# Project Neptune: Critical Component Tests for a Fully Flooded Direct-Drive Linear Generator for Wave Energy Convertors

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*Abstract*— **A significant challenge for Wave Energy Convertor (WEC) designers and manufacturers is the efficient conversion of differing wave types into useful motion to produce electricity. The height, period and orientation of waves vary greatly as do their respective power levels [1]. In order to efficiently and cost effectively convert the kinetic energy of wave motion into electrical energy, a Power Take Off (PTO) system must be able to withstand the harsh environment of the offshore marine environment, provide efficient energy extraction over various wave load states whilst maintaining low O&M costs over a long life span [2].**

***Keywords***— **Direct-drive, Linear, Generator, Wave, Prototype**

## I. INTRODUCTION

Direct drive PTO’s contain minimal complex mechanical components, when compared to their high speed geared counterpart’s, and thus leads to a potential reduction in O&M costs whilst offering improved efficiencies over a wide range of load profiles. The nature of the offshore environment is notably inhospitable and difficult to access, therefore high reliability, modularity and survivability are key to providing an effective power extraction system. Project Neptune is a Wave Energy Scotland Stage 3 PTO Research initiative, which aims to design, build and demonstrate a 75 kW direct drive linear generator based on the C-GEN technology developed at the University of Edinburgh [3][4]. Project Neptune focusses on the design, modelling and testing of critical components for marine energy PTO’s in order to simplify and reduce O&M costs of the overall device. The outcomes of which will be integrated into the C-Gen generator topology through the utilisation of small scale models and test rigs with the ultimate aim to improve C-GEN design tools for marine operation.

The authors of this paper have identified the following critical aspects for study:

- Bearings and seals
- Coil module Cooling
- Marinisation and Survivability

A brief summary of the results of these simulations, tests and their incorporation in to a 75 kW linear C-Gen generator prototype will be provided within this paper.

## II. C-GEN TECHNOLOGY AND APPLICATIONS

C-GEN is an innovative multi-stage air-cored PMG technology that is applicable to direct drive, slow or medium speed generator designs. The differentiating design features of the patented C-GEN design include:

- An axial flux topology with C-shaped rotor core
- An air-cored stator arrangement
- A generator divided into several axial generator stages that are electrically independent
- A generator rotor and stator divided into low weight standardised modules around the circumference or length of the machine

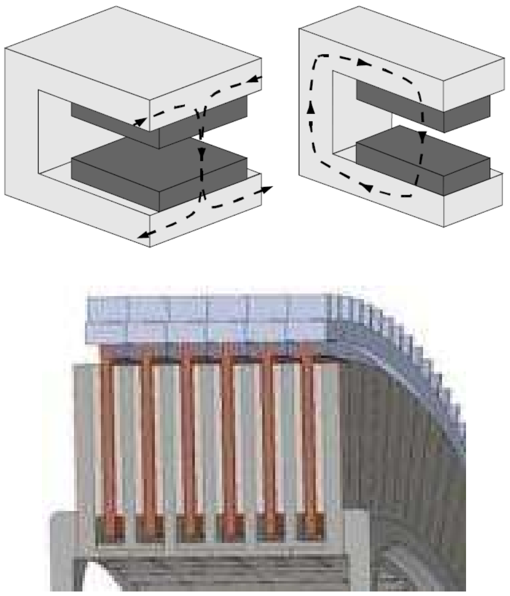

Fig. 1. Top: C-Core topology with flux path indicated. [1] Bottom: Adjacent stacked C-Core topology. [2]

C-GEN is made up of light weight stator and rotor modules as described in Fig 1. The comparatively lightweight C-GEN module topology reduces O&M costs compared to traditional iron-cored, radial flux PMG systems. The maintenance of drive train components, if necessary, can be carried out with lighter lifting equipment or an internal turbine crane. Multiple generators consisting of simple, lightweight modules can be "stacked" back-to-back along the shaft of a wind turbine to create a multi-MW rating without increasing the machine diameter. This means that for certain generating system line failures, one generator line can be isolated, enabling the wind turbine to continue generating revenue whilst maintenance is scheduled. This redundancy characteristic is even more relevant for remote areas with challenging conditions for access, e.g. offshore wind farms. In C-GEN the number of generators in operation can be adjusted based on wind conditions to optimise the power output, efficiency and increase longevity.

### *A. Rotary Applications and linear Applications*

C-GEN technology has been demonstrated at various scales:

- 20 kW rotary machine proof of concept. [1]
- 15 kW rotary machine successfully installed and operated on a wind turbine. [1]
- 6 kW rotary machine successfully installed and operated on a wind turbine.
- 25 kW axial flux multi-stage rotary machine as proof of concept of multi-stage topology pre scale up to 1 MW.
- 1MW axial flux multi-stage rotary machine, demonstrator of a slice of a 6 MW direct drive generator.
- 50 kW linear machine for wave energy applications. [3]

Fig. 2. 1 MW axial flux multi-stage rotary machine

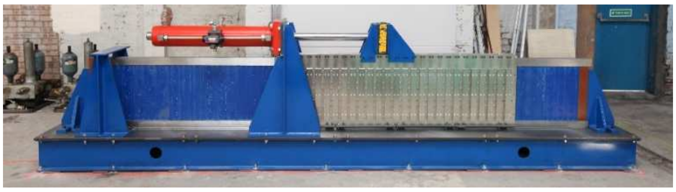

Fig. 3. 50 kW C-GEN linear generator prototype and test rig. [3]

C-GEN technology has been demonstrated at various scales. For small wind applications the technology is at TRL 5, as it has been demonstrated in the real environment, but at multi-MW scale it is at TRL 4 and for marine energy at TRL 3.

## III. POLYMER LINEAR BEARINGS

The installation of power generation devices in harsh marine environments places increasing pressure on the reliability and longevity of mechanical components such as bearings. In addition, the forecasted size and rating of these machines forces bearing technology to the limits of its capacity. Polymer bearings are simplistic in nature, mostly produced from one material, they are relatively easy to produce in any topology, when compared to metal or alloy bearings. They have been proven to be corrosion resistant with low friction values, normally operating on a self-deposited thin hydrodynamic film of material which gradually wears the bearing down over time. These self-lubricating bearings can operate in both dry and wet conditions, dependant on load and velocity. In this manner the life span of a polymer bearing can be assessed based on its wear rate whilst operating in conditions above its minimum load requirement.

However results from linear bearing testing are scarce, especially when it comes to linear polymer surface bearings since their large scale application is predominantly in the shipping industry for rotary prop shaft applications. Therefore the testing of various polymer bearing samples was carried out on a purpose built reciprocating linear test rig, Fig 4 and Fig 5.

### *A. Bearing Testing*

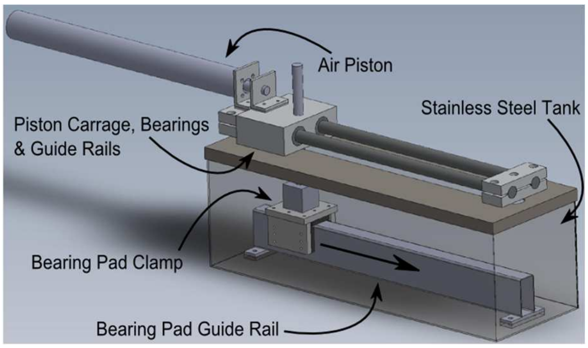

Fig. 4: Linear Bearing Test Rig Basic Topology

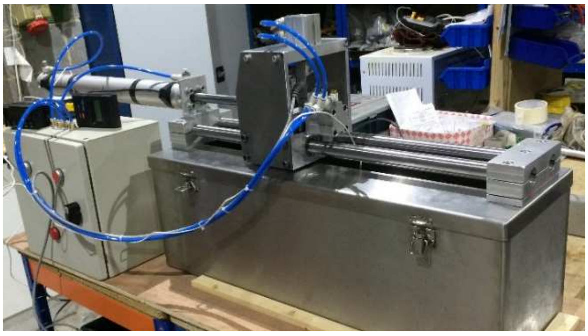

Fig. 5: Linear Bearing Test Rig Basic Topology

A total of 5 polymer bearing materials were chosen from various companies and subjected to continuous operation in both wet and dry environments. The testing methodology for the bearing samples was to bolt each sample in to a c shaped support bracket, Fig 6, which could be removed easily for bearing assessment and sample removal. The c-support was attached to the piston carriage which in turn drove the bearing samples back and forth on a stainless steel box section guide. The introduction of springs behind the bearing pads allowed the bearings to maintain more contact with the guide rail, thus aiding the production of the desired hydro-dynamic fluid layer.

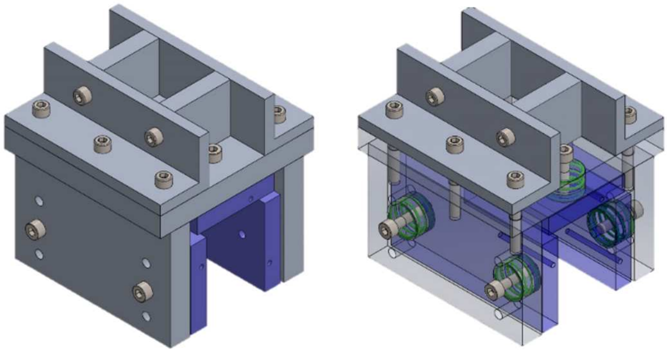

Fig. 6. Linear Bearing Test Rig Clamp with sprung bearing pads

A stroke was considered to be one cycle of the piston movement, equal to 1 m, each cycle was recorded on a counter thus providing the distance travelled in meters. In addition to the basic reciprocating operational design, compressed air actuators mounted on the piston carriage apply vertical and torsional loads to the c-support and in turn to the bearings.

Before testing, each sample was weighed and imaged, if the bearing is being tested wet, the pads were soaked in water over a week and weighed in order to define their saturated mass. Once clamped in place and installed into the test rig, a thermocouple was installed within the top bearing pad to monitor the bearing pads operational temperature. The samples were tested for 24/7 operation at velocities between 0.3 and 0.6 ms$^{-1}$ with torsional and vertical loads of 20 – 50 N applied throughout the stroke. During testing observations were made every 50 - 100 km, at which point the samples were removed, briefly dried (if required) and weighed up to a distance of 500 km.

### *B. Linear Bearing Test Results and Discussion*

The results of the bearing tests were used to calculate the average wear expected per 100 km. A summary of this data is provided in Fig 7. Wear rates during wet testing were found to be higher across the board. Fig 8 indicates the wear pattern on both a wet and dry tested bearing sample with (B2) dotted area indicating a region of no wear whilst (A2) shows a smooth wear profile across its surface. Water saturation of the outside layers of material may have been a factor in the increasing wear pattern whilst the authors also propose that during dry testing the bear samples were unable to create a fully formed hydrodynamic fluid layer, leading to less wear.

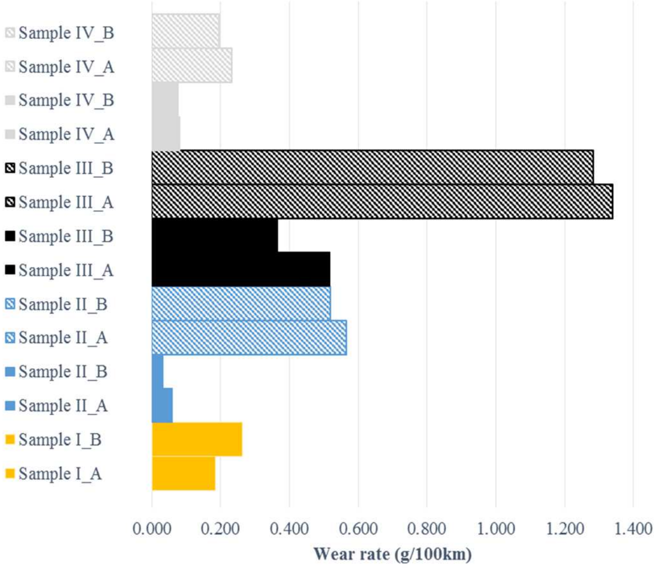

Fig. 7. Wear rates over the samples during testing, solid for dry testing, and shaded for wet testing.

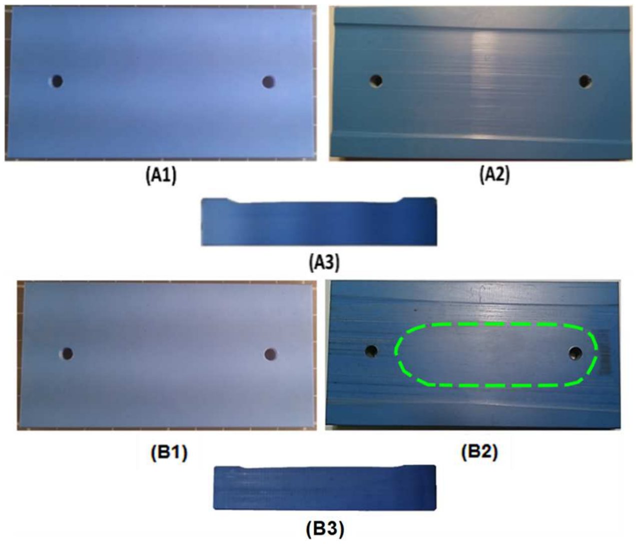

Fig. 8. Pads (1) New Pad. Pads (2) Surface wear after 350km. Pads (3) Side View of surface wear. A and B denote wet and dry testing respectively

The friction coefficient for all dry and wet test samples were calculated and found to be up to three times that of the values provided by the manufacturers. However the values were still well within the region of mechanical bearings and can be explained by difference between radial and linear operation.

## IV. MARINISED COIL AND COOLING INVESTIGATION

Investigation of passive cooling concepts were carried out to assess the difference between laminar and turbulent water through the airgap geometry in the machine. The use of passive cooling eliminates the need for ancillary equipment such as pumps and heat exchangers, which will have an O&M requirement. The C-Gen stator and rotor surface topologies can be either smooth or salient. Fig 9 shows both a smooth stator/rotor topology and a castellated rotor/smooth stator topology.

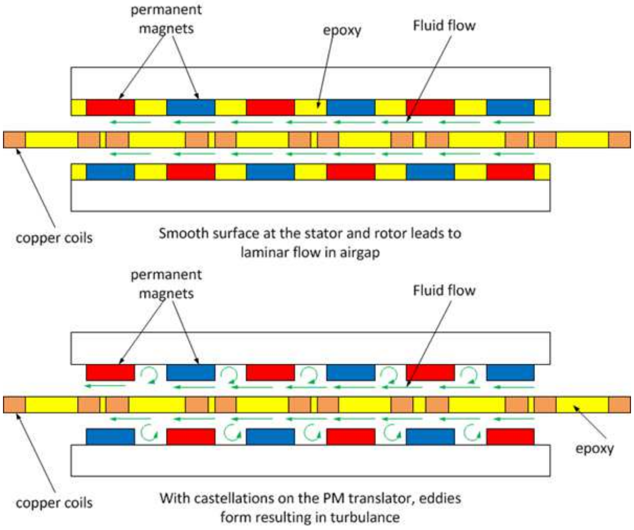

Fig. 9. Stator and rotor surface topologies. Top: Smooth stator and rotor topology. Bottom: Smooth stator and castellated rotor topology.

Smooth surfaces are achieved through encasing the windings and translator in epoxy or stainless steel. Both protect against corrosion, and both have been adopted in other generator technologies used in marine devices, eg the rim generator used by Open Hydro. Additionally various studies were undertaken to allow the airgap of the machine to be fully flooded with sea water, thus removing the requirement for seals within the machine and allowing operation without secondary cooling equipment and removing the potential for humid enclosed conditions creating a simplified machine topology for a submerged C-Gen device. This section will present results from CFD simulations, verified and expanded by experimental test results.

### A. CFD Simulations

CFD simulations were performed for a reciprocating 6 coil geometry surrounded by both a smooth and castellated magnet geometry. The copper coils were defined as naked with a 80 $Wm^{-2}$ heat flux boundary condition and the oscillating motion through the stator was defined by [0.6Sin(0.8t)]. Fig 10 shows a preliminary temperature scene at a cross-section through the stator.

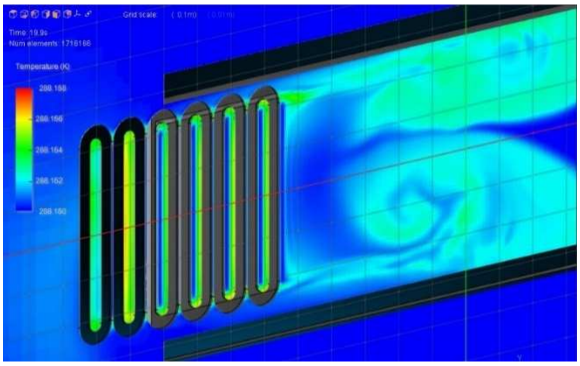

Fig. 10: Temperature scene at a cross-section through the stator

The preliminary extent of heat transfer in both an air and water medium for both smooth and castellated magnet topologies are provided in Fig 11 and Fig 12 respectively.

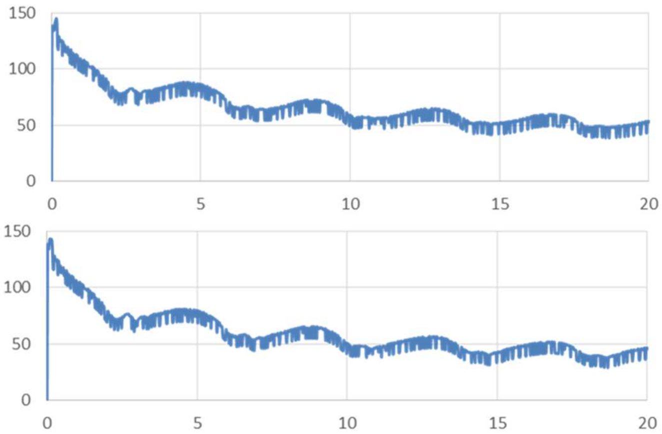

Fig. 11: Heat transfer values for an air filled airgap. Top: Smooth magnet topology. Bottom: Castellated magnet topology.

The results established that in both air and water, a multiple magnet design provides for greater heat transfer. Peaks in heat transfer are seen midway, when coils are moving fastest. These peaks are greater due to the greater fluid circulation between multiple magnets.

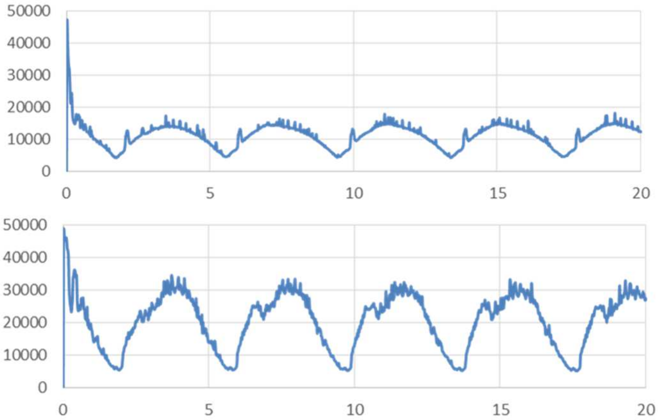

Fig. 12: Heat transfer values in a water filled airgap. Top: Smooth magnet topology. Bottom: Castellated magnet topology.

Since the flooded airgap showed such effective heat transfer values, the next stage was to investigate the heat transfer coefficient across the external resin operating in a real world test rig prototype flooded tank for three different permanent magnet designs as shown in Fig 12. The temperature distribution for each is shown in Fig 14 – Fig 16.

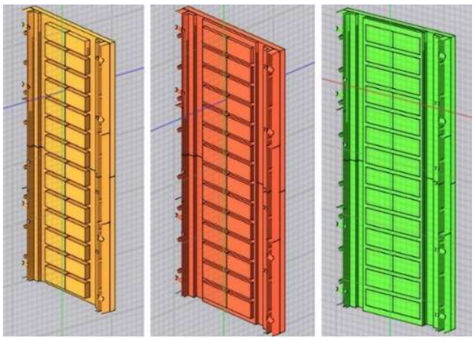
Fig. 13: Left: Castellated topology. Centre: Partially castellated topology. Right: Smooth magnet topology

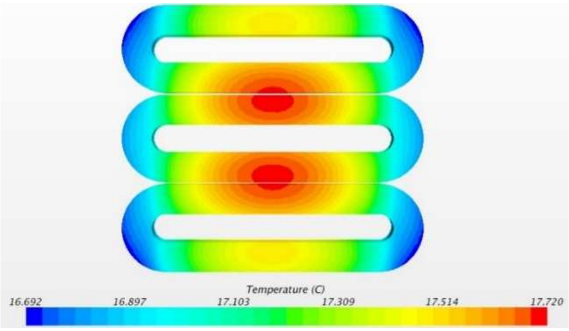

Fig. 14: Temperature distribution for the castellated magnet topology.

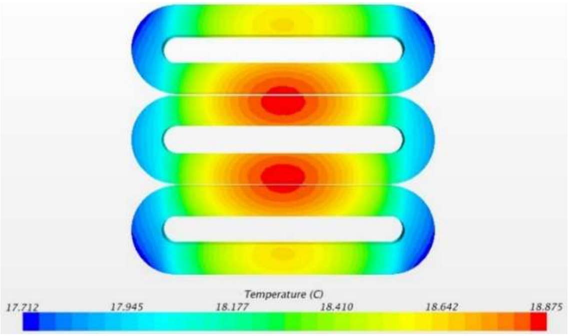

Fig. 15: Temperature distribution for the partially castellated magnet topology.

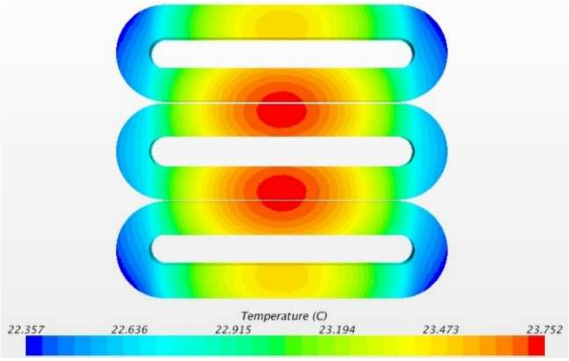

Fig. 16: Temperature distribution for the smooth magnet topology.

The extent of power in the coils is set at 54W per coil, whilst the position law defining the coil motion is 0.16Sin(4.5+5t), giving a peak velocity of 0.8ms$^{-1}$. The temperature increases due to smoother surfaces in the additional stator designs, establishing again the significance of castellated designs for the maximising cooling.

A miniature test-rig, described within the next section, was constructed to confirm these CFD simulations. It was designed to operate a three coil armature module (translator) through a castellated magnet topology at a peak velocity of 0.3 ms$^{-1}$. Therefore for completeness Fig 17 shows the temperature distribution from an additional simulation for the equivalent peak velocity.

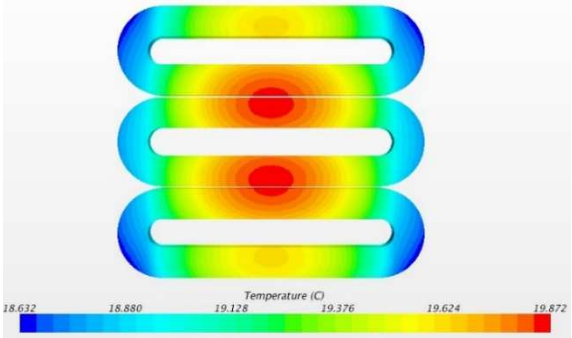

Figure 17: Temperature distribution for PM design 1 at 0.3m/s peak velocity.

## B. *Linear Rig Testing and Verification*

This section will investigate the benefits, in terms of cooling and generator efficiency, that a flooded airgap or marnisation can offer a real world machine. In addition this section will expand the discussion to include an assessment of various protective and structural potting materials for marinised coils. Finally this section will assess the operation of a large 5 kW C-Gen machine topology while operating in both dry and flooded conditions.

### ***Miniature Linear Test Rig***

A small linear test rig and generator topology was designed and built in line with the topology provided for simulation in the previous section. The topology consists of a double sided castellated magnet stator bolted vertically into a stainless steel tank with a viewing port, Fig 18. A pneumatic air piston is installed at the top of the tank, to which various translator designs can be connected from reciprocating linear testing. Sample copper windings contained within a translator structure for testing are presented in Fig 19.


Fig. 18. Linear test rig with a miniature PM machine.

In order to investigate the benefits of a flooded air gap, three topologies of translator were considered, a simple enamelled VPI coil blade translator, an epoxied coil blade translator with gaps and a fully epoxied coil blade translator. For all translators, three copper windings were installed, the specifications of which are provided in Table 1. The epoxy resin used within these tests is PC5308 blue epoxy.

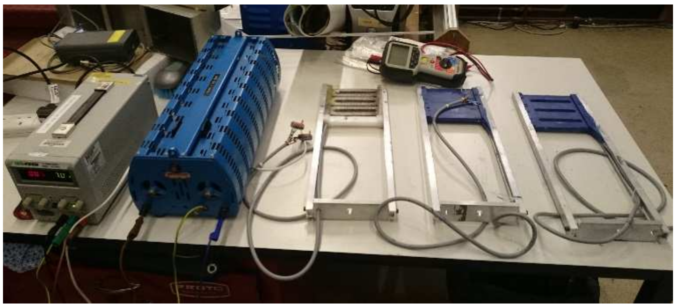

Fig. 19: Miniature linear rig samples.

TABLE I

SPECIFICATIONS OF SMALLER LINEAR MACHINE WINDINGS PER TRANSLATOR SAMPLE

| | |
|---|---|
| Number of turns | 130 |
| Diameter of wire | 0.75 mm |
| Active length | 100 mm |
| Width | 41 mm |
| Number of coils | 3 |

For each test a coil sample was inserted into the test rig and connected to a power supply via a variable resistor used to vary the excitation current. The coils were excited with DC current in order to simulate actual loading. The resistance of the coils was measured are regular intervals to assess increases in internal coil temperature while thermocouples were placed on the external face of the translator located in the centre of the second embedded coil. The pneumatic air piston was connected to a compressed air supply that allowed for a maximum velocity of 0.3 $ms^{-1}$ during testing. The average speed was recorded and noted for each test. A summary of the experiments preformed are provided below:

- Static dry and flooded tests for all coil samples from 1 Amp to 3 Amps excitation.
- Static excitation from 1 – 8 Amps in flooded conditions followed by reciprocating motion for each coil sample.

To emulate the marine environment for flooded testing, the translator was submerged in a salt water solution of 3.5 g salt per kg water, matching the average salinity of the North Sea. In order to prevent damage to the coils, testing was stopped once the coils temperature approached 90$^0$C, therefore the experiments were paused every 5 minutes in order to record the temperature and coil resistance data. A summary of results are provided in Fig 20 – Fig 22.

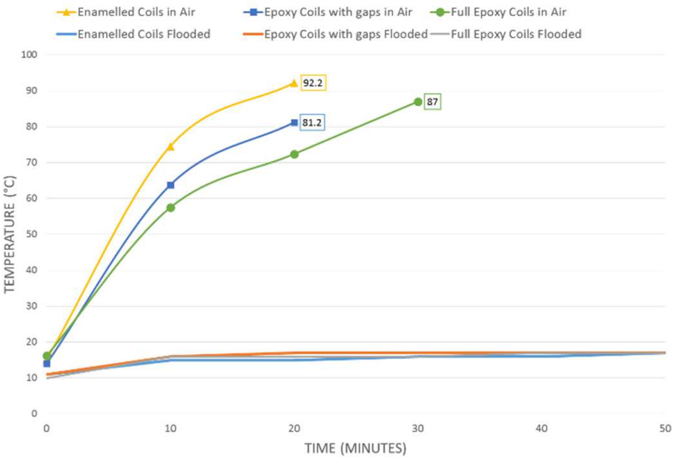

Fig. 20. Thermal results for static excitation of 3 Amps/coil for both dry and wet environments

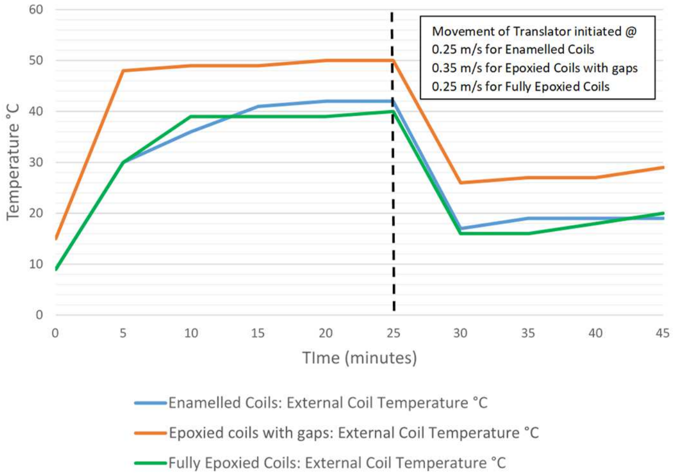

Fig. 21. Coil blade samples flooded. 8 Amps/coil

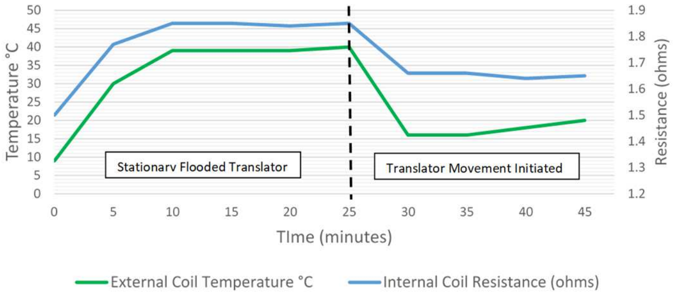

Fig. 22. Correlation between internal resistance and temperature for a fully epoxied coil blade flooded. 8 Amps/coil

For all coil translator topologies the experiments clearly demonstrate the benefit of running a fully flooded air gap in terms of thermal performance. With natural air cooled machines a current density of 4 $Amm^{-2}$ is typical, but these results suggest that more than 18 $Amm^{-2}$ could be achieved for these coils with wire diameter of 0.75 mm, at a current of 8A.

### *5 kW C-Gen Linear Test Rig*

Based on the results in the previous section a six coil translator was fabricated using a fully epoxied support structure. The linear test rig comprises of two servo driven ball screw linear actuators, requiring a 3 phase 32 Amp power supply. The rig has an active stroke of 1m and the capability of variable speed operation up to a maximum of 1 $ms^{-1}$. A linear pull cord transducer is used for position and speed feedback, while the servo drives are controlled using a Workbench control software. The water tank has a capacity of ~ 960 litres with two viewing sides each containing three polycarbonate windows. The test rig design and final manufacture are presented in Fig 23, whilst the generator specification is provided in Table II.

Thermo-couples were installed within the epoxy resin at a position towards the middle of each coil in order to provide temperature data whilst two s-beam load cells are secured between the top the translator assembly the linear actuators horizontal support beam, the load cells were rated to 5 kN. Before testing began the translator windings were connected in series with a star 3-phase connection with each phase monitored for voltage and current.

TABLE II
5 kW Linear generator specifications

| | |
|---|---|
| Stroke Length (m) | 1 |
| Power Output Peak (kW) | 5 |
| Velocity Peak ($ms^{-1}$) | 1 |
| Active coil length (m) | 0.45 |
| Number of coils | 6 |
| Wire diameter (mm) | 1 |
| Number of turns | 590 |
| Air gap (mm) | 2 |

Fig. 23. Left: CAD detail of 5 kW C-Gen machine and test rig. Right: Fabricated test rig installed at the University of Edinburgh.

Fig. 24. 5 kW C-Gen machine in a flooded test tank.

A test programme including no load, load and a heat run was undertaken under dry and flooded conditions. The linear actuator drive system was programmed to follow a trapezoidal velocity profile.

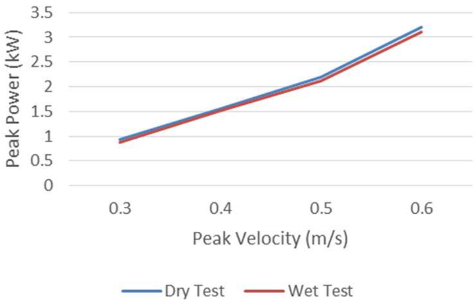

Fig. 25. Generator three phase power output over a range of velocities in both dry and wet conditions.

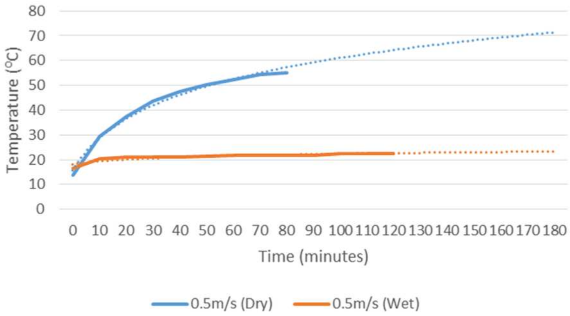

Fig. 26. Coil temperature varying over time at a maximum velocity of 0.5 $ms^{-1}$ and a peak current of 22 Amps per phase during dry and flooded operation.

Fig 25 provides the load test three phase peak power output for the generator over various speeds for both dry and wet operation. It indicates that there is a very slight reduction in power output during flooded operation due to increased drag forces. However Fig 26 provides an example of the temperature results recorded during operation, clearly demonstrating fully flooded operation leads to a significant improvement in thermal performance.

### C. *Simulation and Experimental discussion*

Results from the CFD modelling indicate that the best surface topology within the airgap consists of salient structures. For the stator a smooth surface was adopted because the epoxy is necessary to provide structure and protection to the armature coils, but a castellated surface was used for the PM rotor. The heat transfer in the flooded condition with a salient structure is 100 times that of the same structure in air. Temperature distributions of the coils in the 5 kW linear test rig and the miniature test rig support the case for fully flooded operation. In all cases the temperature never exceeds the insulation ratings, and so in terms of thermal performance the coil reliability is expected to be high. Experimental results from the miniature test rig gives confidence in the CFD modelling performed and the methodology adopted to obtain temperature distributions. The heat transfer coefficients for the smooth stator/salient rotor case have been incorporated into the design tool thus refining the analytical thermal model.

Results in this section demonstrate that significant current can flow in the machine whilst maintaining reasonable temperatures in the windings. Thus the power density could be increased by about a factor of 5, which would reduce material costs per kg. However it is proposed by the authors, that rather than optimise for higher power density, machines are designed for optimum efficiency, within reasonable economic constraints, and at normal current densities in the region of 5 A/mm$^2$. Fully flooded operation will then allow the machine to absorb extreme events. For example short circuit winding faults would not lead to excessive winding temperature. The machine could be used to shed high loads during storm conditions through resistive loads. Under such conditions the machine would have to be disconnected from the power converter. Electric braking could also be used to limit motion of the wave device during extreme waves.

## V. FLOODED COIL MODULE OPERATION ANALYSIS

Often the corrosive nature of the sea effects seals and whist at times the inability to transfer heat away from the vital power take off components decreases machine efficiency. Thermal modelling presented here indicates that a flooded airgap would provide a more efficient method of heat transfer within a PM machine topology. Not all generator topologies suit a flooded airgap, however a low speed PM machine with adequate material protection has the potential of harnessing the heat transfer available within sea whilst removing seals, mechanical bearings and additional protective structures such as nacelles.

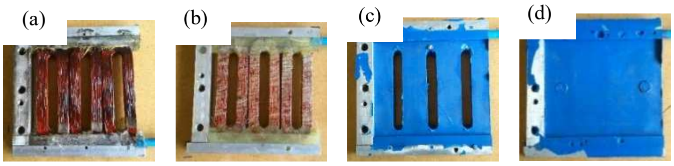

Fig. 27: Coil blade samples. (a) Enamelled varnished (EV). (b) Enamelled VPI (EVPI). (c) Epoxy encapsulated with gaps (OC). (d) Full epoxy encapsulated (FEE).

This section will assess various coil blade coatings and their operation in dry and wet conditions. The first series of tests aims to further understanding of the capacitance effect between coils placed in different potting materials and ground in seawater compared to ground in air. The second series of tests investigates voltage exposure on each coil sample. Each samples is composed of 3 coils with 130 turns of 0.75 mm cemenflex wire. The potting materials chosen for this study are shown in Fig 27 and include:

- Sprayed enamelled and vanished coil blades (EV)
- Wrapped and VPI enamelled coil blades (EVPI)
- PC5308 epoxy resin potted coil blades with gaps (OV)
- PC5308 epoxy resin potted coil blades (FEE)

Through these tests a better knowledge of potted coils operating in a flooded environment can be deduced.

### *Switching Tests*

A MOSFET driver combined with an IGBT replicate the switching happening in a power conversion stage in a direct drive machine, as illustrated in Fig 28.

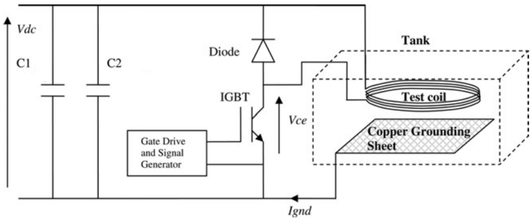

Fig. 28: Representation of coil tested in sea water.

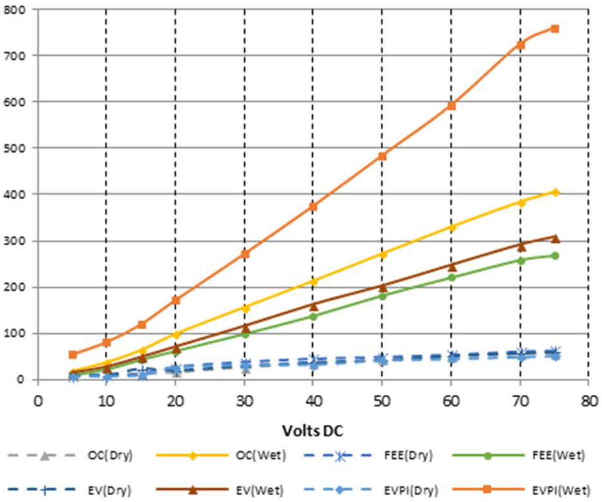

Fig. 29: $I_{gnd}$ peak to peak comparison of wet and dry dV/dt capacitance switching tests.

Each geometry presents a different surface area, hence different capacitance with respect of sea water. Thus, resulting in different discharging currents when the coils is switch ON and OFF. The results of each coil configuration in the high frequency circuit can be seen in Fig 29.

### *Voltage exposure*

Voltage exposure tests were run in two parts using a HAL 101 tester, shown in Fig. 30. The tests were completed as follows:

1. Completely dry samples
    a. conductive plates to each coil: the test was set to 600 volts at 50hz for 15 seconds
    b. coil to coil: the test was set to 150 volts at 50hz for 15 seconds
2. Right after wet switching test
    a. conductive plates to each coil: the test was set to 800 volts at 50hz for 300 seconds
    b. coil to coil: the test was set to 150 volts at 50hz for 300 seconds

After the experiments, it was observed that none of the samples failed on the coil to coil test, either in dry or in wet environment. This was expected since the space and material between coils makes it difficult for any leakage current to pass. The only coil that failed the high voltage test was the enamel varnished. It is important to mention that the failure was presented after the wet switching test. However it is reassuring that coils potted with in epoxy all passed the high voltage experiment.

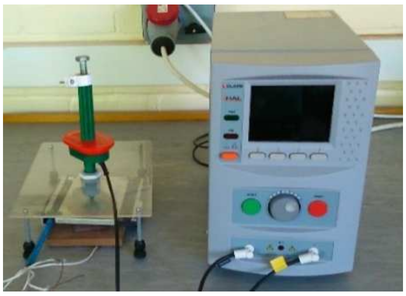

Fig. 30: Variable voltage test on coil sample using HAL tester

## VI. 75 kW LINEAR TEST RIG

Using the information gathered from the studies outline within this paper, it has been proposed that a linear C-GEN machine will be constructed and tested fully flooded within the North Sea environment. To simulate wave loading conditions, part of the machine will be run as a linear motor, with the generator section rated at 75 kW peak. The machine will utilise a flooded airgap with polymer surface bearings and epoxy potted coil blades. The specification of the generator is supplied within Table III, whilst an over view of the test rigs design and proposed testing is presented next.

TABLE III

75 kW LINEAR GENERATOR SPECIFICATIONS

| | |
|---|---|
| Stroke Length | 3 m |
| Power Peak | 75 kW |
| Active coil length | 300 mm |
| Number of coils | 216 |
| Wire diameter | 1.4 mm |
| Number of turns | 258 |
| Air gap | 4 mm |
| Peak velocity range | 1 - 1.5 $ms^{-1}$ |
| Voltage | 415 V rms (line), 339 V(pk) phase (star) |
| Current density | nominal 4-5 $A/mm^2$, overload > 20 $A/mm^2$ |
| Efficiency | > 60-80% for peak velocity range |
| Overload | 200% continuous, 500% short term rated |

### *A. Test Rig Design*

To operate the linear C-Gen generator with in a flooded environment, the test rig comprises of linear C-Gen generator sections and linear G-Gen motor sections. The linear C-Gen motors will be used to apply simulated wave loading to the generator modules without the requirement of a WEC device or external mechanical input.

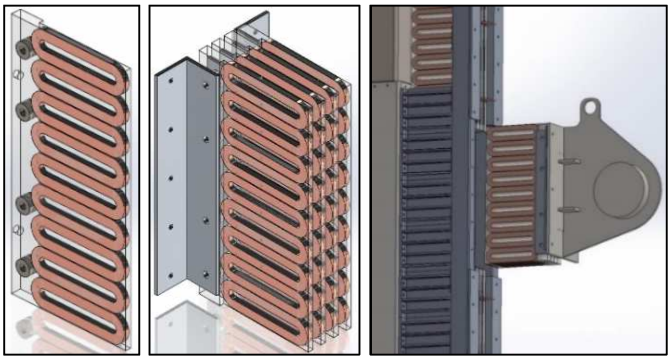

Fig. 31: Left: 9 coil epoxied armature blade. Centre: 4 blade armature module. Right: Proposed module removal process.

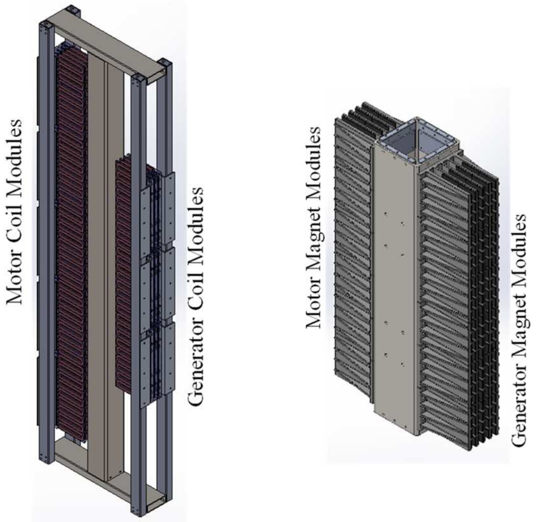

Fig. 32: Left: Single, linear machine stator assembly with motor/generator modules indicated. Right Single, linear machine translator with motor/generator modules indicated.

The stator armature blades for both the generator and motor assemblies will be constructed from multiple coils potted in epoxy. Each epoxied blade will consist of 9 air cored copper windings. The modular aspect of the C-Gen design allows for the coil module to be produced from 4 stacked coil blades. Fig 31 describes the assembly of the coil blades, coil module and the modular removal/installation procedure. The translator, Fig 32, consists of a 2 m length of box section with a total of 12 magnet modules mounted on opposite sides for operation with the generator and motor. Each magnet module has been cast from ductile iron and includes pockets for permeant magnet insertion, Fig 33. The translator box section also includes 8 modular polymer surface bearing carriages split between the top and bottom of the assembly, Fig 34.

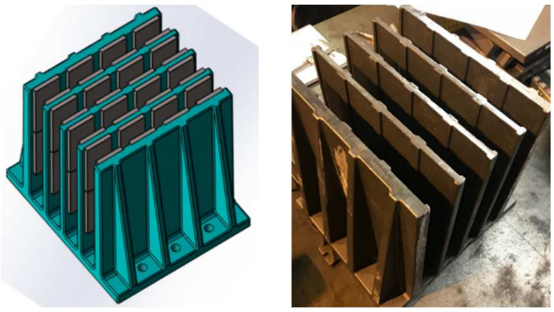

Fig. 33: Left: CAD drawing of magnet module with magnets shown in dark grey. Right: Cast magnet module.

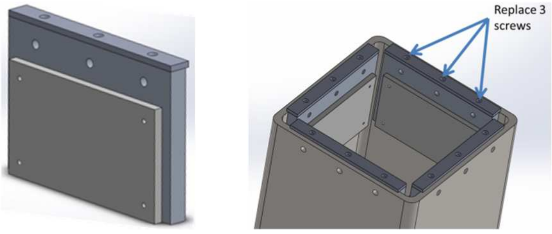

Fig. 34: Left: Bearing carriage with polymer bearing pad shown in light grey. Right: Four bearing carriages installed on translator, carriage module removal indicated.

Due to restrictions in water depth at the test area, the rig has been split into 2 identical back to back machines. Each machine consists of 3 generator blade modules, 5 motor blade modules and 1 translator assembly, Fig 31. Each linear motor-generator pair will be mounted on its own support column, which are connected by link beams, Fig 33. By separating the pairs of motor-generator sets, it is possible to build the pairs one at a time, which in terms of testing logistics is very advantageous. Assembly of the motor-generator system can be demonstrated, and functional tests can also be undertaken on a single pair. Each linear motor-generator pair is now rated at 37.5 kW. The two pairs of generator will be connected in parallel, thereby producing a maximum output of 75 kW. The linear motor has very different load requirements to the linear generator. To reduce the load on the motor, counterweights (as described in Fig 35) are to be installed. With no counterweight option the motor must also provide force to overcome the mass of the system as well as drag forces. These forces place significant demands on the current rating of the motor and hence the power converter. In the final design counterweights will be used, so that the motor must provide in the region of 75 kN peak force, compared to a previous peak force of 135 kN.

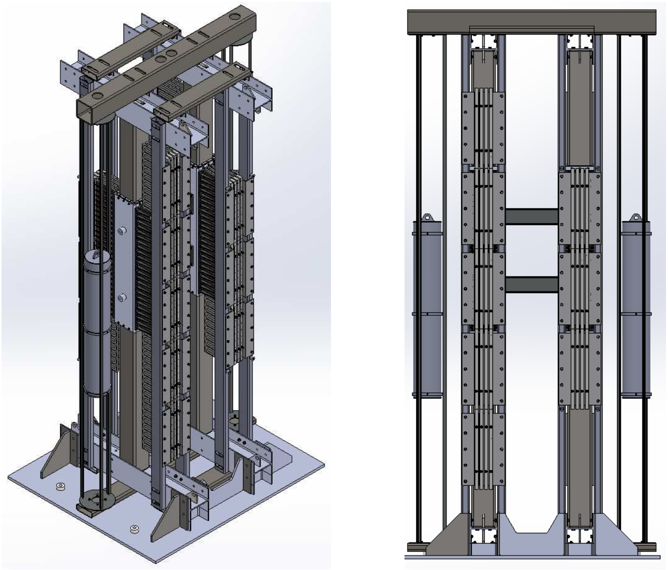

Fig. 35: Proposed test rig construction. Left: Isometric view. Right: Side view showing counter weights either side and motor modules on left and generator module on the right.

### B. Proposed Testing

Functional tests, both dry and wet, will be undertaken on the complete assembly. Dry testing at no load generator operation will demonstrate motoring operation and control of one half of the demonstrator. No load voltage results from the generator will provide some design verification. The coil modules will then be wet tested in the test pits using clean water, in order to test for water ingress, and with some initial load tests at ¼, ½, ¾ and full load to verify electromagnetic, thermal and structural performance. Functionality of the control system and the ability to emulate wave load profiles will also be verified in the system functional tests.

The wet test programme is aimed at demonstrating operation of the complete system in a real environment, in order to verify the underpinning aspects of C-GEN and the associated USPs. Wet testing is planned to take place at Leith Docks, Edinburgh, Scotland, over the course of 6 months. During this time the following tests have been proposed:

- No load, ¼, ½. ¾ and full load testing
- Operational loading and mechanical fault toleration testing
- Overloading operational testing

In addition component sampling will investigate wear, corrosion and marine growth. The modularity features of the C-Gen design will be also be assessed by removing the test rig from the water and replacing a stator module via an overhead crane, as indicated in Fig 32. The operation will be filmed and timed to inform maintainability metrics and O&M procedures. Design verification will be completed by analysing the test results with comparisons to the original design made.

## VII. CONCLUSIONS

The authors have described several critical components within a direct drive permanent magnet generator and suggested alternatives in order to simplify or remove them from the machines operation. Physical testing of various polymer surface bearings have noted that wear rates are highly predictable in both dry and wet conditions and confirmed their suitability for flooded linear PTO. Thermal modelling using CFD has proposed that flooding the airgap of a PTO system and allowing a rough magnet surface topology would aid the thermal properties of the armature coils. Physical testing on both a miniature and a 5 kW linear test rig has confirmed the cooling advantages of a flooded airgap. Coil samples were tested in both wet and dry conditions to assess the potting medium suitability to the environment. The outcomes of these investigations have been used to design a 75 kW flooded linear C-Gen generator, aspects of which have been described including all test procedures aimed at verifying the design.

## ACKNOWLEDGMENT

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