A Novel Lightweight Permanent Magnet Generator for Direct Drive Power Take Off in Marine Renewable Energy Converters

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Abstract

The evolution of a novel permanent magnet (PM) generator topology is described in the paper. It has the significant potential to be lighter than conventional PM machine topologies, making it attractive for direct drive applications in wind, wave and tidal current generators. The philosophy of the generator concept is based upon reducing the structural mass by eliminating large unwanted magnetic attraction forces that exist in all conventional iron-cored electrical machines. A comparison with an existing commercially available rotary PM generator for a 100kW turbine is presented to show the potential of the new topology

Keywords: Permanent magnet generators, direct drive, wave energy, tidal current energy

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1 Introduction

In a direct drive system, the mechanical interface required to convert the reciprocating motion in a wave device to high speed rotary motion, such as hydraulics, is eliminated. The mechanical interface introduces another loss component reducing the overall efficiency and more moving parts leads to potential reliability issues. Direct drive power take off is foreseen to be more reliable and efficient, particularly at part load. The potential of direct drive in marine energy applications has been demonstrated by various researchers at model scale [1, 2 &3]. A MW-scale device incorporating direct drive has been designed and built [2] and recently Uppsala published results of sea trials of a heaving buoy coupled to a seabed mounted linear generator [4]. 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 [5].

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, and there is increasing interest as turbine rating increases. In [6] 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 have been developed by the authors. Results published in [7] indicate that the structural mass can be in excess of 60% of the total mass. Clearly if this structural mass can be reduced, cost savings can be made.

The shear size and mass of direct drive generators is due to the use of conventional electrical machine topologies, namely one iron surface with magnets attached moving relative to a stationary iron surface in which copper is inserted in slots. This paper will expand on the issues associated with using conventional machine topologies, and outline a novel machine topology, which has the potential to overcome some of these issues.

2 Linear Generator Topologies for Direct Drive

Linear generator topologies used within the Archimedes Wave Swing (AWS) and that used within the Uppsala device are of conventional structure. Figure 1 shows the generic structure for such machines. Magnets are mounted on an iron section, which moves relative to a stationary section made from iron laminations in which copper wire is inserted into slots punched into the iron laminations. Figure 1 shows a double sided linear machine. The stator is sandwiched between two PM translators, but it is also possible to have one translator sandwiched between two external stators.

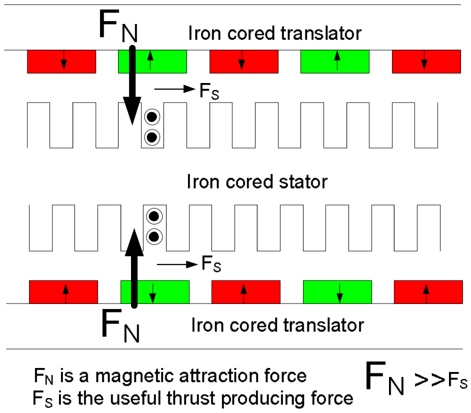

Figure 1: Electromagnetic forces in an electrical machine.

Uppsala proposed an octagonal linear machine, which is simply 8 single sided linear machines positioned on an octagonal closed surface [8].

There are 2 main electromagnetic forces in an electrical machine:

- The torque or thrust producing force, F_S, acting at a tangent to the rotor surface
- The normal force, F_N, between 2 iron surfaces

These forces are given by equations 1 & 2 :

$$\sigma_S = BK \quad N/m^2 \qquad 1$$

$$\sigma_N = \frac{B^2}{2\mu_0} \quad N/m^2 \qquad 2$$

where B (T) represents the rms airgap flux density and K (A/m) is the rms electric loading.

Typical values of airgap flux density vary from 0.5 to 0.8T, and for air-cooled machines a typical electric loading would be of the order 50kA/m. Figure 2 shows how these two force densities vary with flux density, for this typical electric loading.

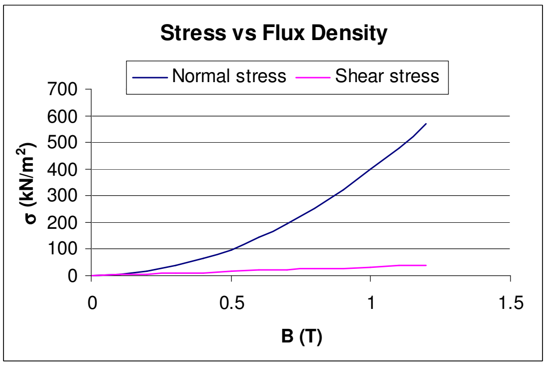

Figure 2: Variation in Normal and Shear Stress

The fact that the force density is limited to a certain value implies that the active surface area of the generator is proportional to the force, which has serious implications in terms of the machine's physical size and mass. If the airgap flux density were 1T, then the normal stress is in the region of 400kN/m^2 and the shear stress is only 31kN/m^2. For a 100kW direct drive machine running at 1m/s, the tangential force required would be 100kN, which would require an airgap surface area in the region of 3m^2. Hence the normal magnetic attraction force would be of the order of 1.2MN, which the machine structure and bearing system would have to overcome in order to maintain the physical clearance between the moving translator and the stator. Provided the airgaps on both sides of the stator are equal the net attraction force acting on the stator will be zero, but any difference between the two airgaps will result in a net force pulling the stator over in the direction of the net force, as demonstrated by Nilsson et al [9]. MW rated linear generators for direct drive will be long – the AWS is in the region of 8m. Owing to manufacturing tolerances it is unlikely that the airgap will be uniform along its length and hence the opposing magnetic attraction forces will not balance.

All iron cored machine topologies, that is those in which one iron surface moves with respect to another iron surface, will suffer from this large magnetic attraction force problem, which as can be seen from the simple example above becomes significant for low speed high force machines. This applies equally to rotary machines used in direct drive systems. Structural analysis of MW rated rotary machines for direct drive wind turbines in [7] shows that the structural mass required to overcome the normal stress can exceed 60% of the total mass.

Elimination of the normal stress will have significant benefits for the structural design of low speed high force/torque direct drive generators.

3 Air-cored Generators

The normal stress can be eliminated by removing one iron surface from the machine, usually the stationary part of the PM machine. The coils are then supported in a non-magnetic material. Figures 3(a) and (b) show the principal features of linear air-cored machines and details of rotary air-cored machines can be found in [10 & 11]

Figure 3(a) shows an air-cored linear tubular PM generator [13]. The translator consists of magnet and iron pieces sandwiched together to provide the alternating N-S poles in the airgap, and the stator simply consists of annular coils supported in a non-magnetic material. In this machine the normal stress as described by eqn 2 is zero, leading to a very simple mechanical machine. The airgap flux density is a peak at the translator surface, and then decays rapidly with radial position from the surface, because there are no iron paths on the stator to support the magnetic flux. Hence the shear stress is low, in the region of 10kN/m^2.

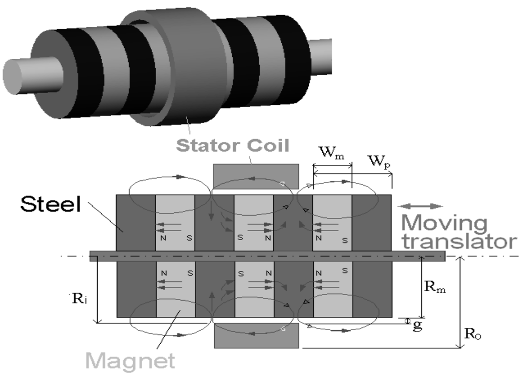

Figure 3(a) Air-cored PM tubular generator

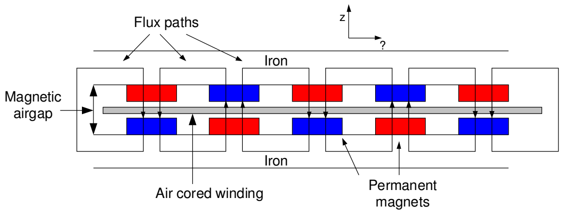

Figure 3(b) Double sided planar air-cored linear generator

The air-cored PM tubular machine represents quite a radical change from the conventional iron-cored machine. A more incremental modification is shown in Figure 3(b), in which the stator winding sandwiched between two iron cored PM translators is now supported in a non-magnetic material. Compared to Figure 1, magnets facing one another are now of opposite polarity. There is no magnetic attraction force between the stator and each translator, but there is an attraction force between the oppositely polarised PMs. Electromagnetically the doubled sided air-cored linear generator is better than the air-cored tubular machine because the flux sees a finite gap between the two translators, whereas flux in the tubular generator effectively sees an infinitely large airgap. Depending upon the design the double-sided air-cored linear generator will have a shear stress that lies between the conventional iron cored machine and the tubular machine. Although the attraction force acting on the stator has been eliminated, the normal force between facing magnets will still have a significant impact on the structural and bearing design.

4 Evolution of New Generator Topology

In order to take advantage of the air-cored topology with finite gap, whilst neutralizing the magnetic attraction forces between the PM translators a new machine topology is being developed at the University of Edinburgh [14].The position of the magnets, copper and iron are very similar to that shown in Figure 3(b), so that flux interacts with the stator winding in the same way. However, the structure of the PM translators have been modified in such a way that the normal forces between facing magnets have been neutralized.

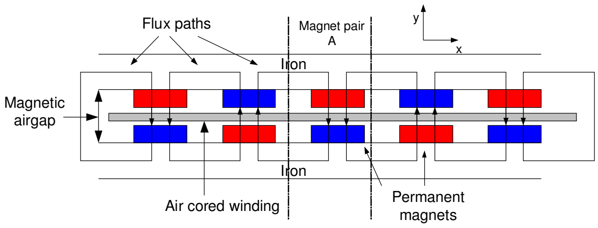

Figure 4(a): Double sided planar air-cored linear with magnet pair highlighted

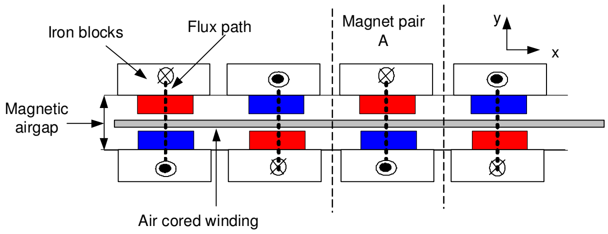

Figure 4(b): Double sided planar air-cored linear with modified structure

Figure 4(a) shows double sided air-cored linear generator with magnet pair A highlighted. As can be seen flux flows in the x-y plane of the machine. Figure 4(b) shows the modified structure. The PM translators are physically cut either side of a magnet pair – the lines defining magnet pair A for example. This leads to the structure shown in Figure 4(b), so that each magnet pair is physically independent. By making this cut the flux is no longer able to flow between magnets in the x-y plane, and hence an alternative flux path is required. For magnet pair A flux now flows into the paper in the top magnet and out of the paper in the bottom magnet crossing the winding as before and completing the path into the upper magnet. In neighbouring magnet pairs the flux flows in the opposite direction maintaining the NSNSNS etc. variation of magnetic poles as seen by the winding. The structure required to provide this alternative flux path is shown in figure 5, which is the end-view in the x-direction of a magnet pair – it is essentially a c-core.

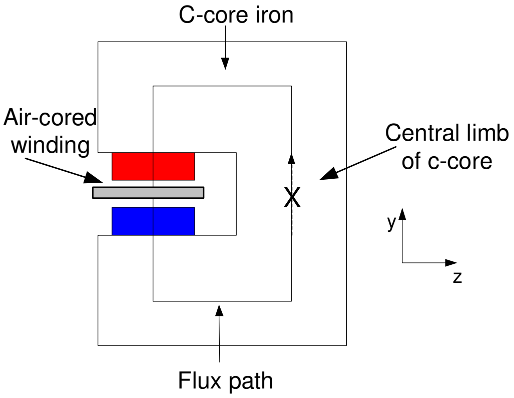

Figure 5: end view of a magnet pair

Each pair of magnets shown in figure 4(b) is replaced by such a c-core arrangement. Magnets are mounted on the inside of the c-core limbs, and an air-cored stator winding will sit in the space between the two c-core limbs. The flux from the permanent magnets flows as shown in Figure 5. The flux return path is now entirely in the y-z plane. There is an attraction force between the two limbs but the structure of the c-core itself can be used to compensate for that. The moment of the attraction force between the two magnets acts about point X in Figure 5. Each magnet exerts an equal but opposite attraction force and thus their effect is neutralized. Hence, the mechanical support structure of the c-core machine only needs to support the weight of active material in the c-cores, magnets and stator winding. Each c-core module is a self contained unit, which can be used in a linear or rotary machine. Figure 6 shows two possible arrangements for a rotary machine: on the left an axial flux machine and on the right a radial flux machine.

With the c-core arrangement assembly is expected to be easier compared to the double sided arrangement as the attraction forces between the two translator places does not have to be considered. De-magnetised magnets could be glued in place in the c-core and then magnetised in-situ, which will ease the problems of handling very large magnets expected in large machines.

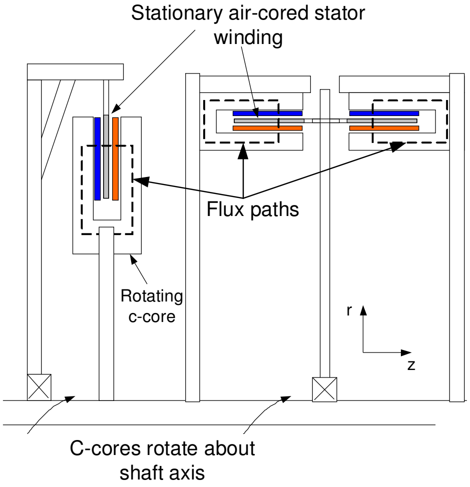

Figure 6: Rotary machine arrangements

5 Variation of the C-core Topology for Linear Machines.

Another way of thinking about the development of the c-core topology is that we have readdressed the relative positions of the active material in the machine, i.e. magnets, copper and iron. The c-core topology is fixed for rotary machines, but there are variations for linear machines, which can lead to significant benefits in terms of the mechanical design.

Figure 7 shows a number of different variations of magnet pairs in the c-core topology leading to the favoured linear topology in Figure 7(d). In each diagram the dark area represents iron and the lighter grey area are magnets. The air-cored winding is positioned in the spaces remaining,

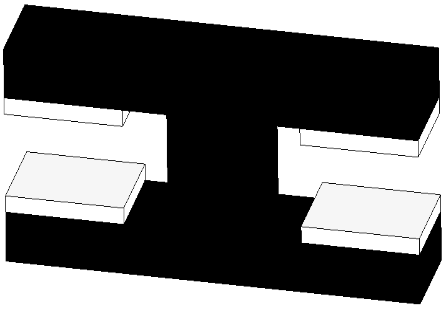

Figure 7(a): Back-to-back c-cores

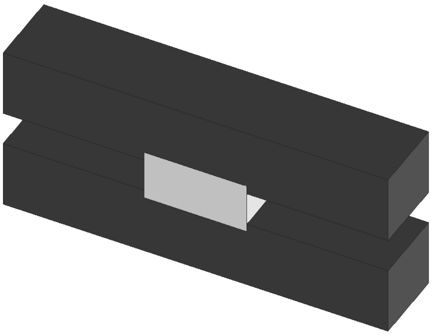

Figure 7(b): Magnet placed centrally

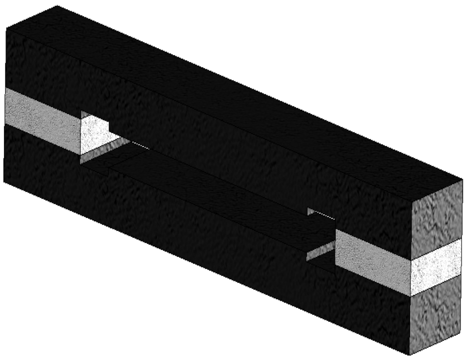

Figure 7(c): Magnets placed in the limbs

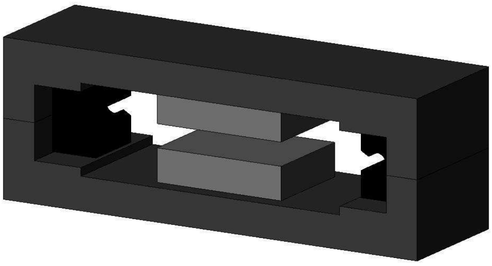

Figure 7(d) Front-to-front c-core arrangement which is either sandwiched between iron sections (7(b) & (c) or between magnets (7(a) & 7(c)). In Figures 7(a) & (b) support structures will be required for the stator windings, which is not the case in the other two topologies. Figure 7(d) is favoured over 7(c) because more of the magnet flux interacts with the winding. In both 7(c) and (d) magnet pairs provide a self supporting structure and allow a fully integrated design as shown in Figure 8. The external iron translator and magnets move relative to the stationary winding in the centre. The bearing is fully integrated into the machine structure. Figure 8(b) shows an isometric view of the machine.

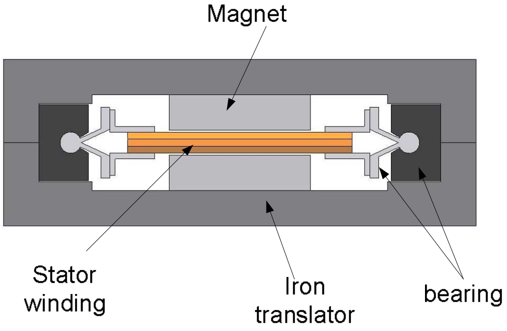

Figure 8(a): Cross section of machine showing integrated nature

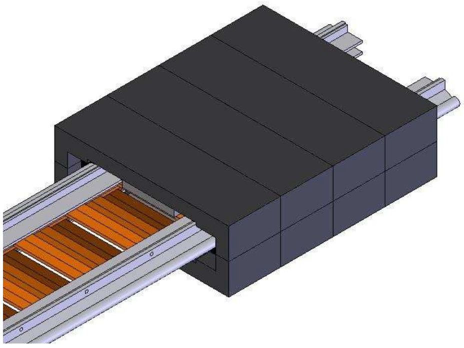

Figure 8(b): Isometric view of the machine.

It can be seen that the topology shown in Figure 8 requires no support structure on the translator to maintain the airgap. The stator is supported by the bearing arrangement and would be held fixed by some external support structure. The bearing load is minimal as there are no magnetic attraction forces on the stator through the use of an air-cored winding. The active material in the translator is now providing both an electromagnetic function and a structural function. By removing structural material, both weight and cost will therefore be reduced.

6 Direct Drive Examples

6.1 Rotary Machine.

A conventional 100kW PM generator has been developed for sale in the US [12] for use in direct drive wind turbines. As a comparison a rotary generator of the new topology was designed for the same operating conditions. The mass of the two topologies is compared in the Table 1.

Generator	Structure material	Mass (kg)
North Wind 100	unknown	6587
New topology	steel	4043
New topology	aluminium	3855

Table 1: Comparison of masses for 100kW rotary

6.2 Linear Machine

The mass of a prototype air-cored PM tubular machine designed and built as part of reference [13] has been calculated. A breakdown of the component masses is provided in Table 2 for both the tubular machine and air-cored machine. The tubular machine mass consists only of active material, where as the new topology machine mass includes the translator structural material, but not bearing material. It is interesting to note that the masses are similar. Both machines are air-cored machines, but the new topology is electromagnetically more effective, which is seen in the difference in the magnet and copper material. Permanent magnet material is the most expensive component, so that overall the new topology will have significantly lower material costs.

	Air-cored PM tubular	New topology
PM mass (kg)	22	7
Copper mass (kg)	18	8
Iron mass (kg)	23	60
Total mass (kg)	73	75
Material Cost (£)	666	247

Table 2: Comparison of air-cored PM tubular with new topology

7 Conclusion

A novel PM generator topology has been introduced in which the relative positions of the active materials: copper, magnets and iron, have been chosen to neutralise the magnetic attraction forces inherent in all iron cored machines. As a result the structural support only has to overcome the mass of the machine in the rotary case and the linear topology has a self-supporting structure. A comparison with a conventional PM rotary machine topologies shows that the new topology rotary machine mass is reduced by over 40% for a 100kW machine. In comparison to other air-cored PM machine topologies the PM material in the new topology will be minimised, which will have a positive impact on cost. Prototype machines are being built to demonstrate the technology, and results will be presented at the conference.

Acknowledgements

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