.
- ¼, ½. ¾ & full load tests under regular load profiles to verify electrical, thermal and mechanical performance.
- Load testing under typical device load regimes and displacement profiles. The control system will be programmed to emulate typical displacement profiles as observed in a real wave device.
- Electrical Fault tolerance tests – during operation a stator module will be purposefully short-circuited providing an extreme load to the generator, whilst operating under a typical load profile.
- Operation and Maintenance – the demonstrator will be removed and a stator module will be replaced on the quayside using an overhead crane. The operation will be filmed and timed to inform maintainability metrics and O&M procedures.
- Overload Operation – the machine will be tested on continuous overload for a short period of time in order to demonstrate survivability in extreme events.

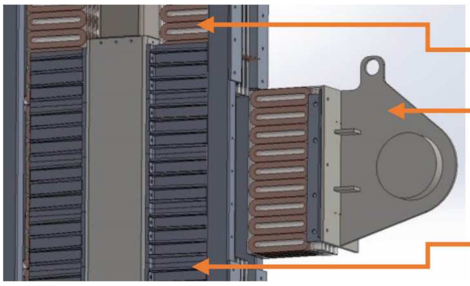

Fig. 32. Method for replacing coil module. Counter balanced lifting assembly for connection to crane

The linear motor generator test rig will be removed from the dock for inspection. A coil module will be removed to investigate the ease of replacing a faulty unit. Fig. 32 indicates this technique, in which a counter balanced unit is bolted to the coil module allowing for a smooth horizontal removal of the coil blades using lifting equipment. Bearing pads will be removed for inspection and wear patterns to ensure the bearing carriage is operating as expected.

CONCLUSION

This paper has described the manufacture of a 75 kW linear motor-generator test rig to demonstrate a direct drive linear C-GEN generator. It has provided details about the marinisation and the C-GEN machines and an overview of the test rigs operation. Results from a both a MagNet and SIMULINK model have been presented, with a brief description of the proposed wet test programme. An overview of the experimental results will be presented at the conference to supplement the paper.

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