

Linear Generator for Direct Drive Wave Energy Applications

Neil Hodgins, Ozan Keysan, Alasdair McDonald & Markus Mueller

Abstract – A 50kW linear permanent magnet generator with a novel topology has been designed and built. The main significance of the generator topology is that there is no attractive force between the stator and permanent magnet translator. The magnetic force between the magnets is reacted within a self supporting structure. The lack of magnetic forces closing the airgap and the modular nature of the generator topology makes the manufacture and assembly of the generator easier than a conventional iron-cored permanent magnet linear generator. Photos of the manufacturing process are included in this paper. The modeling techniques used to design the generator are described and a summary of the design is presented.

Index Terms – air-cored winding, direct drive, linear generators, permanent magnet machines, wave energy

I. INTRODUCTION

Wave energy converters (WECs) have working surfaces that reciprocate at low speed and operate over a wide range of loadings. Developers of marine energy converters tend to focus on the prime mover aspects and use off-the-shelf systems to generate electrical power. A gearbox or hydraulic system is often used to interface the slow moving prime mover to a conventional high speed rotary machine. The use of gearboxes or hydraulics introduces a potential for extra scheduled and unscheduled maintenance. The cost of maintenance for off-shore devices is much higher than on-shore equivalents and access can be problematic. The gearbox or hydraulic system is eliminated when the generator is directly coupled to the prime mover. Direct drive has been successfully demonstrated in the wind industry at the MW scale by Enercon & Vensys [1 & 2]. There is only one direct drive wave energy device at a similar scale, the prototype Archimedes Wave Swing [3], which is no longer operational. A number of other developers have built direct drive systems at the kW level, such as Trident Energy in the UK and Seabased in Sweden [4] and Oregon State University in the US. Although direct drive has the potential to be more reliable and robust than gearbox or hydraulic systems there are significant engineering challenges to be overcome. The low speed of a rotational system can be compensated for by increasing the airgap diameter and thus the tangential velocity of the generating surface. For a linear reciprocating system, common in wave energy converters, this is not possible and the translator speed is equal to the low speed motion of the prime mover. A large airgap surface area is therefore required to produce the large forces required for large kW and MW scale power takeoff. This tends to lead to heavy

machines. Most designs of direct drive linear machines are double sided with iron cores and surface mounted permanent magnets (PM). An attraction force will be present between the iron core and the PM acting to close the airgap and being reacted through the bearings. In a double sided machine, these magnetic attraction forces theoretically cancel out, but any difference between the two airgaps will result in a large net force between translator and stator (as demonstrated by Nilsson et al [5]). MW rated linear generators for direct drive will be long (the AWS generator is around 8m long) and it is unlikely the airgap can be kept uniform along this length. A stiff structure is therefore required to maintain the airgap. Caraher et al [6] have shown that an integrated design approach in which the electromagnetic and structural design are optimized together leads to the most lightweight and economic solution. The magnetic attraction forces in large iron-cored PM generators can make assembly challenging, increasing cost. The additional loading on the generator bearings will also increase the cost and complexity of this component.

The magnetic attraction force between the stator and translator can be negated by removing the iron core from the windings. Air and iron cored machines are described by Polinder et al [7]. Polinder compares the air cored and iron cored machines in [7] finding the iron core to be advantageous but does not take structural mass into account. McDonald et al [8] compares air and iron cored rotary PM generators but takes the required support structure into account, demonstrating that the air-cored generator can be lighter but not necessarily cheaper for a complete design. The main advantage of an air cored linear generator is the reduced bearing load. A dedicated comparison for linear generators by McDonald et al [9] shows that passive bearings for iron cored generators will require yearly replacement. Active bearings could be used but at the expense of increased complexity (especially sealing), cost and power consumption.

Although there is no force to close the airgap in a double sided air cored machine there are still magnetic attraction forces between opposing PMs (although lower than in an equivalent iron-cored machine) which must be considered in structural design but does not affect bearing design.

A novel PM linear generator topology referred to as C-GEN has been presented in [10] & [11]. This topology addresses the major challenges in the design of PM machines for direct drive applications. This paper summarises the principal characteristics of the C-GEN topology and gives details of the design and manufacture of a 50kW(pk) linear generator.

II. C-GEN CONCEPT

The C-GEN topology is similar to the double sided PM machine shown in Fig. 1, however the layout of the structure of the PM element has been altered so that the attraction forces between facing magnets are reacted by the flux carrying material. This structure forms a C-shape. A single module with two magnets mounted on the C-core is

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illustrated in Fig. 2. The dashed lines show the main flux paths within the machine, through the core back and from core to core. This gives a 3 dimensional flux path.

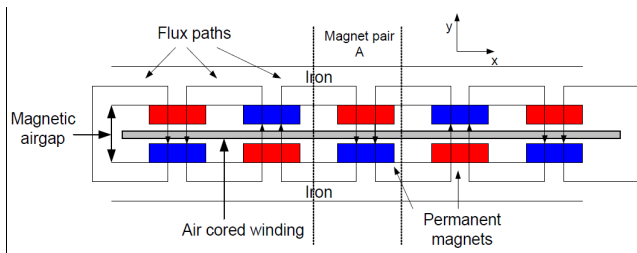


Fig. 1. Double sided planar air-cored linear machine with magnet pair highlighted

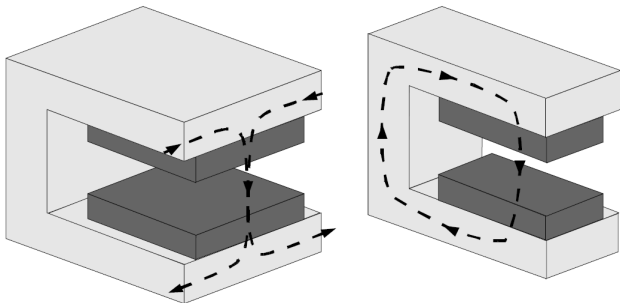


Fig. 2. C-Core module and flux paths within module and between modules

A rotary generator requires a C shaped structure into which the windings are cantilevered. A linear generator may close the core and increase the rigidity of the structure. The main flux present in the core is stationary, due to the permanent magnets, thus magnetic steel is unnecessary. C-Gen prototypes have been created with standard steel components, allowing a wide range of core shapes to be used while reducing cost. The module in Fig. 4 uses two machined sections of mild steel and two channel sections to form the core.

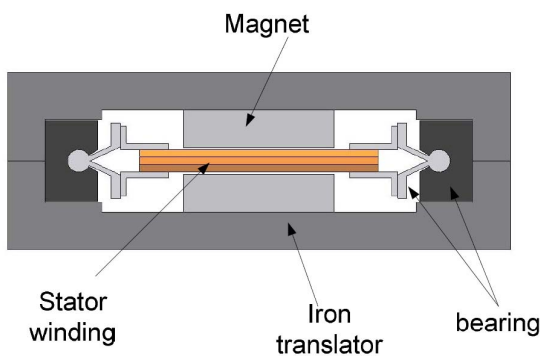


Fig. 3(a). CAD drawing of a linear module

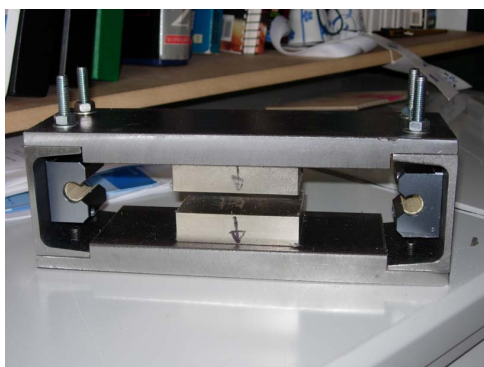


Fig. 3(b). Completed linear module

Fig 4. shows a generator constructed from the closed core modules used for bearing tests.

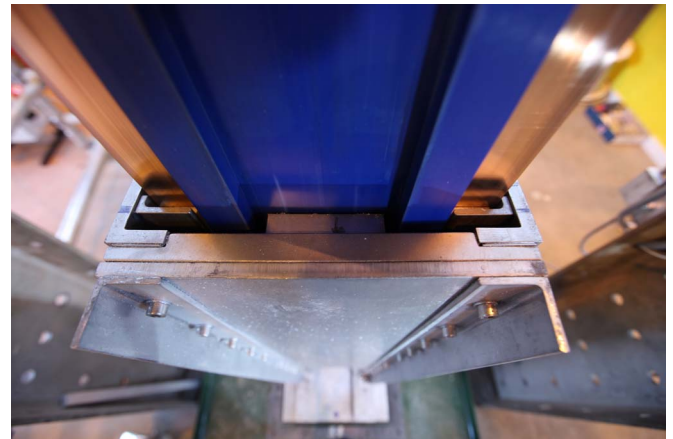


Fig. 4. Small scale linear prototype, coils held in blue translator block

The 50kW prototype linear generator was constructed with an open C shaped core. However the bearings on the open end of the core behaved structurally as a closed core. The core was left open so each winding could be brought out individually, increasing the flexibility of the generator and allowing a wider range of research work to be conducted.

III. 50kW C-GEN LINEAR GENERATOR

A. Electromagnetic Modelling

Flux paths are modeled using a reluctance network. Flux flows across the airgap and then back through the c-core module or between c-core modules and there is also a flux path between neighbouring magnets. Fig. 5 shows the reluctance network used for the core to core and airgap flux and labels the different flux paths through the generator. There is also a flux path around the core back but this is less pronounced for longer magnets.

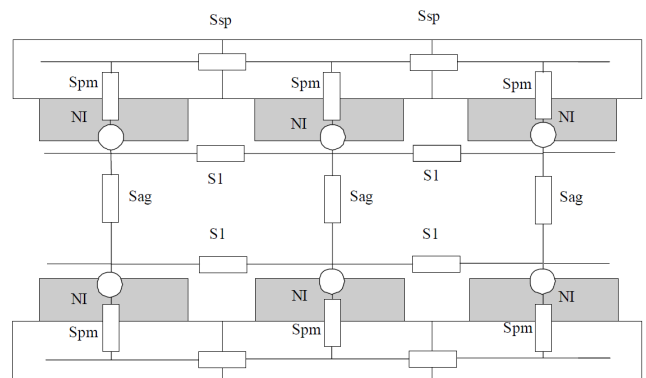


Fig. 5. Main reluctance network

The elements (labelled S1) in the reluctance network shown in Fig. 5 represent the tendency of flux to 'jump' between closely packed magnets. This represents a loss to of airgap flux density as this flux does not link the generator coils. The results obtained with this analytical model are compared to those found using Vector Fields finite element modelling software.

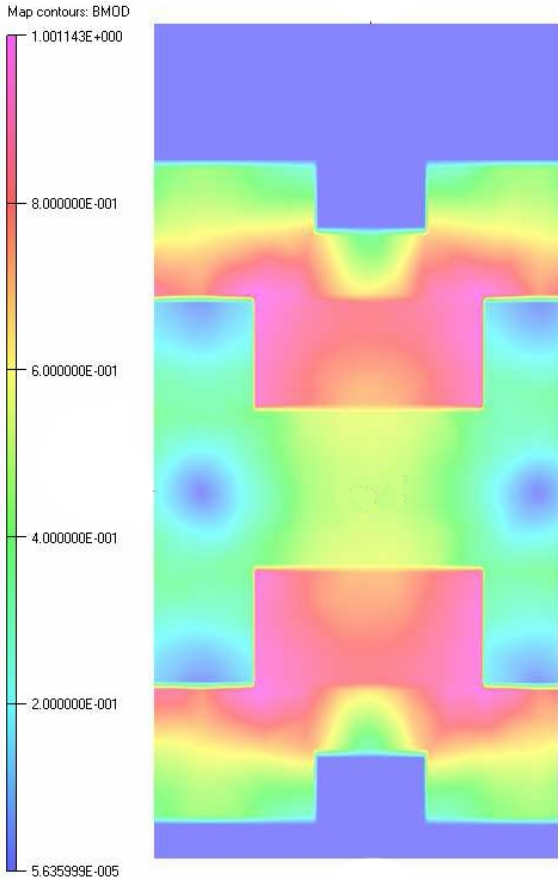


Fig. 6. Flux density plot from 3D solution, left hand scale in Teslas (pink = 1T)

A slice of a 3D model is shown in Fig. 6. The pink region represents the area of highest flux density. The peak airgap flux density is 0.53T, the flux between neighbouring magnets is between 0.2 and 0.4T.

In order to verify the reluctance network and finite element model the flux density was measured under 4 magnet pairs in the 50kW prototype. The results are given in table 1. The measured flux density is 10% higher than that predicted by finite element analysis and 5% higher than that predicted by the analytical model.

TABLE 1: MEASURED AIRGAP FLUX DENSITY

| Magnet | Flux Density (T) |
|--------|------------------|
| 1 | 0.60 |
| 2 | 0.62 |
| 3 | 0.59 |
| 4 | 0.61 |

B. Structural Modelling

The axes used for analysis of a single linear generator C-Core are illustrated in Fig. 7. The generator long axis is the C-Core axis labelled t , the height is labelled h and the core long axis is labelled L . The structural analysis concerns the response of the L direction beam to the attractive force between the magnets. This response is approximated analytically by a uniformly distributed load on a beam with fixed ends.

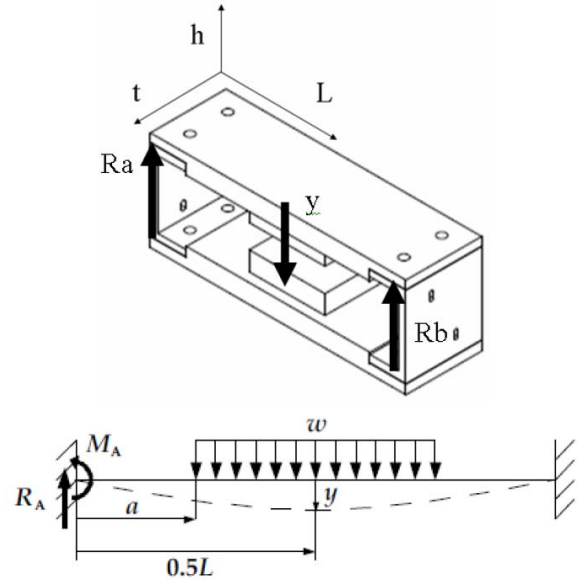


Fig. 7. Structural model for magnet attraction induced deflection

Different shapes of beam can be used to react this attractive force. The larger required beam thickness for structural strength or flux determines the required dimension of this beam. A model of the core was made in the ANSYS structural modelling package to check the fixed ends approximation. The weight of the translator, per module, is 85N. This weight is much lower than the magnetic attraction force in an iron cored machine and is the only force seen by the bearings in a closed core linear generator. If the generator was to be mounted with long axis vertical, as in the AWS prototype, then a misalignment force would be the only bearing load.

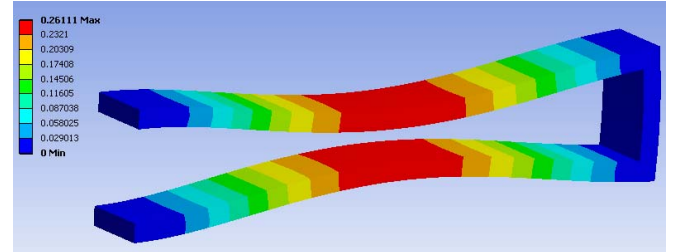


Fig. 8. ANSYS model of single core, deflection exaggerated

The predicted deflection from the beam theory model is 0.21mm, the ANSYS model predicts 0.26mm. Both of these deflections are acceptable.

C. Thermal modelling

A lumped parameter thermal model is used to calculate the coil temperatures within the generator. The coil temperature affects the lifespan of the insulation, the coil resistance and can affect the bearings.

In the 50kW prototype the stator winding is longer than the PM translator. The translator is half the length of the stator and thus only half the windings are active at any one time. This complicates the thermal network for heat flowing from each coil as it changes according to translator position. The thermal model calculates the network for the heat flow for a coil in an exposed and enclosed position. A ratio of time spent enclosed and exposed is used to calculate the resulting thermal resistance seen by each coil.

D. Exposed convection

The convection from the exposed coil surface will be a mix of natural convection and forced convection from the movement of the translator. The forced convection can be estimated from flat plate heat transfer correlations and is around $2\text{W/m}^2\text{K}$ at maximum and varies to zero when the translator is stationary at the end of stroke. The natural convection cooling varies around $12\text{-}16\text{ W/m}^2\text{K}$ and is thus the dominant form of cooling when the coils are not enclosed in the PM translator.

E. Enclosed convection

When the coil block is enclosed in the PM translator, the heat transfer paths are either by conduction through the bearings, along the translator long axis or across the airgap. Airgap heat transfer between the relatively slow moving translator and the stator is mainly by conduction and can be readily calculated. This heat transfer path has a very large surface area

F. Measurement

The winding for a 1kW prototype (Fig. 9) was instrumented with thermocouples and used to measure the heat transfer from the coils in this type of machine. The winding was heated by means of a DC power supply and the power input was measured. Measurements of the exposed convection coefficient showed a marginal improvement ($13\text{-}16\text{ W/m}^2\text{K}$ as opposed to $12\text{-}14\text{ W/m}^2\text{K}$) when the coil long axis (L) was orientated vertically rather than horizontally.

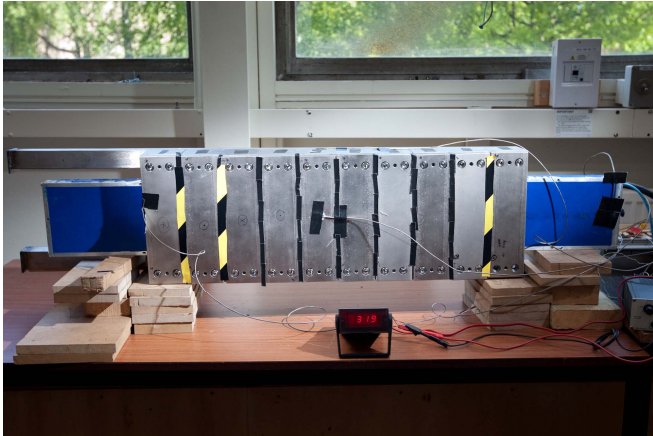


Fig. 9. 1kW prototype used for thermal measurements under test while enclosed in C-Cores

The thermal network for an enclosed coil is shown in Fig. 10. R_w represents the average resistance for the copper loss to reach a point external to the coil. R_L represents the heat flow path along the coil long axis, through the bearing and into the stator steel. R_h represents the heat flow across the airgap, through the magnet and into the stator steel. R_{ta} represents the heat flow along the generator long axis out of the enclosure into the surrounding air. T_r represents the heat flow from coil to coil.

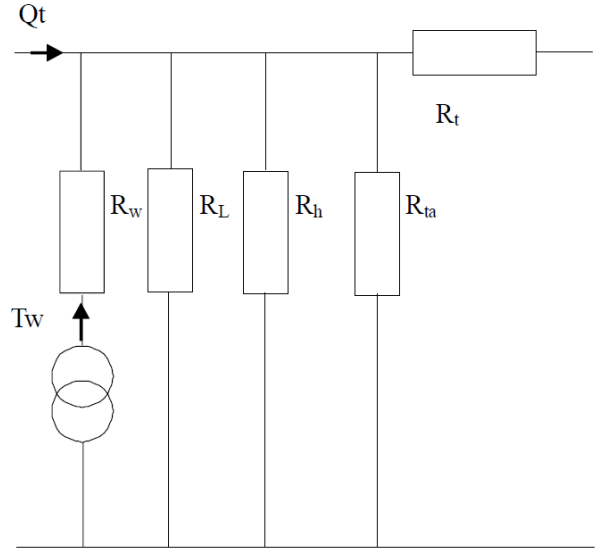


Fig. 10. Thermal network of a single coil in enclosed in the translator of a C-GEN linear generator

It is assumed that conduction is the most predictable heat transfer method. The areas involved are well defined and the conductivity of the materials used is relatively well known. The convection heat transfer involves a less defined area and the measurements made on the 1kW prototype were used to calibrate the convective heat transfer coefficients. The winding was heated with and without the core sections sealed at both ends, removing R_{ta} and allowing the airgap heat transfer coefficient to be measured independently.

The winding was heated with a current of 1.5A for 7 hours and the temperature rise was monitored in the coil, on the surface of the magnet and on the surface of the steel, on the exposed coils and in the surrounding air. The coil temperature with and without the end of the stator sealed is shown in Fig 11.

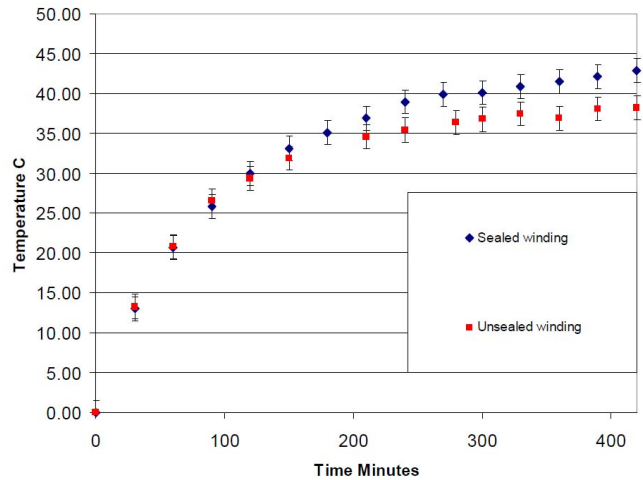


Fig. 11. Coil block temperatures with 1.5A DC per phase applied and coils partially enclosed in translator sections

The outcome of the enclosed and sealed test is shown in Table 2. The steel convection coefficient (H_{stah}) is given along with the airgap convection coefficient (H_{ag}).

| | H_{ag} | H_{stah} |
|----------|----------|------------|
| Measured | 12.24 | 7.56 |
| Max | 13.58 | 9.69 |
| Min | 11.14 | 6.20 |

As the airgap changes in thickness between the small linear generator and the 50kW prototype, the measured Nusselt number of the airgap is used to perform thermal analysis. The long axis convection was measured in the 1kW prototype as a thermal resistance of 6 K/W, assuming that the resistance scales linearly with core length, this gives a relatively high resistance of 16 K/W for the 50kW generator.

G. Final Design

The main parameters of the final design are given in table 3:

TABLE 3: SPECIFICATION OF 50kW LINEAR GENERATOR

| | | |
|-------------------------------|-------|----|
| Peak Power Output | 50000 | kW |
| RMS Power Output | 25000 | kW |
| RMS Voltage | 139 | V |
| RMS Phase Current | 40 | A |
| Pole pitch | 0.075 | m |
| Coil pitch | 0.1 | m |
| Active length | 0.45 | m |
| Magnet thickness | 30 | mm |
| Total poles | 28 | |
| Total coils | 42 | |
| RMS efficiency (at full load) | 65 | % |

IV. PROTOTYPE ASSEMBLY

The 50kW prototype was manufactured by Fountain Design Ltd in County Durham in the UK [12]. Fig. 12 shows 3 racetrack type coils mounted in a mould for potting in epoxy to form a single stator winding block. The stator blocks were mounted into rails on the test platform as shown in Fig. 13. The magnets were supplied by Hallamshire Magnets in Sheffield. The magnets were supplied screwed to a steel plate (Fig 14) which forms part of the C-Core. A complete C-Core module is shown on the right in Fig. 14. Since there are no magnetic attraction forces between PM C-Core modules and the stator winding an engine hoist (Fig. 15) was used to mount the modules on the generator. The bottom end of the C-Core was held open by bearings (Fig. 16) to allow the winding configurations to be changed. Fig. 17 shows the finished prototype, installed and ready for testing.

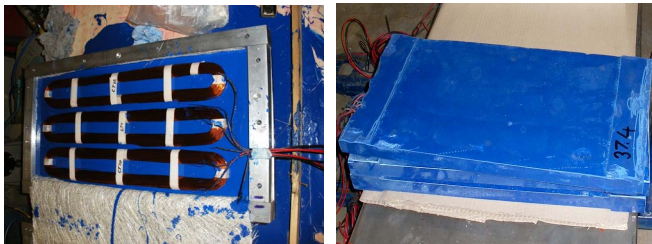


Fig. 12. Manufacture of stator coil blocks

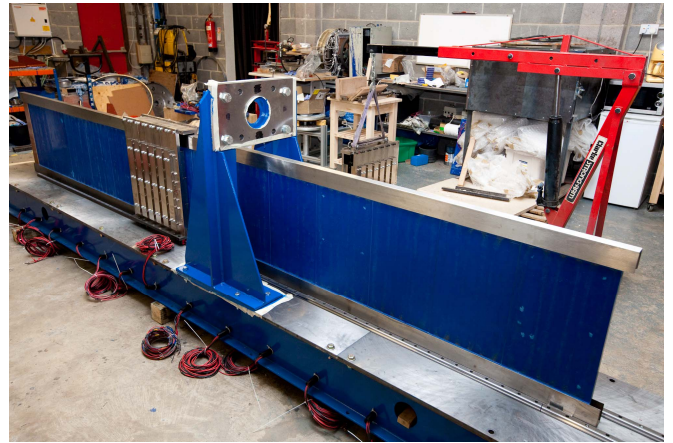


Fig. 13. Completed stator winding

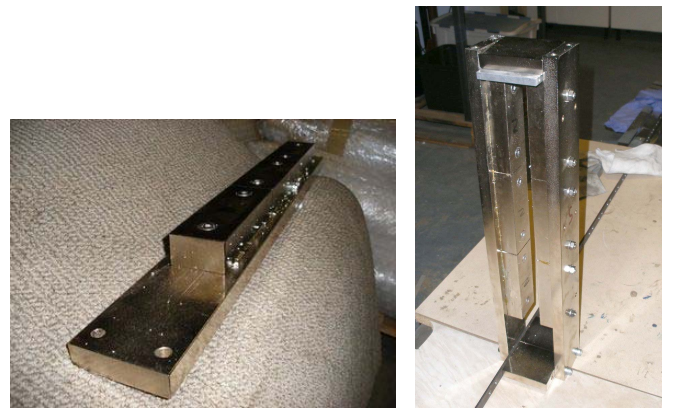


Fig. 14. Assembly of a c-core module



Fig. 15. Mounting the c-core modules using an engine hoist

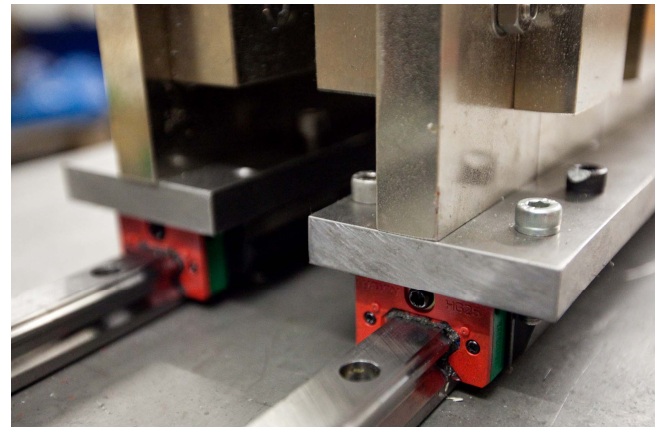


Fig. 16. Bearings act as structural element of C-Core in prototype

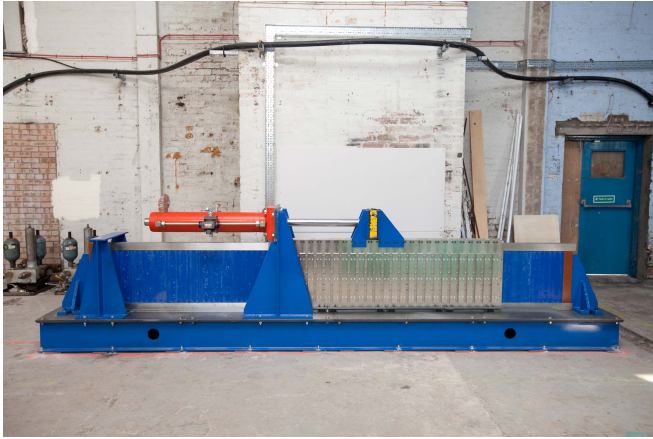


Fig. 16. Completed prototype installed ready for testing

V. CONCLUSION

The authors have described a modular air cored linear PM generator. There are no magnetic attraction forces between the stator and translator. The C-Core structure reacts the attraction forces between the permanent magnets. Electromagnetic, structural and thermal models have been described from which the final design was completed. The high degree of modularity and the ease of assembly was demonstrated in prototype assembly. The prototype has been installed and testing is currently underway. The test results will be presented at the conference to verify the modeling techniques developed.

VI. ACKNOWLEDGEMENT

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VIII. BIOGRAPHIES

Neil Hodgins graduated with a 1st Class Honours Degree in Electrical and Mechanical Engineering from the University of Edinburgh in 2005. He graduated with a PhD from the University of Edinburgh in 2010 under the supervision of Dr. Mueller on thermal modeling of induction generators for wave energy devices. In Sept 2008 he became a research assistant working on C-GEN and is currently funded by EPSRC on the Supergen Marine Project.

Ozan Keysan graduated in 2008 with a Masters from the Middle Eastern University in Ankara, Turkey. In February 2009 he joined the Electrical Machines Group in the Institute for Energy Systems at Edinburgh to work on the design of C-GEN for wave and tidal current energy converters funded by npower juice. In February 2010 he started a PhD at Edinburgh investigating high temperature superconducting machines for direct drive systems.

Dr. Alasdair McDonald graduated with a 1st Class Honours Degree in Electrical & Mechanical Engineering from the University of Durham in 2004. He graduated with a PhD from the University of Edinburgh in 2008 under the supervision of Dr. Mueller. In his PhD he developed analytical design tools for the structure of direct drive generators. In 2007 he became a research assistant to work on C-GEN funded by Scottish Enterprise, and is co-inventor on a patent. In 2009 he co-founded NGenTec with Dr. Mueller, which was established to commercially exploit the C-GEN concept.

Dr. Markus Mueller graduated with a 2.1 in Electrical Engineering in 1988 from Imperial College. In 1991 he was awarded a PhD from the University of Cambridge for his work on modeling induction motors. Subsequently he worked at Cambridge as a research assistant working with Brook Crompton Motors. After 2 years with SR Drives Ltd as a Senior Development Engineer, he took up a lectureship at the University of Durham in 1997. In January 2004 he moved to the University of Edinburgh and is currently a Reader. His main research interests lie in the design of electrical machines for renewable energy converters. In 2006 he was awarded the Donald Julius Groen prize by the IMechE for his work on direct drive linear generators for wave energy converters. He has published just under 100 papers, and is the inventor of C-GEN for which 2 patents have been filed. In 2009 he founded a spin out, NGenTec, to scale up and commercialise C-GEN technology for the offshore wind sector.