

# A lightweight low speed permanent magnet electrical generator for direct-drive wind turbines

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## Abstract:

The evolution, design and test results of a novel permanent magnet generator for use in direct-drive wind turbines are presented. The novelty in the concept lies in the arrangement of electromagnetically active components – magnets, steel and copper – such that the structural mass can be reduced. It has also been designed such that during the assembly of large diameter permanent magnet machines there are no magnetic forces to worry about.

**Keywords:** Direct-drive, permanent magnet generator

## 1 Introduction

As wind turbine unit rating increases there has been an increasing number of gearbox failures [1]. Hence there is more interest in direct-drive systems amongst manufacturers, but the mass of such generators is a significant issue. Work presented at EWEC 2007 by the authors showed that the structural mass of a direct-drive generator can be in excess of 80% of the total mass [2]. This structural mass is required to overcome the magnetic attraction force between the stationary and moving parts of the generator (Figure 1). This attraction force is a result of the normal component of Maxwell stress. It can be 10 times the torque producing shear stress (Figure 1 and 2). The airgap clearance between the rotor and stator must be maintained; otherwise the generator can be damaged.

A successful directly-driven generator will be able to produce a moderate to high shear stress while elegantly negating the effect of the magnetic attraction. In this paper the authors present a new topology which has the potential to meet that challenge, without having to resort to exotic structural or magnetic materials such as superconductors.

The innovative step in this new concept has been to take the active materials in the machine – copper, magnets and steel – and change their relative positions to minimise the effects of the normal force. The result is a machine in which the structure only has to support the mass of the active components, leading to a reduction in total mass in the region of 55% compared to conventional permanent magnet (PM) machines.

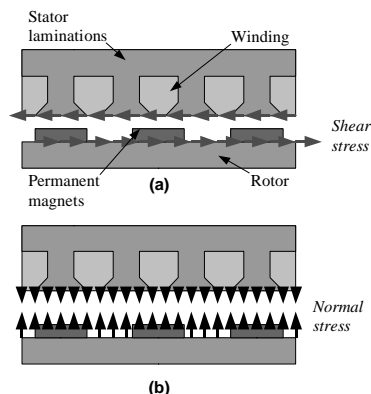


Figure 1: Section of a conventional permanent magnet generator showing (a) Shear stress and (b) Normal component of Maxwell stress

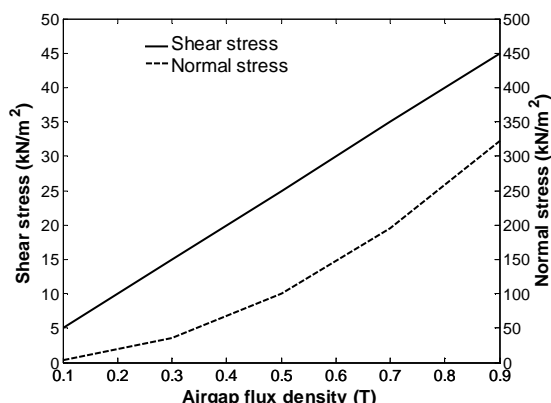


Figure 2: Shear and normal stress for airgap flux densities 0.1-0.9 T

The paper will show the benefits of the new concept compared to conventional machines by describing its evolution using the conventional surface mounted PM machines as a reference. Electrical and mechanical design tools developed have been used to demonstrate the potential for mass reduction.

In order to demonstrate the potential benefits of this new generator concept, design results will be presented to show a reduction in mass, whilst maintaining high efficiency at all loads. Experimental results of a 20kW, 100rpm prototype will be presented to verify the expected performance. In addition there will be a description of the build stage of the prototype to demonstrate the benefits for assembly.

## 2 A new air-cored machine

### 2.1 Introduction

The new 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 [3].

In two-sided axial-flux air-cored machines, the two rotors have an attraction for each other. Because the airgap flux density,  $B$  is lower than for an iron-cored machine, then the shear stress,  $\sigma$  is lower as shown by equation (1),

$$\sigma = BK, \quad (1)$$

where  $K$  is the electrical loading [4].

In order to produce the same torque,  $T$  the axial-flux machine outer radius,  $r_o$  must increase to accommodate the lower shear stress because

$$T = 2\pi\sigma \int_{r_i}^{r_o} R^2 dR = \frac{2}{3} \pi \bar{\sigma} r_o^3 (1 - k_r^3), \quad (2)$$

where  $k_r$  is the ratio of inner to outer radii. The increase in machine radius (when moving from iron-cored to air-cored designs) can cancel out the reductions in structural mass [2].

The company Evolving Generation has proposed an ironless radial-flux generator which has no airgap closing force [4]. This is due to using an ironless outer stator. The generator has a very large radius,  $R$  and this is held in place by a lightweight spoked structure. The ironless stator produces a large effective airgap, meaning that the flux density and shear stress are small. Such a large airgap radius is needed because of the low shear stress. Equation (3) is the radial-flux equivalent of equation (2), where  $l$  is the axial length,

$$T = 2\pi\sigma R^2 l. \quad (3)$$

In [2], 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.

### 2.2 Development of a 'C' core machine

A logical development of such axial-flux disc machines (as shown in Figure 3) is to increase the rotor shaft radius.

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 3(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 3(c)). A further step is to allow flux to cross the web of the 'C', and to make the rotor out of modules (Figure 4) each carrying a pair of magnets. By rotating the 'C' core modules by 90° a radial-flux machine can be produced (Figure 3(d)). By increasing the axial length, the radial-flux generator's torque rating can be increased without increasing the outer diameter.

This new topology is introduced in [5] and the patent is in [6].

#### 2.2.1 Finite airgap length

This topology has a number of advantages over existing ironless designs. A radial-flux ironless permanent magnet machine has a very large effective airgap. This 'C' core machine, however, has a finite airgap length and so higher flux densities and shear stress values are possible. A corollary of this is that less permanent magnet material is needed to produce the same flux density, so the design will be cheaper.

This machine also has the advantage that there are two main flux paths (longitudinal and transversal as shown in Figure 4) not just the one. Given that the amount of magnetically active steel is dependent on its non-saturation, this should be a lighter machine than the axial-flux two disc machine.

#### 2.2.2 Combination of active and inactive material

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 5(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 5(b)). This topology means that the steel in the 'C' core fulfills both active and inactive roles.

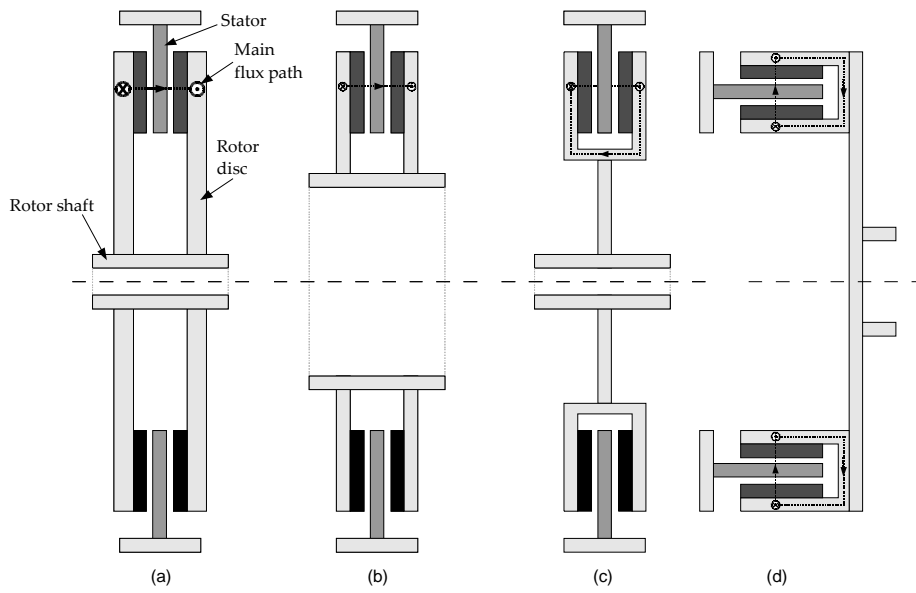


Figure 3: Cross section of double sided axial-flux machine (a) Baseline design (b) Increasing rotor shaft radius means that the thickness of the rotor discs can be reduced (c) 'C' core machine with extra flux path (d) Radial-flux 'C' core machine.

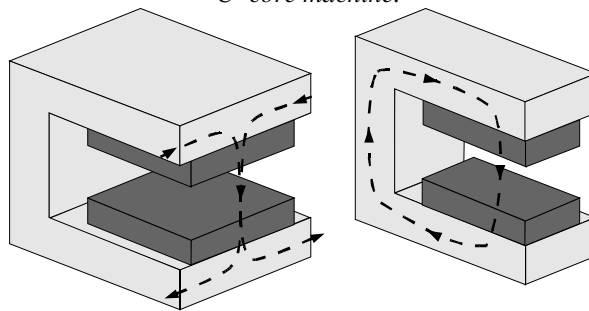


Figure 4: Steel 'C' core module with magnets (a) Longitudinal flux path (b) Transverse flux path

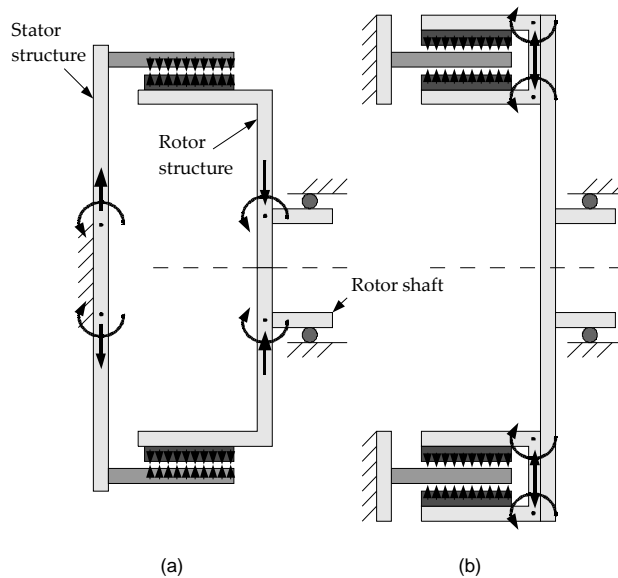


Figure 5: (a) Conventional permanent magnet radial-flux generator, showing normal forces and their impact on all of the stator and rotor structures (b) 'C' core machine, showing how normal component of Maxwell stress is isolated within the 'C' core and does not affect the rotor structure

### 3 Prototype build

A 20kW, 100rpm generator was designed at the University of Edinburgh and built by Fountain Design Ltd. [7]. This section describes the build process and highlights topology's manufacturing advantages.

The rotor of the prototype 'C' core machine was made up of 32 modules, each module carrying a pair of permanent magnets similarly orientated. In this small machine, the 'C' core module was assembled from three trapezoidal pieces of mild steel, with the magnets being slid onto the inner and outer pieces. For larger machines the magnets could be glued in place in an unmagnetised state and then magnetised in situ. This would ease the problems of handling very large magnets. The modularity allows large scale volumes to be produced cheaply and efficiently.

Once a module is assembled it is quite benign and safe to handle, as there is relatively little leakage flux outside the confines of the 'C' core. The modules can be brought together and fixed to a common rotor structure. In the case of the prototype machine this is an aluminium disc.



Figure 6: Lowering the 'C' core stator to meet the rotor is simpler and safer than for a conventional PM machine.

The bringing together of the rotor and the stator can be a difficult and dangerous task in a conventional permanent magnet machine because of the large magnetic attraction forces. This is liable to pull either the rotor or stator off centre (i.e. eccentrically) and produce an unbalanced magnetic pull, thereby closing the airgap clearance even further. One of the features of the 'C' core machine is that because there is no iron in the stator, there is no force of attraction between the rotor and stator. This makes the threading of the stator winding into the rotor very straightforward. Figure 6 shows how the stator of the new machine was lowered into place using an engine hoist.

The stator in the prototype is made up of 24 pseudo arc-shaped concentrated coils, clamped between two rings (Figure 6). The discrete nature of these coils means they can be replaced relatively easily. This will be of significant advantage in larger machines, as electrical faults are one of the more common causes of failure for direct-drive generators in wind turbines [8]. Again, it is worth noting that the modular nature of the stator lends itself to high production manufacturing.

### 4 Results

Figure 7 shows the 20kW prototype machine on the test rig machine at Edinburgh University. Figure 8 shows the perfectly sinusoidal no load voltage waveform of 26.7 Hz frequency at 100 rpm. Figure 9 gives the mechanical-to-electrical efficiency of the prototype generator over a range of speeds for a range of loads, typical for this size machine. These results show that the generator can match the performance of conventional PM synchronous machines.

### 5 Designs for larger machines

Conventional PM machines tend to have optimal aspect ratios (the ratio of axial length divided by airgap diameter) [9]. In terms of electromagnetically active material, less material is needed with a small aspect ratio and large airgap radius,  $R$ . This is because the active mass is approximately proportional to the airgap surface area ( $2\pi Rl$ ) whereas the torque, according to equation (3), is proportional to  $R^2l$ . Increasing the radius therefore increases the specific torque (with respect to the active mass).

There are though two main limits to how small the aspect ratio can be. There is a practical limit to how big the airgap diameter can be so that the generator can be transported [10] and fit into a nacelle. The other limit is the structural material: the structural mass of radial-flux machines is proportional to the square of the airgap radius (for a constant axial length and for a deflection fixed in relation to the airgap clearance) [2].

The 'C' core machine follows the same scaling laws for the active mass, but has a different law for the structural material. In the 'C' core modules, the limbs deflect into the airgap as modelled by a cantilevered beam of length,  $l$  and a second moment of area,  $I$  with a uniformly distributed load,  $w$  (a product of the normal component of Maxwell stress and the breadth of the limb),

$$y \propto \frac{wl^4}{I}, \quad (4)$$

where  $y$  is the deflection [11]. For a fixed axial length and a trapezoidal cross section, the mass of structural material (needed to limit  $y$  to a fixed proportion of the airgap clearance),  $m_{str}$  is related to the airgap radius thus,

$$m_{str} \propto R^{0.64}. \quad (5)$$

This means that the specific torque with respect to structural mass also rises with increased airgap radius [12]. Figure 10 shows the generator mass based on the 'C' core generator concept design for 100kW to 2MW wind

turbines. The electromagnetic design used the same basic pole pitch layout as the 20kW machine, with the number of poles and coils varied proportionately to the airgap radius. The airgap clearance above and below the coil was taken as 0.1% of the airgap diameter. The magnetic flux was modelled using a simple lumped parameter magnetic circuit approach and the iron was not allowed to saturate. For the structural modelling, the maximum deflection of the 'C' core limbs was restricted to 10% of the airgap clearance.

Figure 10 shows the results for five different axial active lengths. As would be expected, the designs with an active length of 0.4m are lightest, as both the active and structural mass is reduced. At larger ratings these axially short machines may cease to be practical because of their large

airgap diameters. Even using the axially longest there is great promise, as these designs are not yet optimised for minimum mass.

Table 1 gives a mass comparison of a 100kW, 72rpm direct-drive 'C' core generator with a commercially available permanent magnet generator.

	NorthWind 100	'C' core design
Machine mass (kg)	6587	2790

Table 1: Comparison of 'C' core generator mass and published figures for the Northwind 100 machine (100kW, 72rpm) [13]

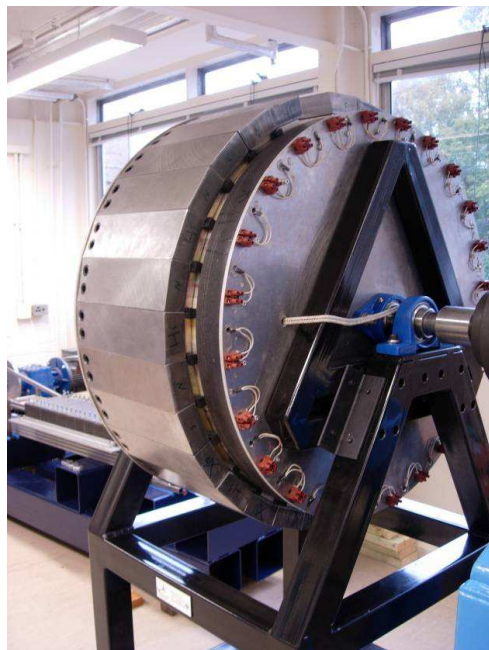


Figure 7: The 20kW, 100 rpm prototype generator on a test rig at the University of Edinburgh

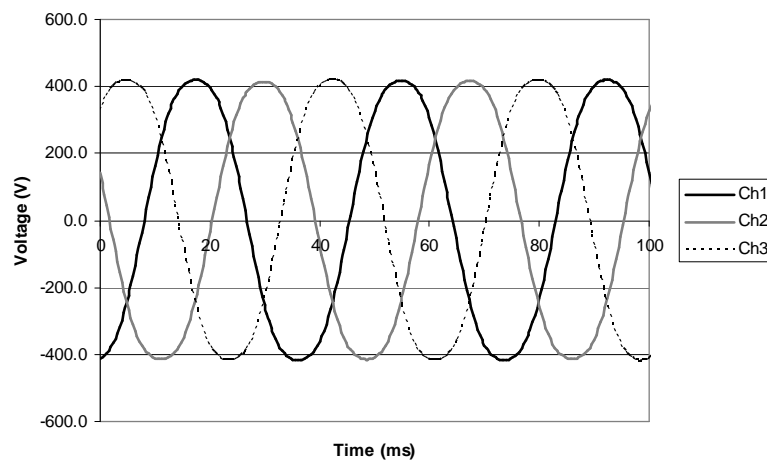


Figure 8: No load voltage at 100 rpm

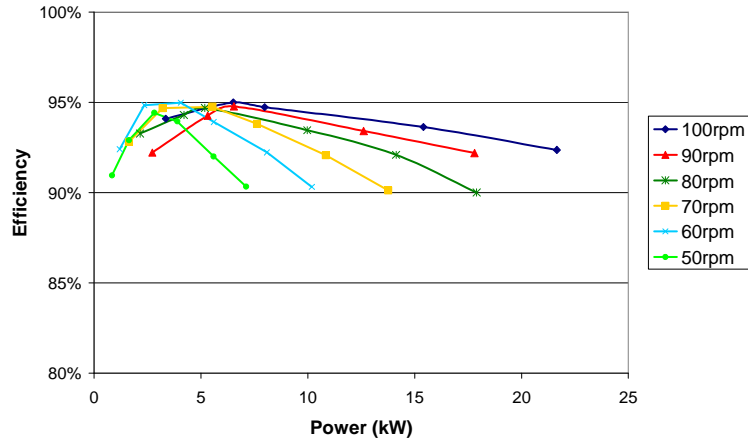


Figure 9: Efficiency results for prototype generator at 50, 60, 70, 80, 90 and 100rpm at part and full loads

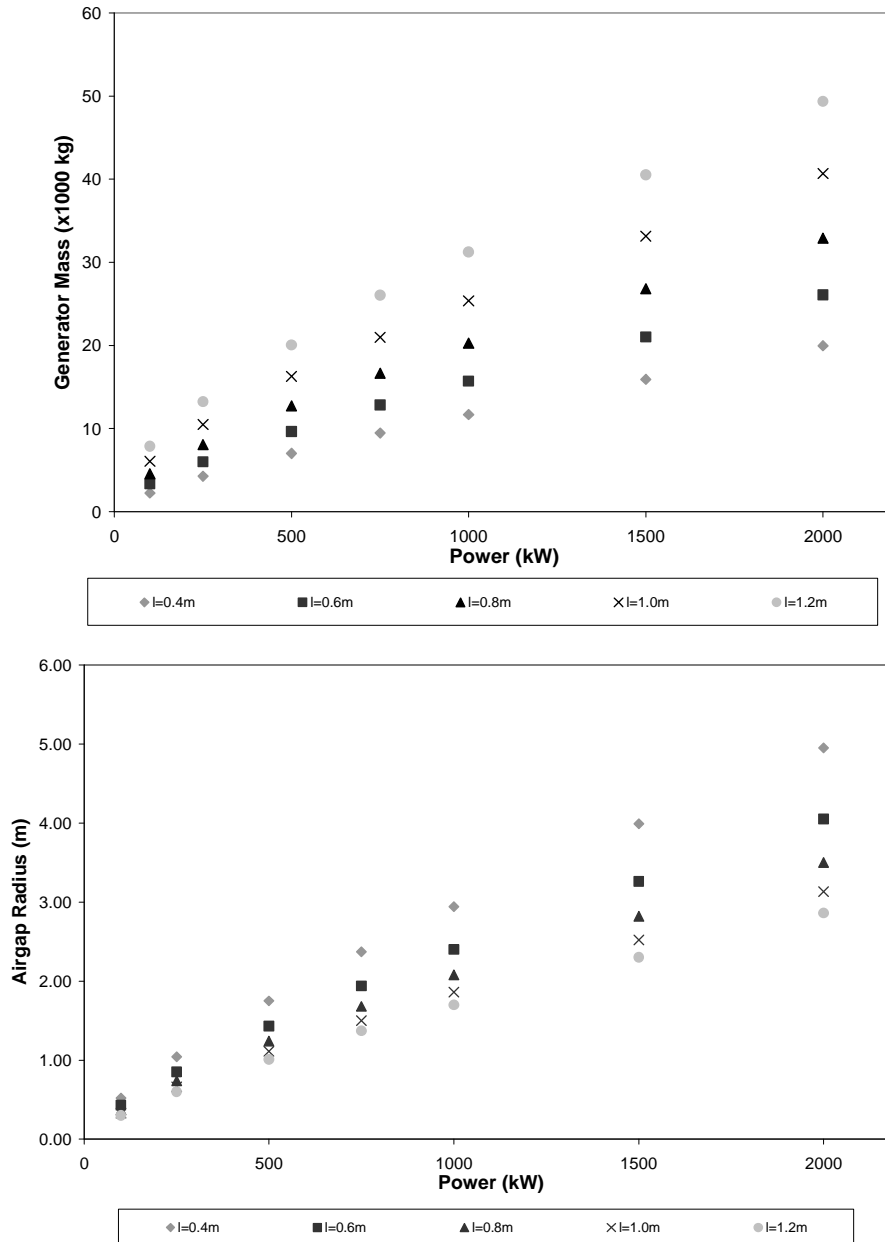


Figure 10: Generator mass and airgap radius based on the 'C' core concept for a range of wind turbine power ratings (and 5 fixed axial lengths)

## 6 Conclusions

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 counter the magnetic attraction forces inherent in all iron-cored machines. As a result the structural support only has to bear the mass of the machine. A comparison with a conventional PM rotary machine topology shows that the new topology rotary machine mass is reduced by over 55% 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. A modular construction is employed in both the rotor and the

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stator, so that large scale production is possible. A major benefit of this topology is that assembly is made simple and straightforward because the attractive force between rotor and stator has been removed.

## Acknowledgements

The authors would like to thank Scottish Enterprise for providing funds and the University of Edinburgh for providing facilities for this project. The authors would also like to thank M. and M. Galbraith of Fountain Design Ltd. for their work on building the prototype generator.

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