

A Comparison of Radial and Axial Flux Structures in Electrical Machines

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Abstract— This paper explores the comparative advantages and disadvantages of the simplest form of axial flux geometry, the single sided version, compared to the most common form of radial flux geometry with an inside rotor, when considering permanent magnet synchronous machines. A detailed literature review of comparisons is presented. New material is presented highlighting the benefits of single sided axial flux geometry. The constraints and assumptions made when comparing possibilities are discussed in detail, including a study of the biases these can introduce. The basis of this comparison is founded on constant electromagnetic airgap shear stress, being the product of electric loading and magnetic loading, and indeed the constancy of both of those factors. The metric used for comparison is simply that of the masses of the active materials, steel, copper, and magnet material. Examples are presented, including a machine which recently went into production in quantity. A range of lesser issues which are relevant when one is making a choice, are presented and discussed.

I. INTRODUCTION

Axial flux geometry is not new. Faraday's first machine in 1831 was an axial flux machine. Tesla patented a disk motor in 1889. This geometry has always appealed to innovative thinkers in electric machines, but has been dogged by some extra difficulties in arranging the mechanical structure. This was primarily in accurately maintaining a necessarily small airgap in a relatively large disk shaped machine. Thus, while many people have researched axial flux induction machines, they have not in general proved economic to manufacture, because of the substantial benefit of a very small air gap in an induction machine.

The advent of rare earth permanent magnets has however made machines designed with rather larger air gaps perfectly feasible. It is likely that this single fact has brought the axial flux machine back into purview.

The current reality is still however, that while much research is carried on in universities regarding axial flux machines, (a recent machines and drives conference had 262 papers with "machine" in the title, 14 of these had "axial flux" or "axial gap" in the title), they have not yet entered into the marketplace at anything like this frequency of occurrence, appearing only in situations where the aspect ratio is a dominant consideration, such as in in-wheel vehicle drives.

The difficulty of making comparisons is bound up in the issue of attempting to compare apples with apples. And so various constraints are imposed by researchers to try and force equality in comparison. The end result is often that the constraints themselves favor one geometry over the other, leading to inconclusive results.

II. PREVIOUS RESEARCH

In the first paper we study [1], Zhang, Profumo and Tenconi laid out a comparison of standard inside rotor radial flux geometry and 3 kinds of axial flux geometry, which they denoted, AFPM-11, (Axial Flux Permanent Magnet 1 stator, 1 rotor), AFPM-12, one stator, two rotors, and AFPM-21, two stators, one rotor. They did not separately study the 2 kinds of one stator two rotor machines, which are also known as TORUS machines. These two types are discussed in detail in [2]. In the first of these two, magnet poles of the same polarity face each other across the stator and the machines are known as TORUS NN types. In the other, opposite polarities face each other. These are known as TORUS NS types. The AFPM-21 studied in Zhang et al is a TORUS NN type. We will see later that using slotted or non slotted stators can add more possibilities to the range of axial flux machines, and the TORUS NS type can be built with no stator iron.

The work reported in [1] was based on the well know sizing equations, using electromagnetic shear stress, and they derived specific torque, or torque/unit mass. They demonstrated an advantage which increased with pole count. Their geometric study appears to not include the volume associated with providing the electric loading, which we will discuss later.

Their summary compared 2 radial flux designs with three axial flux designs, all with 8 poles, and deduced that compared to the best radial flux design, the AFPM-11 was better by a factor of 1.8, the AFPM-12, by a factor of 2.1, and the AFPM-21 by a factor of 2.4.

In [3] Huang, Luo, Leonardi and Lipo reworked the sizing equations with more much more detail, comparing the AFPM-12 with a TORUS NN machine. No direct comparison of radial and axial flux structures was covered. However they did observe that a PM axial flux machine has a significantly lower volume than a standard squirrel cage induction machine.

In [4] Simsir and Ertran looked only at the TORUS NN machine comparing it with a traditional radial flux machine, for a single application. They concluded that the axial flux brushless dc motor has a much higher specific torque than the radial flux brushless DC motor, and again that this advantage increases with pole count.

In [5] Huang, Aydin and Lipo studied not so much the sizing of the machines, but rather the noise and torque ripple characteristics for marine propulsion.

In [6] Sitapiti and Krishnan studied radial geometry and 4 different axial flux geometries. These were a slotted single sided, an unslotted single sided, (both AFPM-11), two stators and one rotor (the AFPM-21), and a variant on the TORUS NS machine in which the single stator had no iron, using just an airgap winding. They carried out detailed designs at 5 different power levels of all 5 geometries, attempting to produce similar performance and efficiency. They concluded that the axial flux machines always have a smaller volume than the radial flux machines for the same torque rating, but also pointed out that slotless designs needed more copper and more magnet material, which would impinge on overall cost.

In [7], Cavagnino, Lazzari, Profumo and Tenconi studied, primarily from a thermal standpoint, the standard radial flux machine and only the 2 stator one rotor machine (AFPM-21). This paper goes into a very high level of detail but ultimately considered designs that ensured that the wasting surface was adequate for the losses generated. They carried out designs for a range of aspect ratios, or D/L ratios, and showed very high specific torque in buildable machines for axial flux machines at large D/L ratio. In general an axial flux machine with a small D/L is not viable.

In [8], Rahman conducted a three way comparison between radial flux, axial flux and transverse flux motors for an “in wheel” motor application for an electric vehicle. The comparison is based on a patented “twin pole” winding scheme. The comparison is done based on a physical size constraint, and 9 pole pairs. The radial flux and transverse flux motors used the configuration of the rotor outside the stator, while the axial flux is a single sided configuration. The motors were also designed with 5 phases. The reason stated for this to reduce cogging torque. The results were that the radial flux motor had a slightly better performance than the axial flux motor. The transverse flux motor had the best performance, but it was designed with 20 pole pairs instead of nine. At nine pole pairs, the transverse flux model would not converge, so 20 pole pairs was used instead. The comparison was done based on one pole count, and a fixed package size. Rahman does state that the axial flux motor would exceed the performance of the radial flux motor if the D/L ratio was greater than 5. With the dimensions used for the comparison, the D/L ratio was 3.5. Rahman also reports that the cogging torque was lower for the axial flux design.

In [9] Parviainen, Niemela, Pyrhonen, and Mantere reported a detailed study comparing traditional radial flux geometry to the two slotted stator one rotor axial flux machine, (AFPM-21). Mechanical constraints were discussed and included in the analysis. Their final comparison was on cost of the active materials only. Their conclusions were that at 8 poles the 2 designs were very similar cost, and that at greater than 8 poles the axial flux geometry was lower cost than the radial flux.

In [10] Akatsu and Wakui began by presenting a design method. Their results reported that a 50 kW radial flux machine had a volume of 2 liters, while the axial flux machine with the same rating had a volume of 1.3 liters.

The general message of all the above is fairly clear, that researchers have demonstrated that at a high pole count, and if the aspect ratio is free or constrained to large D/L ratios, any of the axial flux geometries should be seriously considered.

III. SINGLE SIDED VS DOUBLE SIDED AXIAL FLUX MACHINES

Only a minority of the studies discussed above considered the single sided, or one stator one rotor, (AFPM-11) axial flux machine. Those that did, tended to compare single and double sided versions at the same radius. However if one has a torque specification and the dimensions of the two competing machines are essentially free, then the single sided machine has a significantly higher utilization of active material.

The development below starts with a single sided machine, and then doubles the amount of material. This is done firstly by staying at the same stator outer radius, and making a double sided machine, (AFPM-21). A second approach is then to reallocate the second lot of active material to make a larger single sided machine. The derivation shows a 41% increase in torque/power for the enlarged single sided machine over the double sided machine. A similar derivation can be applied to the TORUS type machines. This will be left to the reader.

Starting with a single sided axial flux machine as a baseline, The torque, τ (Nm) in terms of the airgap area A (m^2), the electromagnetic air gap shear stress σ (Pa), and the average radius of the airgap annulus R_{av} , (m) is

$$\tau = \sigma A R_{av} \quad (1)$$

We introduce the ratio of inner to outer radius $\alpha_{ax\ r}$ (the subscript denoting “axial” and “radius”), so that we can write equations in terms of the outer radius R_o .

In [3], Huang et al. showed that the optimum value of $\alpha_{ax\ r}$ is dependent on many factors such as electrical loading, flux density, frequency, material and machine topology and therefore cannot be simply expressed as a single number. They also state that the optimum ratio of $\alpha_{ax\ r}$ is in a relatively narrow band. Many derivations in the literature have supported this observation. To clarify this analysis, the ratio of $\alpha_{ax\ r} = 0.6$ will be used. Interested researchers can readily proceed through the analysis with their own values if they wish.

Using this value we can write the air gap area as

$$A = \pi(R_o^2 - (0.6 R_o)^2) = 0.64\pi R_o^2 \quad (2)$$

And the average radius can be given as

$$R_{av} = 0.8R_o \quad (3)$$

The torque in (1) can now be written as

$$\tau = \sigma(0.64\pi R_o^2)(0.8R_o) = 0.512\sigma\pi R_o^3 \quad (4)$$

If the overall axial length of the machine is L, the volume is

$$V = \pi R_o^2 L \quad (5)$$

And the torque density (torque/unit volume) is then

$$\frac{\tau}{V} = \frac{0.512\sigma R_o^2}{L} \quad (6)$$

Now if we double this motor by putting another stator on the other side of the rotor, thus 2 airgaps, requiring double the magnet thickness, the air gap area will double and the axial length will not quite double, since we do not need the rotor iron. However since we are discussing machines with high pole counts, where the rotor iron thickness tends to 0 as the pole count rises, we will keep the analysis simple by assuming the axial length doubles. This machine has twice the airgap area of the single sided machine, thus we can see that the torque doubles, and also the volume doubles, so that the torque density remains the same. This result is observed in the literature discussed above.

Rather than doubling the air gap area by adding a second stator, the single stator machine can be made with a larger radius that doubles the air gap area. The new outer radius R_o' is got from simple geometry, equating areas, and is clearly

$$R_o' = \sqrt{2} R_o \quad (7)$$

A very good estimate of the torque of the larger radius single sided machine is

$$\tau' = \sigma 2A R_o' = 2\sqrt{2} \tau \quad (8)$$

Since the electric loading (the slots and copper) are the same, and the magnet thickness is the same, the volume approximately doubles. More yoke and rotor back iron would be needed at the same pole count, however a good designer would increase the pole count for the larger diameter to better handle end turn loss, so a good estimate of the volume increase is that it doubles.

The torque density of the larger radius motor is therefore

$$\frac{\tau'}{V'} = \sqrt{2} \frac{\tau}{V} \quad (9)$$

Thus while doubling the active material by taking a single sided machine and doubling it at the same radius to produce a double sided machine results in the same torque density,

reallocating the extra material to a larger single sided machine results in an increase in torque density by a factor of $\sqrt{2}$

Therefore a single sided machine has a torque density, or a torque per unit mass of active material that is $\sim 41\%$ larger than that for a double sided machine.

IV. ROTOR VOLUMETRIC ADVANTAGE

There is a very definite volumetric advantage to axial flux machines at reasonably high pole counts. The inside volume of a traditional radial flux rotor, or indeed the stator on an outside rotor radial flux machine, is not used electromagnetically. Ingenious solutions for “slinky” style wound stators for outside rotor machines, and spiders to support a rotor structure, will not save volume, but will save active material, and hence both active and passive mass.

Figure 1 shows a single sided axial flux starter alternator attached to an 11 hp (8 kW) single cylinder i.c. engine. All of the 8kW mechanical power from the i.c. engine is converted to electrical form, at $\sim 94\%$ efficiency by the alternator. The relative volumes of the two machines are salient.

A. Derivation of Volumetric Advantage

We will derive here an estimate of the volume “wasted”, i.e. not used for electromagnetic purposes, in both an axial flux and a radial flux machine rotor. We make a few numeric assumptions for clarity, however the analysis can be redone with different numbers than those assumed here. We begin by assuming machines typically have a flux density in the rare earth magnet of 0.8 T and in the steel of 1.6 T. Under these assumptions then the amount of rotor back iron necessary is



Fig. 1: 11 hp (8kW) i.c. engine with 8kW single sided axial flux starter alternator attached

equal to $\frac{1}{4}$ of the magnet pole arc width. In an axial flux machine this is computed at the average radius, and results in the thickness of necessary rotor back iron. If the α_{axr} is 0.6, then clearly 36% of the circular blank is not used for electromagnetic purposes. This is independent of the pole count. In a radial flux machine the fraction of unused material is strongly dependent on both the pole count and the rotor radius.

For consistency we define an α_{radr} being the ratio of the rotor radius of a radial flux machine to the outer radius of the stator, for which we will continue to use R_o . Thus the rotor radius can be written as $\alpha_{radr} R_o$. If there are p poles, then the maximum width of a magnet pole is $2\pi\alpha_{radr}R_o/p$. If the radial length of the magnet piece is l_m , then the inner radius of the used back iron

$$R_{inner} = \alpha_{radr} R_o - l_m - \frac{2\pi\alpha_{radr}R_o}{4p}, \quad (10)$$

And the wasted volume, for a stack length of l_s , is

$$V_{waste} = \pi R_{inner}^2 l_s. \quad (11)$$

Since the rotor outer radius is $\alpha_{radr} R_o - l_m$, the fraction wasted, $\alpha_{radwaste}$ can be derived as

$$\alpha_{radwaste} = \left(1 - \frac{\pi\alpha_{radr} R_o}{2p(\alpha_{radr} R_o - l_m)}\right)^2 \quad (12)$$

This is plotted below using some typical values such as $l_m = 3\text{mm}$, firstly at a rotor radius of 50 mm, as a function of p , and then at a value of $p=10$ for a range of rotor radii.

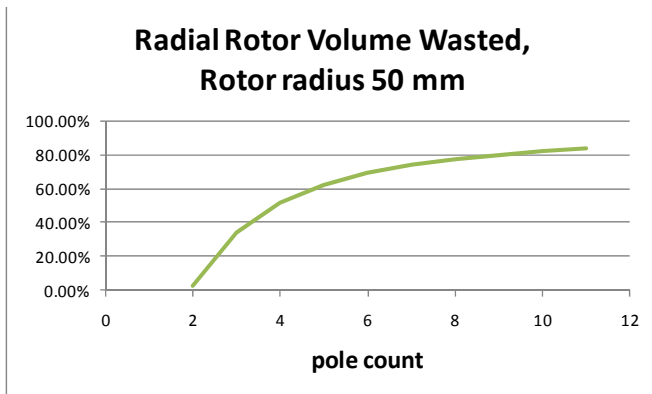


Fig. 2. Percentage of volume wasted in a 50 mm radius radial flux rotor as a function of pole count

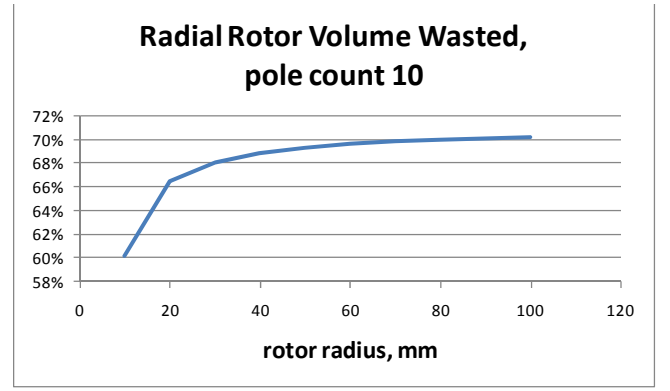


Fig. 3. Percentage of volume wasted in a 10 pole radial flux rotor as a function of radius.

These values should be compared with the 36% for the typical axial flux machine.

V. TORQUE PRODUCTION

The torque produced by a single sided axial flux machine using the introduced notation is, as derived above, with the variable α_{axr} restored, as

$$\tau = \sigma \pi R_o^3 (1 + \alpha_{axr} - \alpha_{axr}^2 - \alpha_{axr}^3) \quad (13)$$

For the radial flux machine, introducing α_{radasp} to denote the aspect ratio, or diameter to length (D/L) ratio,

$$\tau = 4\sigma \pi R_o^3 \left(\frac{\alpha_{radr}^3}{\alpha_{radasp}} \right) \quad (14)$$

For a given torque and electromagnetic air gap shear stress, each of these can be solved for an R_o . Then the actual air gap areas can be computed. Plotted below in Fig. 4 are the designs for a torque of 100 Nm at a shear stress of 20 kPa. For the axial flux machine, the parameter α_{axr} has a significant effect, so we have plotted over a range of possible values. It should be obvious that at a fixed α_{radasp} , there will be only one value of radial rotor radius, independent of α_{radr} . The lower airgap area of the axial flux machine is clear, although for large values of α_{radasp} the radial machine tends toward the axial machine.

The lower area required by the single sided axial flux machine compared with all but the most disc like radial machines is significant. It is also worth noting that this is on top of the volumetric saving. Thus a radial flux machine with an α_{radasp} of 3 will actually have a stator diameter of about 10 - 15 % more than the axial flux machine, and also a longer axial length.

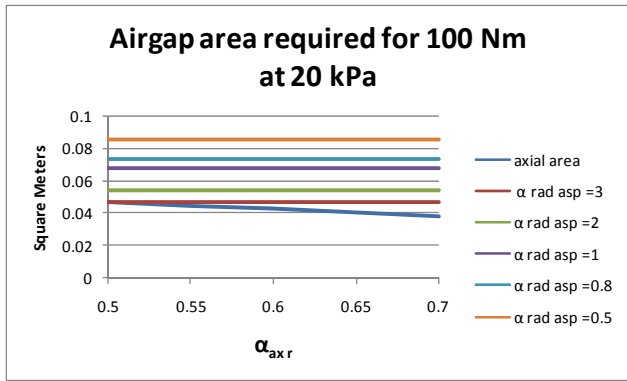


Fig. 4. Airgap area required for a single sided axial flux machine producing 100Nm using an airgap shear stress of 20 kPa, as a function of the ratio of inner to outer radius. Above this are shown the areas required for a range of radial flux machines for the same performance, parametrized by their aspect ratio.

This result directly influences the relative amounts of copper and magnet material in the two machines, as discussed below.

VI. DETAIL OF CONSTANT MAGNETIC LOADING

One might initially expect that the cost of magnetic loading in axial and radial structures would be the same per unit area. There are some variations however, firstly since at this stage of axial flux machine development it is common to use larger airgaps, as discussed earlier. This would then imply a higher cost for a given magnetic loading in the axial flux structure. The reality is that the differences are much smaller than one might imagine, and sometimes non existent. It turns out that the surface PMs for a radial flux machine, having curved surfaces, are invariably ground to shape from a pre-sintered block of material, and the cost of such magnets includes the wasted material. Thus premiums on cost of the order of 30% are usual. Then to aid retention, there are a range of examples in the market place where recourse has been had to some form of glass fiber or Kevlar “bandage” This retention mechanism then adds to the effective airgap from a magnetic point of view, so that the radial flux machine has a larger effective airgap than an axial flux machine. A common solution to both the cost of the curved magnet piece and the problem of magnet retention in a radial flux machine is to “shallowly embed” the magnets in pockets in the rotor, allowing use of flat magnet pieces. However the embedding of a magnet provides flux shorting paths, and the effective flux of the magnet is reduced by a factor of up to 20%. Further, attempting to reduce the “flux shorting” must be balanced against a reduced burst strength capability under over speed conditions. On top of this the manufacturing process for rotor assembly are particularly challenging.

So while the costs are close, we have not been able to derive a workable analytic relationship, and each case should be considered independently.

VII. DETAIL OF CONSTANT ELECTRIC LOADING

The physical amount of copper involved in the slot is clearly the same for a given current density, fill factor, and electric loading. Differences then appear in the end winding wastage. Most new machines are however using non overlapped windings, so the effect is smaller than it was historically. We will therefore assume that there is no significant difference in the copper cost per unit area for a given electric loading.

We then compute the amount of iron necessary in typical designs to

- a) Provide the teeth to enclose and support the copper, and
- b) Provide the yoke.

We compute this as an area/unit length of the circumference of airgap in a radial machine, and of the circumference at the average radius in an axial flux machine. Clearly this then represents volume per unit length of the stack in a radial flux machine, and per unit length of the stator thickness in a single sided axial flux machine.

The requisite length will in general not be the same in two comparable machines, as shown in V above, however we are simply determining the cost per unit length around the machine on the understanding that this gives the area of steel per unit length, or by including a depth as discussed above, the cost of the steel per unit area for a given electric loading.

As stated above we assume a constant current density in the copper, and a constant slot fill factor.

We make a simplifying assumption that with rare earth magnets, the tooth width is the same as the slot width at the airgap. This results from a design for 0.8T in the airgap and a maximum of 1.6 T in the tooth. Interested researchers can readily follow this analysis with a different ratio.

We fix the slot length from the airgap to the slot bottom in the axial machine as $l_{ax s}$. We assume a constant yoke “thickness” l_y from the bottom of the slot to the outer radius (radial) or the back of the stator (axial).

We compute the amount of steel necessary to hold the same copper area/ unit length in both cases. The copper area in the axial machine per unit length is simply $\frac{1}{2} l_{ax s}$. The slot length $l_{rad s}$ will be less in the radial machine for the same area since the slot fans out. If the air gap radius in the radial machine is R_i , we can compute the copper area/unit length as,

$$\frac{\frac{1}{2}\pi((R_i+l_{rad s})^2 - (R_i)^2)}{2\pi R_i} \quad (15)$$

Equating the two areas produces a quadratic in $l_{ax s}$, which for a given values of R_i and $l_{ax s}$ can be solved. Taking only the positive root, This gives

$$l_{rad s} = \left(-1 + \sqrt{-1 + \frac{2 l_{ax s}}{R_i}} \right) R_i \quad (16)$$

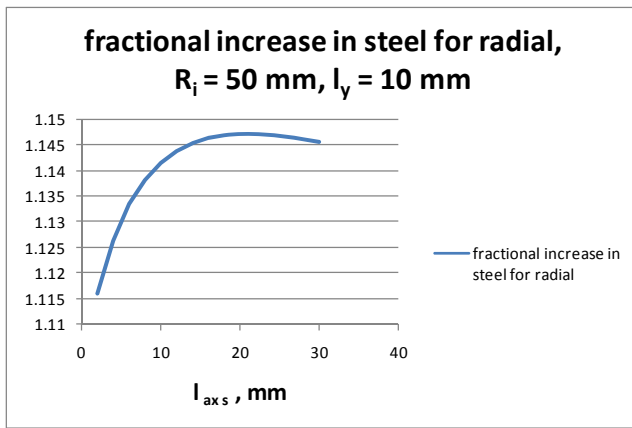


Fig 4. The fractional increase in steel, in a radial flux machine compared with an axial flux machine, in order to provide the same electric loading. This graph fixes l_y as 10 mm, and R_i as 50 mm, and allows the slot length in the axial machine, $l_{ax,s}$, to vary

Given this, the area of the annulus needed for the radial machine per unit length, ignoring the scrap cut out for slots can be readily computed, simply adding l_y . The axial case is similarly simple. For comparative purposes, Fig. 5 above shows, for an R_i (radial) of 50 mm, and a range of axial slot lengths from 2mm to 30 mm, the fractional increase in steel required for constant electric loading in a radial flux machine.

VIII. SUMMARY OF COMPARISONS

Simple geometric manipulations have shown that the single sided axial flux machine has a considerable volumetric advantage over the traditional radial flux machine, and if the rotor of the radial flux machine is filled with electrical steel, a substantial consequent mass and cost advantage.

On top of this, the single sided axial flux machine can have a larger “effective torque arm” than the inside rotor radial flux machine at similar outer radii, which leads to a requirement for a lower airgap area to produce a given torque at a given magnetic and electric loading. This has a significant impact on the active material cost. Finally the cost of the same electric loading is shown to be noticeably higher in the radial flux machine.

IX. “SHOW STOPPERS” & “URBAN MYTHS”

The observation made in the introduction about the relative uptake of the single sided axial flux machine in academia and industry is revealing. There are a range of issues some of which are either reputed to rule out the axial flux structure, and some of which are claimed to be significant advantages. Various of these have more basis in scientific fact than others. A sampling is introduced below.

A. Axial Attractive Force

This is high, and a surprise to most people when they first encounter it, leading to concerns. However standard deep groove ball bearings do have quite a high axial load rating, and

careful design and testing has shown that standard ball bearings, correctly used, are entirely adequate in a well designed machine. In fact it is usual practice to add axial loads to radial flux machines to reduce bearing noise using wave washers. Fasco has recently taken out a patent to reverse the usual wave washer thrust on one of the bearings to subtract from the magnetic force.

B. Stator construction

Prototypes and small production quantities are invariably produced by the expensive process of milling or spark eroding slots in a tape wound toroid. However mechanically controlled “Punch and Wind” machines abound in the patent literature, and a lesser number of successful machines have been in operation for many years. Fasco Australia has developed a numerically controlled machine with a single punch and die that produces stators at a high rate, at low cost. Advantages are that the slot shape can be changed very easily, and the only steel wasted is that cut out for the slots. Such a stator production method should be seriously compared to the very expensive progressive die machines used for large scale radial flux lamination production.

C. Stator coils

Coils on single teeth are in fact planar in an axial flux machine. Thus they are very easy to wind, and the use of rectangular section copper for high performance machines for example, is much simpler.

D. Airgap Maintenance

It is true that PMs have allowed more leeway in this area, and most designers have taken advantage of that. However the efforts of practicing engineers in the process of continuous improvement is a remarkable thing, and we are finding ways to gradually refine our airgap tolerances

E. Magnet Retention

This is a substantial positive for the axial flux machine, where a simple lip on the rotor can manage magnet retention with no practical speed limitation.

F. Heat Paths

In many applications it is relatively easy to allow the single rotor in free air to enjoy very poor heat paths from the source of heat in the stator, protecting heat sensitive rare earth permanent magnets, and allowing a lower heat specification for the magnet material. Further the flat back of the stator can usually be arranged to have excellent heat paths to whatever surface it is mounted to.

X. AN EXAMPLE

Fasco Australia has recently gone into production of a single sided axial flux, non overlapped winding PM machine with integrated electronics for the swimming pool pump market in Australia. Fig. 4 below shows the 900 W machine as produced, fitted to the wet end, along side the single phase induction machine version it replaces. Fig. 5 shows a cutaway of the assembled axial flux motor. The rotor with magnet segments can be seen, the stator is cut away, but extends from the rotor to the left end shield carrying the bearing, a very small fraction of the volume of the already smaller case. The integrated electronics occupies approximately the same volume as the machine.



Fig. 4. Pump assemblies, with the original single phase induction machine version on left, PM axial flux version on right

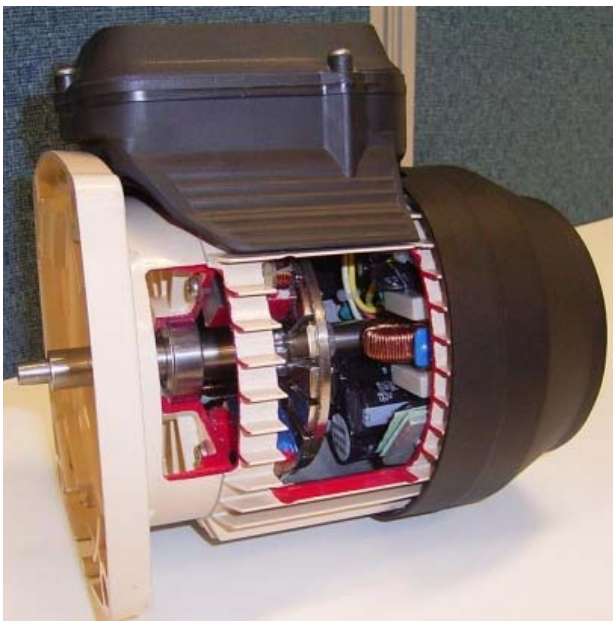


Fig. 5. A cutaway version of the motor on the right in Fig. 4 above.

XI. ACKNOWLEDGMENT

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