C-GEN – a Lightweight Permanent Magnet Generator for Direct Drive Power Take Off Systems

M. Mueller A.S. McDonald
Institute for Energy Systems,
School of Engineering & Electronics, University of Edinburgh,
Edinburgh, EH9 3JL, Scotland, UK.
markus.mueller@ed.ac.uk

Abstract

A new type of air-cored permanen magnet generator – known as the "C-GEN" – is introduced. For both linear and rotary types this machine removes the normal component of Maxwell stress between the stator and the moving part of the generator. By eliminating the magnetic attraction forces, the assembly process is easier than for conventional machines. The performance matches that of conventional PM machines but has the potential to scale up to large power levels without the need for large supporting structures.

1. INTRODUCTION

The power take off in a wave or tidal current energy converter transforms the motion of the prime-mover into high speed rotary motion. For example in a wave energy converter high pressure oil hydraulics converts the reciprocating motion into high speed rotary motion suitable for a conventional induction generator. A gearbox performs a similar function on a tidal current turbine. Such mechanical interfaces introduce another loss component reducing the overall efficiency and more moving parts leads to potential reliability issues. Gearbox failures in multi-MW wind turbines are an increasing problem for the wind industry [1]. In a direct drive system the generator is coupled directly to the prime-mover, leading to a potentially more reliable system. Direct drive generators are dominated by permanent magnet (PM) technology, which exhibit high part load efficiencies. The major disadvantage of direct drive is the physical size and weight of the generator due to the low velocities involved – in a wave device at most 1-2m/s and in a tidal current generator typically 10rpm. Direct drive has been shown to be commercially viable within the wind industry by German manufacturer Enercon, who use a field wound generator rather than a PM generator. Vensys, Harakosan and Scanwind are examples of wind turbine manufacturers pioneering PM direct drive generators [2-5]. In 2008, Siemens Wind Power embarked on a trial of direct drive PM generators by retrofitting two different PM machines to the 3.6MW machine [6]. There is increasing interest in direct drive in the wind sector as turbine rating increases.

The potential of direct drive in marine energy applications has been demonstrated by various researchers at model scale [7-9]. A MW-scale device incorporating direct drive has been designed and built [8] and recently Uppsala published results of sea trials of a heaving buoy coupled to a seabed mounted linear generator [10]. In terms of tidal current energy, Open Hydro have utilized a direct drive rotary PM generator, in which the generator is mounted on the rim of the turbine [11].

In [12] a number of generator topologies are compared and it was concluded that the current AWS prototype was actually best, but the comparison only included the active materials in the generator, namely the iron, magnets and copper that contribute directly to the generation of electrical power. A significant support structure is required to overcome the large magnetic attraction forces in an electrical machine and hence maintain a small airgap between the stationary and moving parts. Analytical tools for estimating the structural mass of low speed direct drive machines described in [13] indicate that it can be in excess of 60% of the total mass to overcome the magnetic attraction forces. Air-cored machines, in which the stationary winding is supported in a non-magnetic material rather than iron as in more conventional PM machines, have been proposed as a way of eliminating the magnetic attraction force [14]. However, in such machines the magnetic flux effectively sees an infinitely large airgap, so that the flux density interacting with the coils decreases rapidly from the magnet surface, resulting in a poor electromagnetic machine. In [15] the authors presented the evolution of a PM topology incorporating a stationary air-cored winding, but with a finite gap in which the flux density interacting with the coils is now constant and at magnitudes similar to that of conventional iron-cored PM machines. Reference [16] outlines the design procedure of this machine.

For completeness sake the authors will provide a summary of the principles of this machine in the paper, and will focus on the development of two prototypes, a linear and a rotary machine to demonstrate the attributes of this new generator technology.

2. C-GEN - a C-CORE PM GENERATOR

2.1. Summary of Evolution

The C-GEN machine is an air-cored design. Air-cored machines do not have iron in the stator and so there is little attraction between the rotor and stator. One example of a direct-drive air-cored generator in a wind turbine is given in [17]. In two-sided axial-flux air-cored machines, the two rotors have an attraction for each other. In [18], iron-cored axial-flux permanent magnet machines were compared with air-cored machines. The simple study showed that air-cored machines have the potential to be lighter for a range of power ratings. Figure 1(a) shows a double sided axial-flux machine. A force of attraction exists between the two PM rotors, which result in a bending moment about the centre of the shaft. In order to reduce this bending moment, a logical development is to increase the rotor shaft radius.

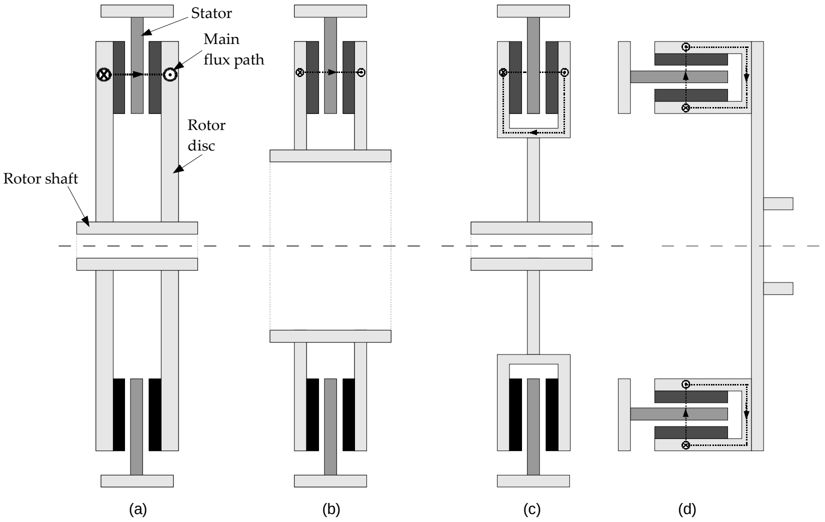

Figure 1. Cross section of double sided axial-flux machine (a) Baseline design (b) Increasing rotor shaft radius means that the thickness of the rotor discs can be reduced (c) C-core machine with extra flux path (d) Radial-flux C-core machine.

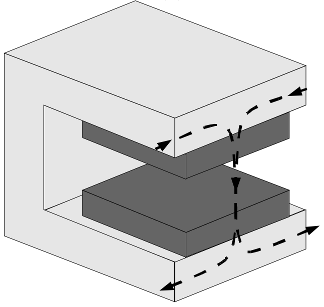

Figure 2. Steel C-core module with magnets (a) Longitudinal flux path (b) Transverse flux path.

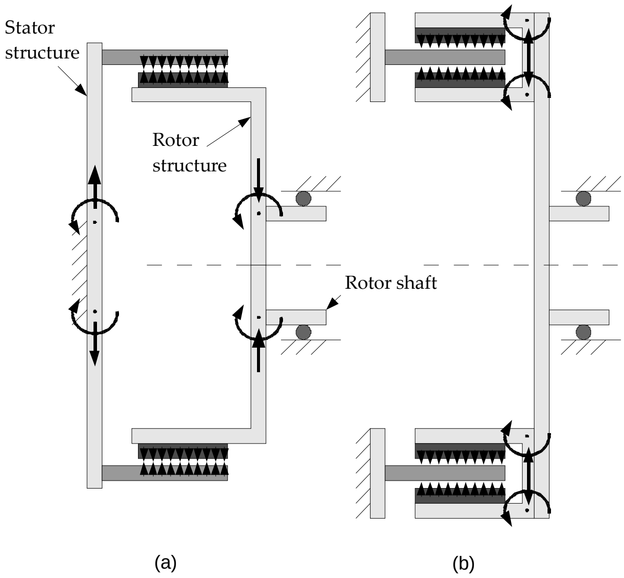

Figure 3. (a) Conventional permanent magnet radial-flux generator, showing normal forces and their impact on all of the stator and rotor structures (b) C-core machine, showing how normal component of Maxwell stress is isolated within the C-core and does not affect the rotor structure.

Because the airgap normal forces act near to the junction of the shaft and the discs, the discs can be made thinner and therefore lighter. This is illustrated in Figure 1(b). Taking this further leaves a ‘C’ cross section, where the limbs carry the magnets and the stator winding is held independently between them (Figure 1(c)). A further step is to allow flux to cross the web of the ‘C’, and to make the rotor out of modules (Figure 2) each carrying a pair of magnets. By rotating the C-core modules by 90˚ a radial-flux machine can be produced (Figure 1(d)). By increasing the axial length, the radial-flux generator’s torque rating can be increased without increasing the outer diameter. A more detailed description of the evolution is available in [19].

2.2 Main Attributes

This topology has a number of advantages over existing ironless designs. A radial-flux ironless permanent magnet machine has a very large effective airgap [14]. This C-core machine, however, has a finite airgap length and so higher flux densities and shear stress values are possible.

The new topology is structurally superior to an iron-cored machine. In a conventional radial-flux machine, the large airgap normal forces can act at distances of several metres from the points where these forces can be reacted against (Figure 3(a)). This implies that the rotor and stator structures must be stiff, large and heavy. By contrast the new machine has no forces on the stator. Although the two limbs of the C-core are attracted to each other, the normal stresses are reacted at points within the C-core – close to their point of application (Figure 3(b)). This topology means that the steel in the C-core fulfils both active and inactive roles. It has been estimated that the total mass of the new generator could be up to 50% lighter than an iron-cored PM direct drive machine.

The C-core acts as a keeper for the magnets, so that once the magnets are attached they will not move. The magnets and C-core can then be safely handled. If it is desired to handle magnets demagnetized, the magnets could be glued to the C-core and then magnetized in situ once required. Regardless of the method of assembly, the C-core PM system is safer to handle than in a conventional arrangement.

The lack of iron in the stator winding and hence forces between the stator and C-core iron makes the final assembly less problematic compared to conventional iron-cored PM machines.

The remainder of the paper will focus on the manufacture and assembly of both rotary and linear C-GEN machine prototypes to illustrate more clearly these attributes.

3. LINEAR TOPOLOGY

A linear module is formed by placing two C-cores face-to-face as shown in Figure 4. The complete module structure is shown in Figure 5, in which the bearing arrangement is completely integrated into the module. The rotor module is completely self supporting. The dotted lines in Figure 4 show the magnetic flux paths within the module, but when the modules are butted up against each other flux also flows between modules, as shown in Figure 6. Intra-module flux is shown in blue and inter-module flux is shown in red. 3D electromagnetic finite element analysis confirms that flux flows both within the module and between modules. Details of electromagnetic and structural design are provided in [16].

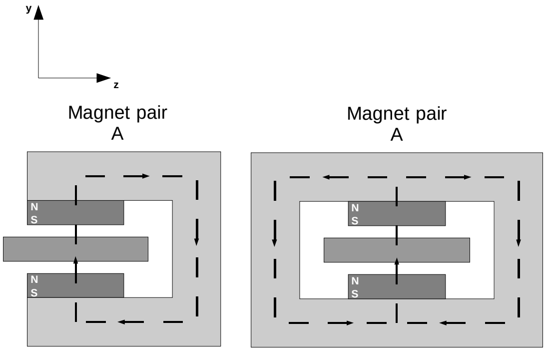

Figure 4. Magnet pair A (a) single C-core module (b) front-to-front C- core modules.

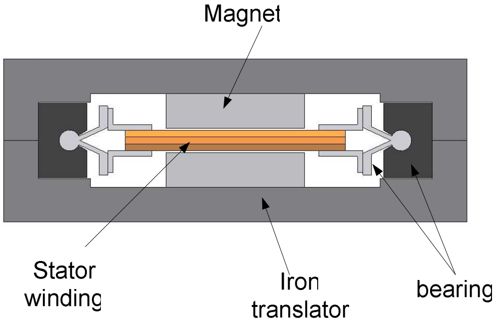

Figure 5. Integrated bearing and air-cored winding inside the C-core iron translator.

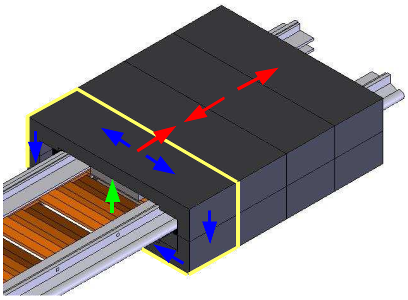

Figure 6. Four modules of a C-core linear machine. The neighbouring modules are brought into contact so that the flux is free to flow in both the x-y and y-z planes.

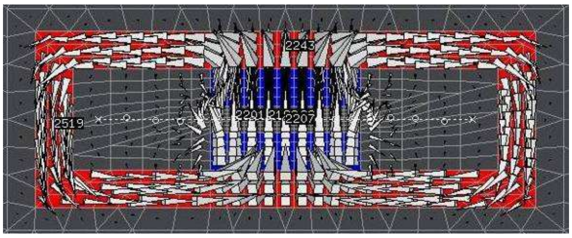

Figure 7. 3D Finite Element Analysis of a linear module.

One aspect of large permanent magnet machines is the difficulty and cost of assembling them. This topology will be easier and safer to handle than existing generator types because the large forces of attraction are dealt with in the modules, rather than between the translator and stator.

A prototype machine was built at the University of Edinburgh based around some spare 20×60×80 mm NdFeB magnets. Figure 8 shows how a C-core module was assembled from common mild steel flat bar and 'C' channel sections. The 20×80 mm flat bar was machined at the ends (Figure 8(a)) to provide the correct airgap clearance. The next step was to slide a magnet onto the steel surface (not shown). Figure 8(b) shows the module part-assembled, with 'C' channel sections, screws and threaded bars (for location) ready to receive the top bar section. Figure 8(c) shows how the steel pieces fit together. All of these parts are common and low cost; the assembly process is easily scalable for larger machines.

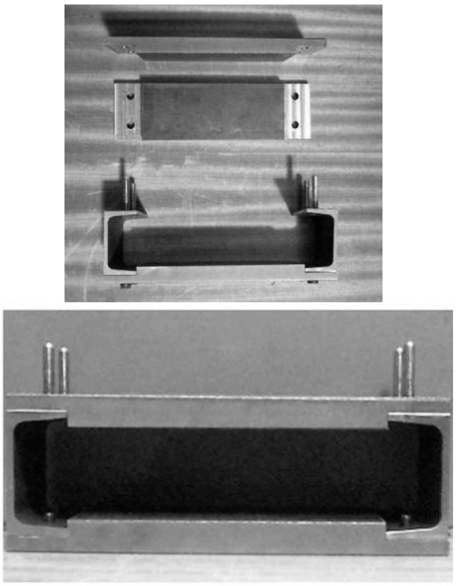

Figure 8. Steel components of C-core module (a) machined flat bar (b) flat bar screwed to 'C' channel sections and threaded bar (c) C-core module assembled without PMs.

Once the C-core module is assembled it is easy to handle. Figure 9 shows ten such modules which together make up the translator. An air-cored winding (total height 12mm), supported by an aluminium frame was built and slid into the airgap, and was located by bearings as shown in Figure 5. Inexpensive bearings can be used because they only have to carry the weight of the windings, rather than counteracting the normal attractive force between the stator and translator.

An airgap flux density of 0.82T was determined from the the 3D finite element model shown in Figure 7. A Hirst GM04 gaussmeter gave peak no load airgap flux density readings in the region 0.80-0.83 T. The structural modelling described in [16] gives a deflection of 1.2×10^{-2} mm for w = 21.3kN/m, l_m = 80 mm, L = 250 mm and E = 200 GPa. The airgap clearance is 1 mm, so a shallower flat bar (say, 15×80mm) could be used to make the machine lighter.

A 50kW linear prototype is to be designed and built within the next 18 months as part of the Carbon Trust Marine Accelerator Strand B programme.

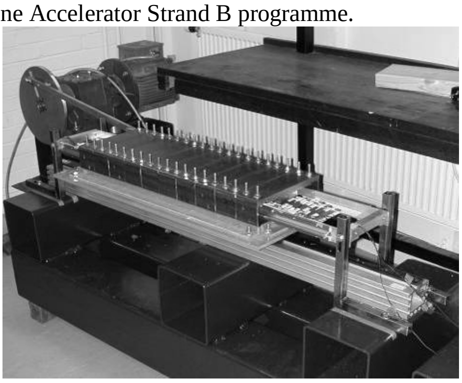

Figure 9. Small prototype machine on test rig, driven by slider-crank mechanism and small induction motor.

4. ROTARY TOPOLOGY

The rotary topology can be either radial-flux or axial-flux, and in either case the C-cores and coils will be made in the same way. A C-core, as shown in Figure 10(a), consists of 2 long sections of mild steel forming the upper and lower limbs of the C-core, and joined by a short section at one end. In order to manufacture a C-core the C-core sections in Figure 10(b) are machined and PMs mounted as shown in Figure 10(c). All sections are mounted onto a back plate to form the C-core rotor shown in Figure 10(d), which is the radial-flux topology. The stator winding consists of single coils, which are manufactured as shown in Figure 11(a), in which copper wire is wound on a former, and then potted in epoxy. The coils are then mounted inside a steel ring, Figure 11(b), which essentially forms a large jubilee clip to keep the coils in position. The completed stator winding is shown in Figure 11(c). It should be noted that there is no steel or iron in the stator construction. Figure 12 shows the final assembly of the stator inside the C-core rotor, which was achieved using an engine hoist and one person. If there were iron within the stator winding such a straightforward assembly would not have been possible.

Figure 10. (a) C-core with magnets mounted (b) Un-machined sections of the C-core (c) C-core sections with PMs mounted (d) Complete C-core rotor.

Figure 11. (a) Manufacture of single coils (b) Single coils mounted inside steel ring (c) Completed stator winding.

Figure 12. Final assembly of the stator winding into the C-core rotor.

Figure 13 shows the 20kW, 100rpm rotary prototype on a test rig used to drive the machine at various rotational speeds. A variable resistive load was used to investigate the variation of efficiency with rotational speed, with the results shown in Figure 14. The efficiency varies between 90 and 95%, peaking at part load, which is a typical characteristic of PM generators.

The machine was run at rated load for 4½ hours during which the average winding temperature was estimated from resistance readings taken at regular intervals. Figure 15 shows that the winding temperature levels out at about 82°C above ambient (20°C on the day of the test). Such a temperature rise is typical and not unexpected.

Figure 16 shows scaling calculations for a C-GEN (with a number of different active axial lengths) for direct-drive wind turbines [20]. These indicative results suggest that C-GEN could be 50% of the mass of conventional PM machines.

Figure 13. 20kW, 100rpm prototype on the test rig.

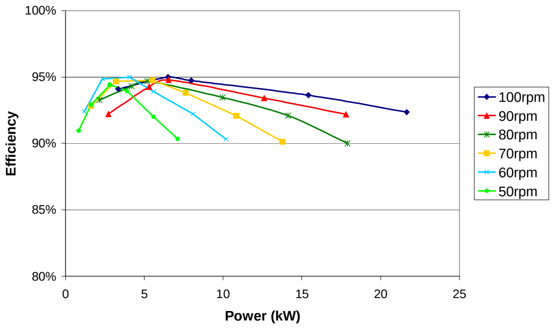

Figure 14. Efficiency results of the 20kW prototype.

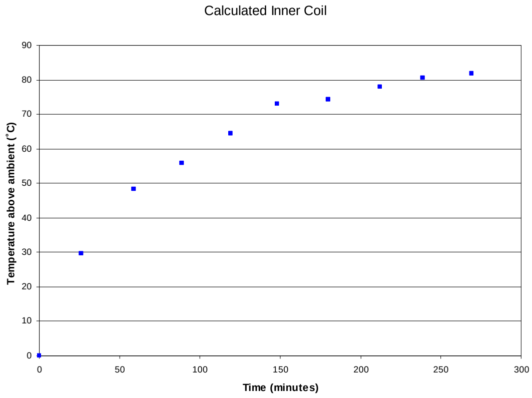

Figure 15. Heat run for the 20kW prototype.

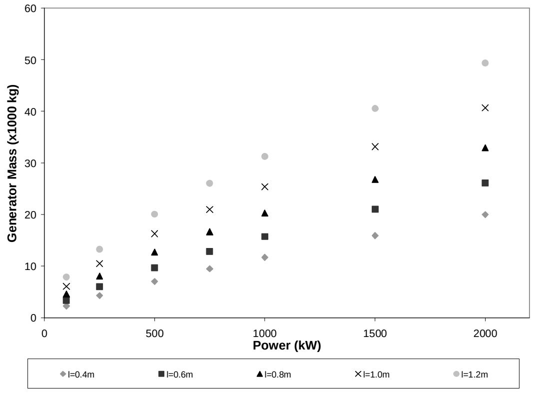

Figure 16. Scaling for direct drive wind turbines (points at torques of 12, 49, 138, 255, 391, 720 and 1100 kNm).

5. CONCLUSION

In this paper the authors have described the evolution of a double sided PM rotor machine with air-cored stator winding – the C-GEN. Both the linear and rotary topologies have been introduced, and in particular the method of assembly as described illustrates one of the attributes of this topology: ease of manufacture and assembly compared to conventional iron-cored PM machines. Efficiency results of a 20kW rotary machine show that the topology is capable of achieving equivalent performance to conventional machines. A 50kW(pk) linear prototype is currently being designed and built, and the outcomes of this work will be presented at future ocean energy conferences.

6. ACKNOWLEDGEMENTS

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