The College of Engineering
University of Wisconsin-Madison

Wisconsin Electric Machines and Power Electronics Consortium

RESEARCH REPORT
90-18

A Low Loss Permanent Magnet Brushless DC Motor Utilizing Tape Wound Amorphous Iron

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A LOW LOSS PERMANENT MAGNET BRUSHLESS DC MOTOR UTILIZING TAPE WOUND AMORPHOUS IRON

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Abstract - An axial field permanent magnet brushless DC motor which utilizes tape wound amorphous iron is proposed. Simplified waveforms and performance equations for this type of machine are presented. The machine equations and waveforms are verified with a proof-of-concept machine. No load iron losses are compared with manufacturers data and full load iron losses are also presented. Output torque for rectangular and trapezoidal current waveforms are measured and compared and explanations for the differences are proposed. Machine designs from a computer program which demonstrate the possible benefits for this type of machine are presented. It is suggested that this type of machine could be considerably more efficient than induction machines and, additionally, cost competitive when a variable speed drive is already a system requirement.

INTRODUCTION

With the increasing cost of energy, techniques to improve electrical machine efficiency continue to be explored. For integral horsepower (HP) sizes, permanent magnet synchronous machines have been shown to be more efficient than induction machines of comparable size [1],[2]. This increased efficiency is primarily due to reduced copper losses resulting from a lack of rotor current. Properly addressing the issue of iron losses is clearly an area where additional gains in efficiency can be made. In particular, amorphous iron has already been shown to reduce iron losses dramatically in 60 Hz power transformers [3] as well as in induction machines [4]. The results from a 1/3 HP induction machine demonstrated that iron losses for an amorphous iron machine are about 33% those of a silicon steel machine of similar design [4]. The fabrication method of the design of Ref. 4 unfortunately required cumbersome manufacturing steps due to the machine topology and the limiting mechanical characteristics of amorphous iron. Specifically, the machine was laboriously built with several thousand conventionally styled lamination segment arcs which were made in a spin casting process.

The coordination of new design concepts together with new materials to yield higher efficiency machines with improved power density remains challenging. While it is apparent that amorphous iron is the material of choice for high efficiency machines having reduced iron loss, the challenge is to find a topology compatible with its characteristics. In this this paper, a novel machine topology which takes into consideration both the magnetic *and* mechanical properties of amorphous iron is proposed. Simplified machine equations are presented for the open circuit terminal voltage and for the torque when operating in a current controlled mode. Measurements from a proof-of-concept machine are compared to these equations to determine their validity and estimate their error. The amorphous iron losses are also measured and compared to manufacturers data.

Upon verification of the machine equations, a first order machine design is used to study various machine design options. The results from this program compare favorably with induction machines in terms of efficiency. These machines are also shown to compare favorably with induction machines in terms of cost when utilized in a variable speed drive.

MACHINE TOPOLOGY

One of the most difficult challenges in constructing a viable motor using amorphous iron is selecting the geometry of the stator core. In order to avoid stamping or cutting the amorphous iron and to reduce cost, a simple stator core constructed of tape wound amorphous iron is used. To avoid high iron losses, the flux in the gap must then be parallel to the width of the tape and therefore in the axial direction. Consequently, the stator was constructed with air gap windings which were wound on the core in toroidal fashion. This type of arrangement is particularly beneficial since the stator windings can be manufactured relatively easily with a toroidal winding machine. The resulting axial field topology is shown in Fig. 1 for an idealized two pole machine. In particular, the flux is shown crossing the air gap from rotor to stator along the axis of the machine (z direction). The flux then travels circumferentially along the iron tape (ø direction), back across the air gap and PM and then through the back iron. Figure 2 shows a detail of the stator and rotor as viewed from the axial direction and shows the layout of the windings along one surface of the tape wound stator core.

With the windings placed in the air gap, one design decision is whether to evenly distribute the winding over a phase belt or to employ a sinusoidally distributed winding. Because the distributed winding increases the possible number of turns, the electrical loading and the output power without making the air gap unduly large, this alternative was chosen over a sinusoidal winding. The three phases are then assumed to be connected in a star or Y configuration with the circuit of each pole connected in series to increase the terminal voltage. With current control, the star configuration also adds another degree of freedom if the neutral connection is available.

Another design consideration is the placement of the permanent magnets (PMs) in the rotor. The PMs must be placed to produce an air gap field parallel to the thickness of the amorphous iron

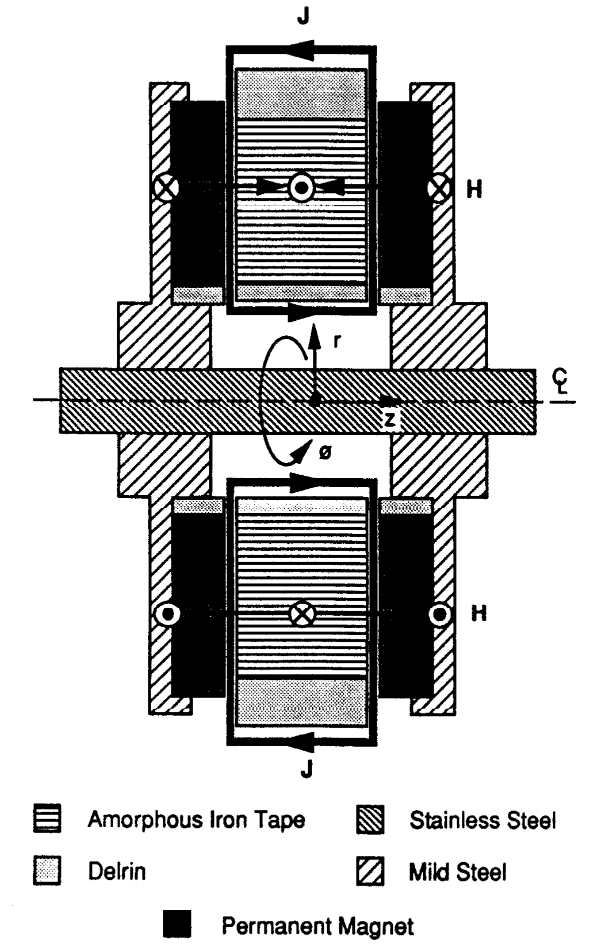


Fig. 1 Two Pole Machine Topology. J Denotes Stator Current Path and H Denotes Magnetic Field Intensity.

tape. With the large air gap due to the winding however, the benefits introduced by using flux concentration are reduced so such a topology is not chosen. While the effective air gap is already large due to the air gap stator winding, a surface mounted magnet design will increase the reluctance further, since the recoil permeability of the PM is close to air. While surface mounted magnets enable larger stator current levels before the permanent magnet is irreversibly demagnetized, it also clearly reduces the air gap flux and increases the leakage flux so that it is an undesirable but necessary requirement.

The next design decision is the selection of the type of PM material. Ferrite was chosen in the case of the prototype machine since the cost of the other PM materials apparently does not presently warrant their selection for a low cost motor (Table I). Ferrites also have a very small conductivity and therefore do not suffer from the eddy current problems which occur in some sintered rare earth materials. Unfortunately, unless laminated, the back iron of the PM rotor will always have some eddy current losses regardless of the PM material. In this design, a simple toroidal ring of ferrite material can be used with the required pole number impressed on the surface of the toroid as shown in Fig. 2.

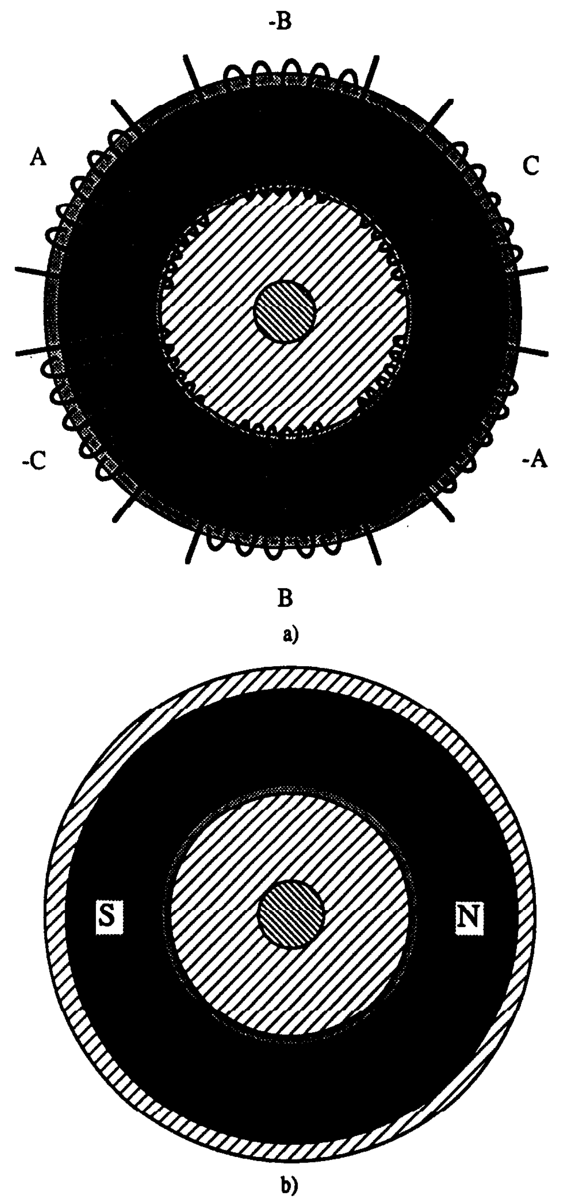


Fig. 2 Axial View of a) Stator Showing Three Phase Winding Pattern and of b) Rotor Showing Location of Magnets.

The last design decision is the number of working surfaces. Unlike radial machines, axial machines may have two working surfaces with two rotors and one stator or one rotor and two stators. The choice of two rotors was again a materials, cost and efficiency tradeoff. With two stators, more than one half of the copper produces heat, but no torque. The cost of amorphous iron is substantially greater than ferrite, so that an additional stator is more expensive than an additional rotor while the increase in power output would be almost identical. Since the stator is toroidally wound and two working surfaces of the core are use (i.e. the two sides), the length of the end turn (inner and outer surface of the core) is relatively small and as much as 3/4 of the winding can be used to produce torque compared to 1/3 to 1/2 as for a conventional winding placed in slots.

MACHINE EQUATIONS

Simplified motor design equations for the machine can be derived assuming idealized current control. The three phase square wave current waveform, which includes a large 3rd harmonic current in the neutral, is shown in Fig. 3. The effects of armature reaction and iron loss are neglected in these equations and the air gap flux density is assumed to be a square wave. This choice allows a simpler analysis which should be sufficient to determine the merit of the machine. With these assumptions, the open circuit terminal voltage can be easily derived from either the flux cutting or the flux linking method. The peak voltage is given as

$$V_{pk} = \omega_m N_p P B_{ave} (r_2^2 - r_1^2) \quad (1)$$

The average output torque can be found by equating the average air gap power and output power while neglecting the iron losses. The average air gap power is easily found by multiplying the open circuit voltage and the controlled current when operating with current control. The average output torque is given as

$$T_{ave} = I_{pk} B_{ave} P m N_p^2 (r_2^2 - r_1^2)\left(1 - \frac{1}{2}\frac{k_{fill}}{m}\right) \quad (2)$$

where

T_{ave}	average torque
N_p	number of turns per pole per phase
P	number of poles
m	number of phases
B_{ave}	average air gap flux density per rotor over a pole face
I_{pk}	peak phase current
ω_m	mechanical speed
r_2	outside radius of the magnet
r_1	inside radius of the magnet
k_{fill}	phase belt fill factor, 1.0 for a distributed winding

EXPERIMENTAL RESULTS

Test Machine

In order to demonstrate the feasibility of the tape wound core and axial air gap concept, a four pole test machine was assembled with a topology similar to Fig. 1 and is shown in Fig. 4. The machine was assembled to test the design equations, and hence was not optimized for reduced copper loss. The machine parameters for the test machine are shown in Table II.

For purposes of motor control, a Motorola 56001 digital signal processor (DSP), current sensors with a 12 bit analog to digital converter and a 4096 count rotary encoder were used. The control algorithm implements a fixed frequency zero hysteresis or delta modulator. A switching frequency of 30 kHz was obtained which resulted in a current ripple of less than 50%. Since the switching frequency was limited by the DSP execution time, the current ripple could not be reduced without adding external elements. Since the addition of external elements might have skewed the test results, none were added during the test. The large current ripple unfortunately

TABLE I

COMPARISON OF MOTOR MATERIAL COSTS

Material	Cost ($/lb)
MQ I (NdFeB PM)	45
Ferrimag (ceramic PM)	1.70
Copper Wire	2.25
METGLAS 2605S-2 (amorphous iron)	9.10 [1]\ 35.50 [2]

MQI is a trade name of GM Delco Remy
Ferrimag is a trade name of Crucible Magnetics
METGLAS is a trademark of Allied Signal
[1] Cost for 4 in wide material
[2] Cost for 1 in and 2 in wide material

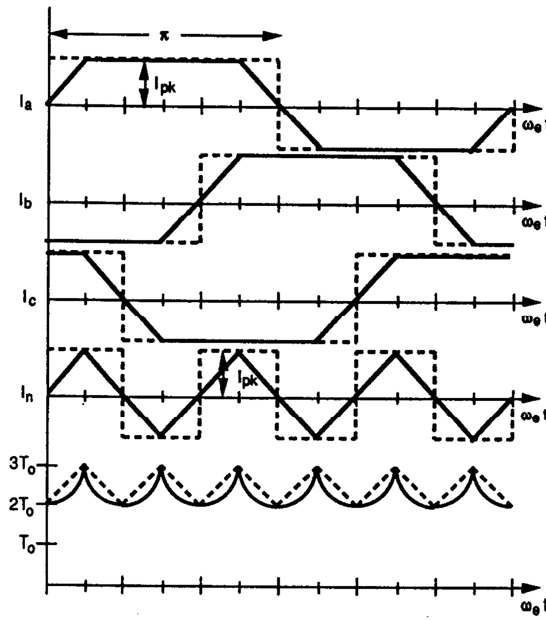


Fig. 3 Instantaneous Current and Torque Waveforms with Large Inertial Load for Square Wave Current (Dashed) and Trapezoidal Wave Current with $k_{fill} = 1$ (Solid)

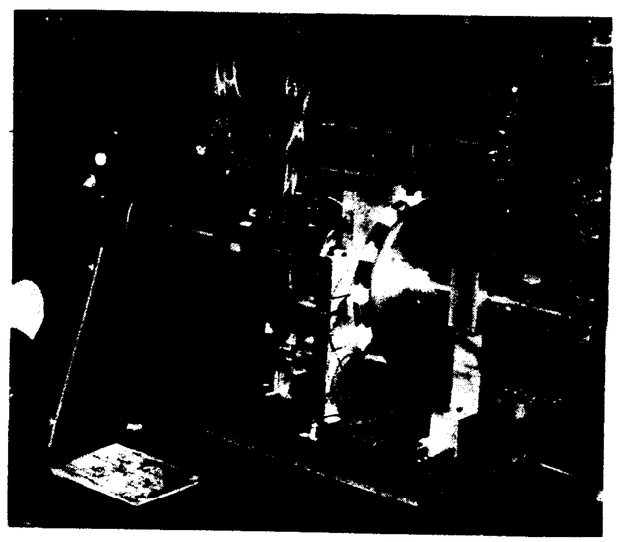


Fig. 4 Axial Field Amorphous Iron Test Machine

made the estimation of the peak current difficult. This error was compensated for somewhat by correlating the controller commanded current and the measured current, since the commanded current was known accurately.

Design Equation Verification

Test were performed to verify the two design equations, Eq. 1 and 2. The open circuit terminal voltage and waveform were verified to within 5% (Fig. 5) and the average torque was verified to within 10% (Fig. 6). The discrepancy in terminal voltage is attributed to variation between rotor magnets, to PM leakage fields and to the PM field shape. It is apparent that the error in terminal voltage compounds the error in torque, while further errors probably result from neglecting armature reaction and from the experimental measurement of the peak current.

Iron Losses

The no load iron loss was measured with a 20 kHz bandwidth power meter by driving the machine with a prime mover both with and without the PM rotors. The measured iron loss values are 2.2 W/kg @ 1800 rev/min and represents approximately 3% of the maximum output power. The values calculated from manufacturers data (0.03 W/kg) are nearly a factor 100 too small. While a factor of 10 is conceivable due to annealing and excitation, a factor of 100 is clearly excessive. After some effort, the added component of no load loss has been identified as eddy currents induced in the aluminum motor frame (not shown in Fig. 1) as well as in the solid steel rotor back iron and not by losses in the tape wound iron. Hence, these currents could be substantially reduced by redesign of the frame of the machine.

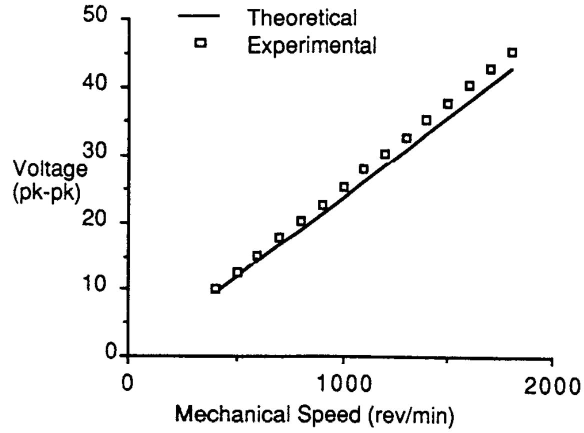
When operated as a motor, the input and output powers were then measured. After correcting for resistive and frictional losses, approximately 5% of the power remains unaccounted for. From the above results and the manufacturers data, the iron losses are approximately half of this loss, or again 3% of the motor maximum output power at rated speed. The loss is greater when motoring loaded *vs.* generating unloaded due to the high frequency of the flux variation in the stator iron and in the rotor back iron. This high frequency flux is a result of the low machine inductance of the test machine due to the air gap winding together with the controller bandwidth. A more accurate estimation of the iron loss power could be done if the annealing history of the material was known and if the current ripple could be reduced. Reducing the amplitude of the ripple current and switching frequency would also clearly reduce iron losses. Such a reduction in losses should be possible with a well designed machine.

Other Results

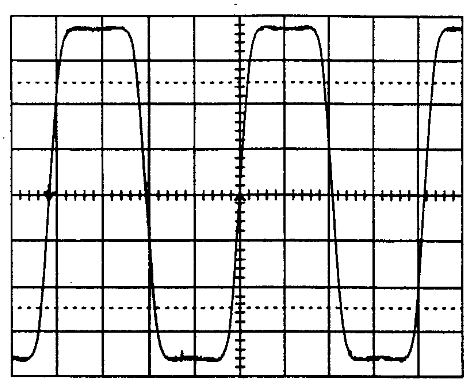
Experimental data was additionally obtained for a trapezoidal current waveform, Fig. 3. This waveform was chosen because it has the same shape as the back emf, Fig. 5(b). Since the product of current and back emf is directly related to the torque, this choice of waveform result in more average torque per rms amp (0.35 N m/A_{rms} trapezoidal *vs.* 0.30 N m/A_{rms} square), but the square wave results in more torque per peak amp (0.30 N m/A_{pk} square *vs.* 0.28 N m/A_{pk} trapezoidal). While the difference is small and the error in estimating

TABLE II
TEST MACHINE PARAMETERS

B_{ave} = 0.24 T	P = 4	R_{phase} = 3.4 Ω
$B_{pk,a\text{-}iron}$ = 0.60 T	m = 3	L_{self} = 850 μH
r_2 = 5.8 cm	N_p = 41	L_{mutual} = 420 μH
r_1 = 2.2 cm	AWG = 22	k_{fill} = 0.77



a)



b)

Fig. 5 a) Comparison of Theoretical and Experimental Open Circuit Voltage, b) Experimental Open Circuit Voltage Waveform

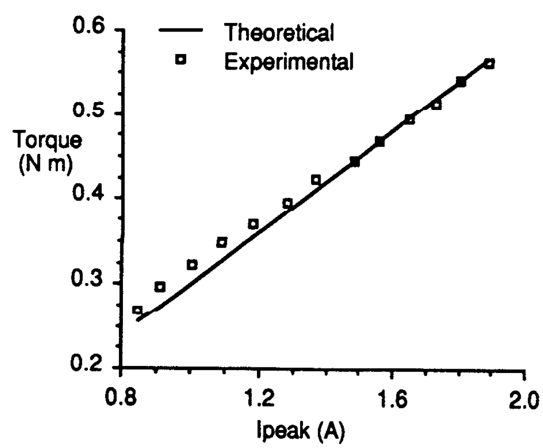


Fig 6 Comparison of Theoretical and Experimental Output Torque

the peak current is appreciable, simplified analysis assuming a large inertial load suggests the reason. Figure 3 shows the instantaneous torque assuming a large inertial load, i.e. an approximately constant angular speed. The rms and average torque are larger for a square wave with the same peak as the trapezoidal wave, while the rms torque per rms amp is larger for the trapezoidal wave current. This result is due to the fact that the rms current for a trapezoidal wave is less than the rms current for a square wave when the peak current are the same. For applications where increased efficiency is important, the trapezoidal wave should be considered since the resistive losses will be less for the same output power.

The radiated sound with the two waveforms was also determined to be different. A subjective observation was that the trapezoidal current waveform was more "pleasant" sounding, but this preference was not unanimous.

COMPUTER DESIGN MODEL

Using the previous design equations, which neglect armature reaction and leakage flux, a computer program was written which calculated motor performance for a variety of parameters. Several machine parameters were calculated as a function of air gap height (including copper) and as a function of inside radius for a 375 W machine. The following conditions and restrictions were also applied.

- The design output power was increased 10% to account for the discrepancy in the design equations.
- The ratio of outside to inside radius was fixed at $\sqrt{3}$ to maintain the maximum force density [5].
- Only commercially available widths of amorphous iron tape were considered.
- The cost of the least expensive iron tape size was used.
- An air gap flux density of 1/2 and 3/4 of the residual flux density was used.
- A line to neutral peak voltage of 180 V and 90 V was used.
- Only machines where the flux in the stator due to the stator winding was less than 10% of the flux in the stator due to the permanent magnets were considered as demanded by the assumption of a negligible armature reaction.
- The wire gauge was also a variable. The largest wire size that fills the air gap, fits through the central window and generates the required terminal voltage was chosen.

Materials cost and copper loss are shown in Fig.7 for a 4 pole machine with a line to neutral peak voltage of 180 V and an air gap flux density of one half of the residual flux density. The steps in copper loss and cost occur when the wire size changes. A pole variation of 2, 4 and 6 was briefly examined, with the 4 pole machine having the best materials utilization for the cost with ferrite PMs. For optimum utilization of the amorphous iron, the most expensive component, the inside radius should be 8 cm to meet the above conditions. This results in a motor that is more expensive than necessary as the copper losses are already low with a radius of 6 cm.

Table III is a comparison of several machine parameters as the PM operating point and line to neutral voltage are changed. An increase in air gap flux density reduces copper losses for increased PM material. But the small value of inductance in these cases may lead to problems similar to those in the test machine where the inductance was so small the current ripple was very large. Table IV is a comparison between the new machine, an induction machine and a PM DC machine. This comparison highlights the increased efficiency that can be obtained with only a moderate increase in machine cost.

TABLE III
DESIGN MACHINE PARAMETERS
Pout=375W @ 1800 RPM, 4 POLE, FERRITE PM

Machine Parameter	l_{gap} = 1.5 cm r_1 = 4.5 cm $r_2 = r_1\sqrt{3}$			
	$B_{gap} = \frac{1}{2} B_r$		$B_{gap} = \frac{3}{4} B_r$	
	V_{ln} = 180 #1	V_{ln} = 90 #2	V_{ln} = 180 #3	V_{ln} = 90 #4
P_{Cu}/P_{out}	0.021	0.021	0.0092	0.012
L (mH/phase)	19	4.8	4.8	1.2
R (Ohms/phase)	3.8	0.95	1.6	0.52
N/pole/phase	310	155	212	106
Wire (AWG)	19	16	17	15
Weight (kg)	9	9	11	10.5
Cost $	56	56	64	61

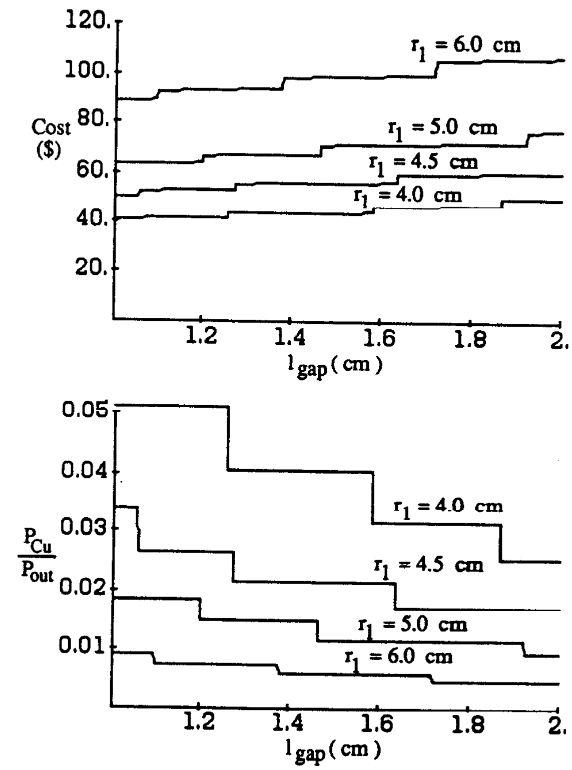


Fig. 7 Machine Cost and Efficiency *vs.* Air Gap Length for Various Values of Radius for a Ferrite Permanent Magnet Machine #1, TABLE III

TABLE IV
COMPARISONS OF INDUCTION, DC PM,
AND AXIAL FIELD PM MOTORS

	Ferrite [1]	Induction [2]	DC, PM [3]
Efficiency (%)	>90	75 - 80	-
Weight (kg)	9.0	10	14
Size (l x d)	3.2" x 6.5"	8" x 7"	12" x 7"
Cost ($)	56 [4] / 171 [5]	20 [4] / 45 [6]	170 [7]

[1] Design machine #1 assuming windage and iron losses are < 6%
[2] 1/2 H.P., 1725 RPM, 3 Phase, 230 VAC, Open Drip Proof, Rigid Mount, NEMA 56 Frame, General Purpose
[3] 1/2 H.P., 1800 RPM, 180 VDC, Totally Enclosed Non-Ventilated, Rigid Mount
[4] Materials cost
[5] Materials cost with current price for 1 in wide amorphous iron
[6] Total manufacturer's cost
[7] Average List Price

The possibility of a rare earth magnet design machine was also examined in this study [6]. In this case, an increase in pole number is desirable to reduce the peak iron flux. This machine was some what smaller but twice as expensive. Rare earth machines should apparently be reserved for larger machines or special applications where the small size is mandatory.

CONCLUSIONS

This paper has presented a novel axial field permanent magnet synchronous machine which utilizes a tape wound stator core equipped with toroidally wound stator windings. Basic design equations were presented for this new machine which are shown to be sufficiently accurate to model basic machine performance. While iron losses could not be conclusively measured, the combination of iron and stray losses was only 6% of the maximum output power at rated speed. The results of the computer model suggests that high efficiencies, for small machines, are possible and at a competitive cost when an electronic drive is already a system requirement. With these encouraging results, the use of tape wound amorphous iron machines should be explored further to produce a more accurate model and to test a well designed machine.

One near term obstacle for an inexpensive machine is the current cost difference between various widths of amorphous iron tape which apparently have been cost reduced for the production of tape wound transformers. Finally, while fractional HP machines are the focus of this work, larger machines of this construction appear to be also possible.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Dexter Brown of Allied Signal Co. for his encouragement and for supplying the tape wound core used for the construction of the machine. The authors are also indebted to the participating companies in the Wisconsin Electric Machines and Power Electronics Consortium for facilities and equipment provided.

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