The "Goodness" of Small Contemporary Permanent Magnet Electric Machines

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Abstract- The interest in adopting electric actuation in Navy ships, and in particular in submarines, usually founders on the issue of the mass and volume of electric actuators, which are perceived to be significantly worse than those of competing technologies. Certainly looking at the volume, mass, power and torque of a typical 3 phase induction machine, even in comparison with a typical automobile engine produces some rather disheartening numbers. This paper will discuss some fundamental principles as originally presented by Laithwaite, as well as some commonly held beliefs, or rules of thumb. The paper will then present some numbers for existing machines, representing standard, generally available technologies today. The paper will then examine some specific designs of special purpose permanent magnet (PM) machines, which produce numbers which appear to confound both the theory and the practice described. Conclusions will be deduced that the small induction machine will eventually lose its place as the drive of choice in small applications, and be relegated to "niche" applications. It will further be concluded that this displacement can be justified on cost alone, with dramatic efficiency increases being simply fortuitous additional benefits.

I. INTRODUCTION

A. The Issues

1. Volume and Mass

The US Navy has expressed considerable interest in electric actuators for submarines, and is actively seeking research into this important area [1].

Electric actuators are a proven technology and offer a number of benefits, including reliability, energy efficiency, and precise controllability. However, they are generally seen to have significantly lower performance than competing technologies in the areas of power density (kW/m³) and specific power (kW/kg). For instance, a typical high efficiency 50 hp induction motor delivers only $\sim 0.2~\text{kW/kg}$, and $\sim\!800~\text{kW/m}^3$, whereas a figure of 0.8 kW/kg is used for internal combustion engines in automobiles, and they achieve close to 2,000 kW/m³.

There have been recent substantial advances in electric motor technology, particularly resulting from advances in power electronics and permanent magnet materials. When these advances are combined with the very high volumetric efficiencies of axial flux geometry, electric machines can be made dramatically better. In 1994 Kaman Electric Corporation published details of a permanent magnet (PM)

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actively cooled double sided axial flux machine, 520 kW peak, delivering ~3.5 kW/kg and ~5,800 kW/m³ [2].

Common understanding among machine designers is that when scaling down to smaller sizes, eg 20 W to 5 kW, most performance parameters would however degrade significantly [3], [4].

2. Peak to Continuous Capability

Another significant issue for most actuators is the amount of time they are actually working as a fraction of the time they are waiting. Lorenz makes the point that for automation systems in general, most actuators are required to carry out their operation as rapidly as possible, and then be idle while other systems, or processes operate [5]. Similarly those who are attempting to design traction systems for vehicles with electric drive, in particular looking forward to the day when the fuel cell is an important part of the automotive industry, will have realized that the most difficult thing about replacing an internal combustion engine with an electric drive is not that of matching what is actually a rather intractable torque speed characteristic, but rather being able to provide the peak to average power rating of 10 or 15 to 1. A typical sedan having a peak power rating of 150 kW, will cruise in urban areas at 60 kph using only 3.5 kW, and will cruise at 110 kph on flat ground using about 16 kW.

It turns out for reasons given below that most modern PM machines are intrinsically capable of very high short term peak loadings, and thus with good design can provide the actuation systems that customers require. While for an induction machine the pullout torque will rarely be greater than 3 times the rated torque, numbers will be presented below for Nd Fe B PM machines with ratios of > 6:1. Further, it is not difficult to design for even greater ratios.

B. The Analytical Framework

In a very famous paper, Laithwaite proposed a measure for the "goodness" of an electrical machine, and by beginning from some very fundamentally determined principles produced a "goodness factor" G for a machine [3]. This factor was significantly determined by physical dimensions, with the conclusion that the larger the machine was, the more opportunity a design engineer had to make it "good". His discussion was concerned with balancing the production of a field by means of electric current, to react against other currents flowing in "armature" circuits. His examples were of induction machines. Thus he began with a definition being the inverse of the product of the resistance of the electric circuit and the reluctance of the magnetic circuit, normalized

by the inclusion of the frequency term, to make G dimensionless. Thus he wrote initially that

$$G = \frac{\omega}{\text{resistance} \times \text{reluctance}} = \frac{\omega \mu \sigma A_m A_e}{\ell_m \ell_e}$$
 (1)

where A is cross-sectional area, l is length, and the subscripts m and e refer to the electrical and the magnetic circuits. Working through a simple induction machine example, he quite simply converted the formulae to

$$G \propto \frac{\omega \mu_0 p^2}{\rho_r g} \tag{2}$$

where p is the pole pitch arc length, ρ_r is the surface resistivity of the sheet rotor in his example, and g is the airgap. This formulation very clearly shows the dependency on the pole pitch, and the airgap.

Very perceptively he observed that nobody would build a small machine, say 1 kW, with a very high pole count, say 100, whereas high pole counts in very large machines were not unusual. High pole counts are often choices in high performance machines primarily driven by end turn loss reduction. He went on to point out that there was a fundamentally limiting relationship between pole fringing, which impacts if the pole count is raised too high, and the physical air gap. It is certainly true that for induction machines the management of an air gap is crucial, and it is also a truth of manufacturing that the production of air gaps measured in micrometers is generally considered to be unmanageable.

Eight years after the first paper, Laithwaite published a second paper called "Magnetic or Electromagnetic - The Great Divide" where he explored machines which might not be bound by his goodness factor [6]. The paper is sketchy, and has not been widely cited. Implicit however in this paper is the notion that permanent magnet machines are not excluded from the goodness factor above, and that only such machines as hysteresis machines might be.

C. The "Accepted Wisdom"

Miller writes that initial sizing of any machine is usually done by considering "Electromagnetic Shear Stress", as defined in Fig 1.

Miller quotes numbers for typical machines as being between 700 and 2000 N/m² for fractional horsepower induction machines ranging up to between 70,000 and 100,000 N/m² for very large liquid cooled machines such as

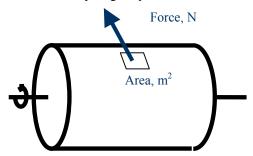


Fig 1 Electromagnetic Shear Stress Definition.

turbine generators. [4].

This is a very accurate and perceptive measure of "the way the world is", and it is common among engineers to assume that the Laithwaite principle and the Miller observation reinforce each other, leading us to believe that that there is very little we can do about it, and that some very fundamental truths are involved.

D. Supporting Evidence

A recent examination of a range of induction motors from a single manufacturer produced the graphs of Figs 2 and 3, of the specific power and power density of three phase 4 pole induction motors, as a function of rated power, from 10 kW to 400 kW. Clearly the bigger motors get better numbers.

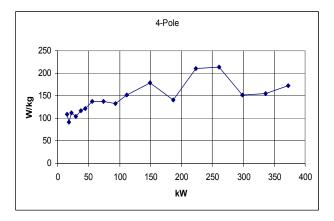


Fig 2. Specific power of a range of 3 phase induction motors

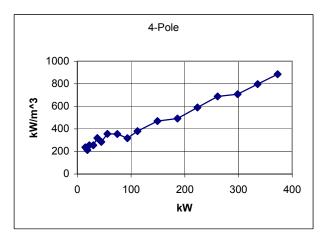


Fig 3. Power density of a range of 3 phase induction motors

II. THE NEW PARADIGMS

A. The Technology

1. Motor Size

The Laithwaite position holds pretty well for induction motors, since the issue of the air gap is so significant. Further, below 1 kW motors tend to be single phase in most

applications, driven by the availability of power, and split phase machines tend to be much more difficult to design to be efficient than three phase machines. However with some permanent magnet machines, these arguments are no longer relevant.

Much of what we see in mass produced motors, or indeed after some study just about all we see, is a reflection of a century of motor design driven by fabrication cost, particularly in the low power region, where the running costs have always been assumed to be negligible. There is a new concern amongst consumers about the need for efficiency, and the immediate result is that the area of small motors is one with a remarkably large range of opportunities for substantial and genuine improvement. Recent figures show that motors account for ~ 64% of the electricity use in the USA, and that $\sim 10\%$ of this is used in motors below 750 W, where the efficiency varies from poor to atrocious [7]. Another 10% is used in machines from 750 W to 15 kW, where efficiencies are still generally poor. In both of these ranges contemporary technology to dramatically improve the situation is readily available.

2. Peak versus Average Ratings

In this case the new NdFeB materials give us an extraordinary opportunity. Small motors built with NdFeB on the rotor surface have very large effective air gaps since the relative permeability of the material is effectively unity, and the likelihood of demagnetization is very small. It is relatively easy to compute the level of current at which permanent demagnetization occurs, and for most small designs this is very high indeed. It is not difficult to increase this further by design if required, but in general the numbers are so large that the issue of current rating of the controller dominates.

III. SOME CONTEMPORARY RESULTS

A. Axial Flux Technology

It is well known that there is a substantial improvement in volumetric efficiency when comparing axial flux to radial flux, particularly at high pole counts, the situation where the best performing motors may well be designed. That is because in the radial flux machine there is a wasted volume inside the rotor.

The examples given below are for single sided axial flux machines. Whilst there is much debate about the best format for axial flux machines, the single sided version has the best combined heat paths. The path for the armature is like that for the single rotor dual stator machine, but it combines very good thermal isolation for the rotor, as for the twin rotor single stator version. [8], [9], [10].

The motor shown in Fig 4 was built in 1993, as a traction system for solar powered vehicles [11]. The laminated stator has a diameter of 260 mm, and the windings extend outside this diameter as can be seen. The complete motor is 50 mm thick. At no stage was the design specifically optimized for minimum volume, or maximum torque, but concentrated on

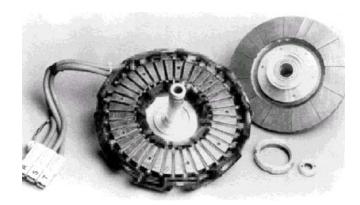


Fig 4. 260 mm od. axial flux machine

maximizing efficiency. Very high efficiency however enables a reduction of volume and mass since the need for thermal mass and thermal paths is reduced. The machine has been used in a marine environment as a generator in an 18 month trial of a 2 kW tidal power generator [12].

A version is being currently developed for an electric vehicle where the top speed is 3000 rpm, and the peak torque is 200 Nm. The controller is not designed to deliver this torque at the maximum speed, but if it were, that represents 62.8 kW. This is not the peak torque the motor can deliver without demagnetizing. The existing motor can deliver up to 360 Nm for periods of $\sim 30 \text{ seconds}$ without damage, and it is not difficult to redesign to raise the peak torque significantly.

The motor in Figure 5 has an outer diameter (again excluding the windings) of 195 mm and a total thickness of 33 mm, and is designed to deliver a peak torque of 86 Nm for 2 minutes. The design criteria were efficiency, torque provision in a volume, and reduced production costs (use of round wire coils).

The motor in Figure 6 is the smallest considered here, with a stator diameter of 100 mm, a total outside diameter of 135 mm and a total thickness of 33 mm. This motor has been designed to operate continuously at 3000 rpm, 3.2 Nm, 1 kW output, at over 91% efficiency. No attempt has been made to analyze its peak torque capability but it would be in the area of at least 30 Nm for short periods. This machine was designed optimizing efficiency, power density, and for low



Fig 4. Stator of 195 mm od. axial flux machine

manufacturing cost (this prototype is wound with bundled round wire).



Fig 6 100 mm od. axial flux machine

IV. BROAD COMPARISONS

The graphs below , Figs 10, 11, 12, show the results of comparing a wound field brushed dc motor of 2.3 kW, (Fig 6); a standard 3 phase 2.3 kW induction machine; a 260 kW peak internal combustion engine, (Fig 7); the Kaman axial flux machine discussed above in section I.A.1; the three axial flux machines illustrated directly above in Figs 4, 5, and 6; and a 44 MW commercial ship drive (Fig 8).



Fig 7. 2.3 kW Shunt excited brushed dc motor, extensively used as traction system in small battery powered utility vehicles



Fig 8. "Corvette" 260 kW internal combustion engine

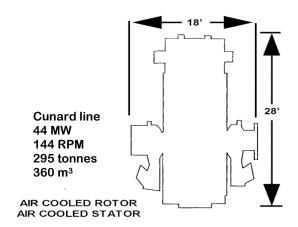


Fig 9. Direct drive traction machine for a cruise liner.

Dimensions are in feet.

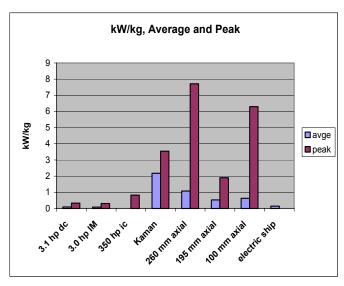


Fig 10. Specific Power of a range of large and small prime movers

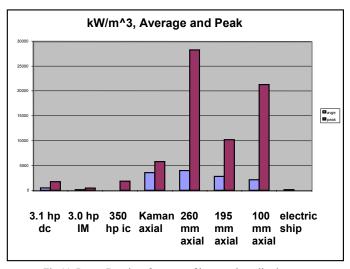


Fig 11. Power Density of a range of large and small prime movers

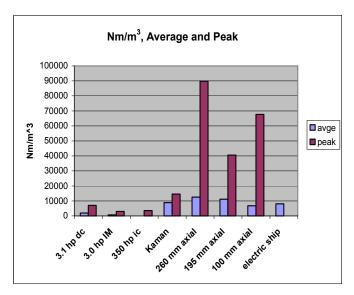


Fig 12. Torque Density of a range of large and small prime movers

The graph of figure 12 is included since torque density is in fact the most consistent metric of electrical machine performance. It indicates the issue for the designers of the ship drive. With a very low rotational speed the power density and specific power don't compare favorably, but the torque density, the prime design driver in such a machine demonstrates the competence of the design engineers.

These graphs reveal 2 important things for this paper. In the first instance it is not difficult to dramatically improve existing specific power and torque, and power and torque density, using modern PM designs. Secondly, and more importantly, it is difficult to see any dependence of these metrics on power rating for the PM machines. It is tempting to say that as far as this very limited data set is concerned, there is no demonstrated output power dependence of these metrics, at least in this range of 1 kW to > 320 kW.

V. SMALL MOTOR PRODUCTION ECONOMICS

A. Background

No matter what evidence is presented about the importance of efficiency in a global sense, and the fact that the small electric machine is a prime culprit in energy waste [13], there will be those who say that ultimately manufacturing cost will dominate all decisions, and that the small induction machine will never be displaced.

The cost of PM material is usually quoted as a barrier to PM machine adoption, however there have been some extraordinary developments in recent times. We are all familiar with the "Moore's law" of computing, that costs have been reducing by a factor of close to 1.6 per annum for some 40 years. A similar factor can be observed for Nd Fe B material reducing by a factor of 1.6 per annum for the last decade. Further the initial patents all expired in 2002, the raw

materials are plentiful, and there is a high level of competition between manufacturers, particularly in China. A recent quote of \$US13/kg for N30 material is in line with these reductions.

Motor manufacturers will tell you that if the production volume is large enough, then the manufacturing costs asymptotically approach the total materials cost. If we consider a motor at 1800 rpm, 500 watts, then a typical single phase machine weighs 14 kg. This is made up of electrical steel, structural steel, cast iron, copper and aluminum. At \$1/kg for the iron and steel and \$3/kg for the copper, an estimate of ultimate minimum cost can readily be made.

B. Hypothesis

1. Assumptions

It is understood that adding power electronics to a motor drive system currently has a significant impact on the total drive cost. However there are clear observable downward trends in the cost of power electronics, and in the area of small machines, where the silicon "real estate" is limited, greater reductions can be observed. Thus it is assumed that inside some foreseeable future time scale, the cost of the power electronics in a small drive will reduce to very low values. This will be aided simply by the production scale, since for small machines, the production volume is very much larger than for large machines.

It is further assumed that the observed reduction in the cost of Nd Fe B material will continue.

2. Statement

It is hypothesized that in the relatively short term future, the production cost of a small drive (eg <500W), following the argument put forward in section V.A, directly above, will approach asymptotically the cost of the bill of materials for the machine.

3. Corollary

The corollary to the above hypothesis, if it is accepted, is that The cost per kW of a small drive will be proportional to the reciprocal of the specific power, as shown in Figure 10.

For example, the PM machine of figure 5 can comfortably deliver 500 W at 1800 rpm, (at an efficiency of $\sim 90\%$). It is comprised of ~ 0.9 kg of electrical steel for the stator, 0.67 kg of copper, 0.11 kg of magnet material, and 0.33 kg of mild steel for the rotor. These give an active mass of 2.0 kg. Applying the rule of \$1/kg for steel. \$3/kg for copper and \$13/kg for magnet material, the total cost of active material is \$4.70. Compare this with the observed mass of 15 kg of the comparable single phase induction machine discussed in V.A above, and the scale of the relative costs is clear.

The real importance of this corollary is however that having observed that for induction machines, following Laithwaite and Miller, that the specific power decreases as the output power reduces, and for the PM machines this is not so, then the smaller the machine, the greater the cost advantage a PM machine will have.

VI. FURTHER WORK

Further work will collate data on typical induction machines in the low power range 100 W to 1 kW, where it is concluded that the uptake of the PM machine will be the strongest, simply on the basis of cost. It is true that most of these machines are currently split phase machines, carrying an increased weight penalty, so that once a power electronic drive is to be included, a 3 phase induction system will always be a better choice than the split phase one. However the important point is that once the split phase machine is dispensed with, and designers are free to choose a new system, and manufacturers need to consider new tooling, the PM machine advantage will be very clear.

VII. CONCLUSIONS

It is concluded that contemporary observations reinforce the long held view that the specific power and torque and the power and torque density of induction machines all degrade as the rated power reduces.

It is also concluded, admittedly from a much smaller observation base, that PM machines do not exhibit the rated power dependence of these parameters.

It is hypothesized that the cost of a small machines in very large quantities will asymptotically approach the cost of the materials in the motor, both with scale of production and with time.

It is then concluded that on the basis of cost alone the small PM machine will displace the induction machine as the default choice, relegating the induction machine to niche applications where for example a very large constant-power speed range is required.

It is additionally concluded that since the specific power of PM machines does not scale, and that the specific power of induction machines does, that the PM machines will capture the application base from the smallest machines upwards.

It is then fortuitous that the replacement of small induction motors, whose efficiency is particular poor, and also a function of size, will automatically provide much higher efficiencies, which are important in our global energy management strategies.

VIII. ACKNOWLEDGMENTS

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