

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 that utilizes tape-wound amorphous iron and an air-gap winding 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. Machine designs from a computer program that demonstrate the possible benefits of 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 (PM) 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]. Results from a 0.33-hp induction machine have 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 that design 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 that 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. Although 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 paper, a novel machine topology that 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. These equations are compared with measurements from a proof-of-concept machine to determine their validity and estimate their error. The amorphous iron losses are also measured and compared with 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. 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 reduce iron losses, the flux in the air gap must be tangential to the surface of the tape and, therefore, in the axial direction. Consequently, the stator was constructed with air-gap windings that 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 for an idealized two-pole machine is shown in Fig. 1. In particular, the flux path crosses the PM and air gap from rotor to stator along the axis of the machine (z direction). The path follows the iron tape circumferentially around the stator (ϕ direction). Finally, the path returns across the airgap and PM and closes

Paper IPCSD 91-102, approved by the Electric Machines Committee of the IEEE Industry Applications Society for Presentation at the 1990 Industry Applications Society Annual Meeting, Seattle, WA, October 7-12. Manuscript released for publication June 25, 1991.

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IEEE Log Number 9106816.

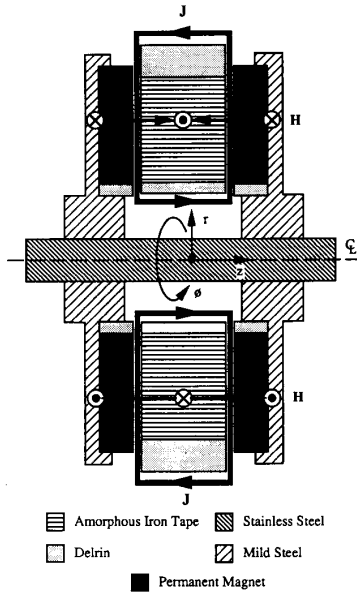


Fig. 1. Two-pole machine topology. J denotes stator current path, and H denotes magnetic field intensity.

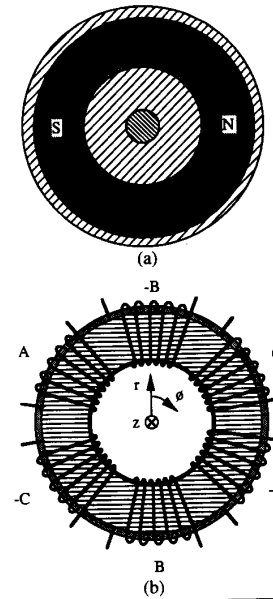


Fig. 2. Axial view of (a) rotor showing location of PM's and (b) stator showing three-phase winding pattern.

through the back iron. Fig. 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 evenly 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 PM's in the rotor. The PM's must be placed to produce an air-gap field tangential to the surface of the amorphous iron tape. With the large air-gap winding, the benefits introduced by using flux concentration are reduced, however; therefore, such a topology is not chosen. Although the gap reluctance 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. In addition, although surface mounting the magnets enables larger stator current levels before the PM is irreversibly demagnetized, it also clearly reduces the air-gap flux and increases the leakage flux, making it 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 that 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. This toroidal ring has the additional benefit of providing mechanical integrity to the PM.

The last design decision is the number of working surfaces. Unlike radial machines, axial machines may have two working surfaces. The combinations of two rotors with one stator or one rotor with two stators are available. The choice of two rotors was, again, a materials, efficiency, and cost tradeoff. With two stators, less than one half of the copper produces torque, and the majority of copper produces only heat. Conversely, with two rotors, the toroidally wound stator has two working surfaces (i.e., the two faces). Additionally, since the length of the end turn (inner and outer surface of the core) is relatively small, as much as three fourths of the winding can be used to produce torque compared with one third to one half as for a conventional winding placed in slots. Finally, the cost of amorphous iron is substantially greater than ferrite; therefore, an additional stator is more expensive than an additional rotor, whereas the increase in power output would be almost identical.

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 third

TABLE I
COMPARISON OF MOTOR MATERIAL COSTS

Material	Cost (\$/lb)
MQI (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
Ferring is a trade name of Crucible Magnetics
METGLAS is a trademark of Allied Signal
¹Cost for 4-in-wide material
²Cost for 1-in and 2-in wide material

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

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

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-b analog-

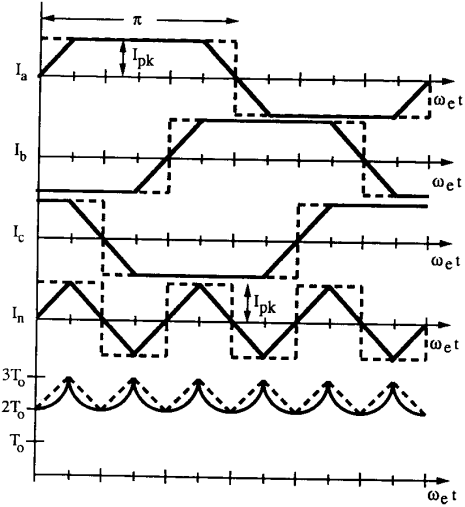


Fig. 3. Instantaneous current and torque waveforms with large inertial load for square wave current (dashed) and trapezoidal wave current with $K_{fill} = 1$ (solid).

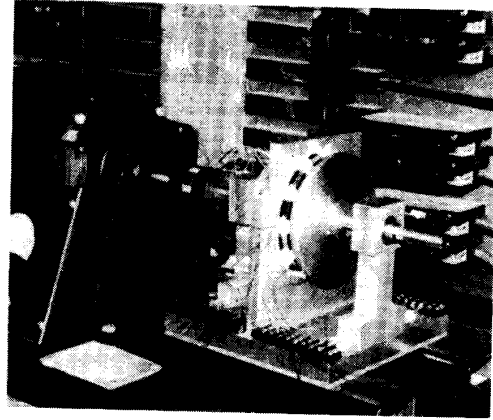


Fig. 4. Axial field amorphous iron test machine.

TABLE II
TEST MACHINE PARAMETERS

$B_{ave, gap} = 0.24$ T	$P = 4$	$R_{phase} = 3.4$ Ω
$B_{pk, a-iron} = 0.59$ T	$m = 3$	$L_{self} = 850$ μ H
$r_2 = 5.8$ cm	$N_p = 41$	$L_{mutual} = 420$ μ H
$r_1 = 2.2$ cm	AWG = 22	$k_{fill} = 0.77$

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 and 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 implementation of additional elements might have skewed the test results, none were added during the test. The large current ripple unfortunately made the estimation of the peak current difficult. This error was compensated for somewhat by correlat-

ing the controller commanded current and the measured current since the commanded current was known accurately.

Design Equation Verification

Tests were performed to verify the two design equations: (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 the two PM rotor fields, to PM leakage fields, and to the PM field shape. It is apparent that an error in terminal voltage compounds an error in torque, whereas 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 r/min and represents approximately 3% of the maximum output power. The values calculated from manufacturers data (0.03 W/kg) are nearly a factor of 100 too small. Although 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) and not by losses in the tape-wound iron. Hence, these currents could be considerably reduced by redesign of the machine frame.

When operated as a motor, the input and output powers were measured. After correcting for resistive and frictional losses, approximately 6% of the power remains to be accounted for. From the above results and the manufacturers data, the iron losses are approximately half of this loss or 3% of the motor maximum output power at rated speed. The loss is greater when motoring loaded versus generating unloaded due to the frequency of the flux variation in the stator iron and in the rotor back iron. This high-frequency flux is a result of the unusually low machine inductance of the test machine together with the current 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 ripple current amplitude and the 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. This waveform was chosen because it has the same shape as the back emf (see Fig. 5(b)). Since the product of current and back emf is directly related to the torque, the square wave results in more average torque per peak amp (0.30 N m/A_{pk} square versus 0.28 N m/A_{pk} trapezoidal). However, the trapezoidal waveform results in more average torque per rms amp (0.35 N m/A_{rms} trapezoidal versus 0.30 N m/A_{rms} square). This result is simply because the rms current for a trapezoidal wave is less than

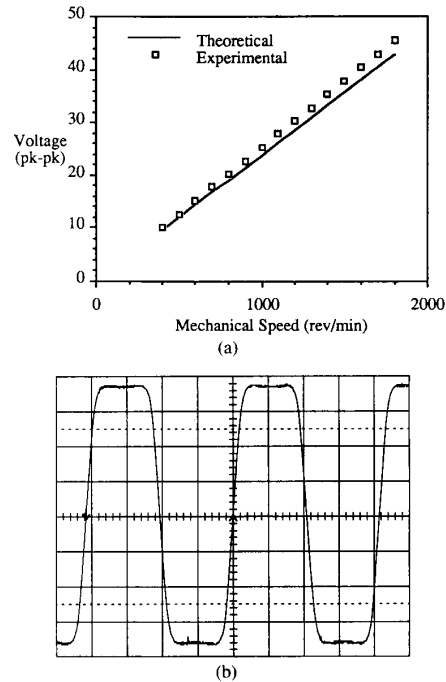


Fig. 5. (a) Comparison of theoretical and experimental open-circuit voltage; (b) experimental open-circuit voltage waveform.

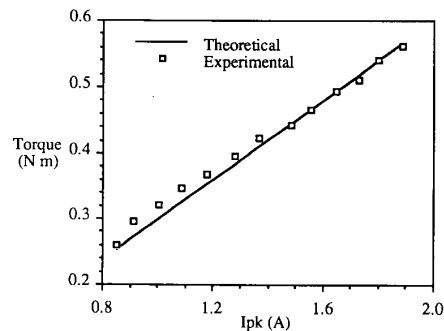


Fig. 6. Comparison of theoretical and experimental output torque.

the rms current for a square wave when the peak currents are the same. Fig. 3 shows the instantaneous currents and torque assuming an approximately constant angular speed.

Both of these waveforms produce some torque ripple. A current waveform without a third harmonic would reduce torque ripple but would also result in less average torque per peak amp. For applications where increased efficiency is important and some torque ripple is acceptable, the trapezoidal wave should be considered since the resistive losses will be reduced for a given 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, another computer program that calculated motor performance for a variety of parameters was written. 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 one half and three fourths of the residual flux density was used.
- A line-to-neutral peak voltage of 180 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 four 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 four pole machine having the best materials utilization for the cost with ferrite PM's. For optimum utilization of the amorphous iron, which is the most expensive component, the inside radius should be 7 cm to meet the above conditions. This results in a motor that is more expensive than necessary as the copper losses are already small with a radius of 6 cm. The lower level of saturation flux density for amorphous iron is not the problem with this design; the reduced levels are a result of constraining the amorphous iron tape width to commercially available sizes. Low loss machines also typically operate at a lower flux density than standard machines.

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. However, the small value of inductance in these cases may lead to problems similar to those encountered in the test machine where the small inductance leads to a large ripple current. Table IV is a comparison between the new machine, an induction machine, and a PM dc machine. This comparison highlights the increased

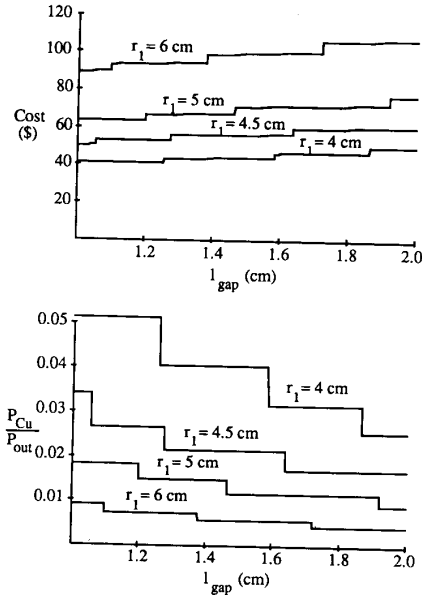


Fig. 7. Machine cost and efficiency versus air-gap length for various values of radius for ferrite permanent magnet machine #1 (Table III).

TABLE III
DESIGN MACHINE PARAMETERS
($P_{out} = 375$ W @ 1800 r/min, four-pole,
ferrite PM, $B_r = 0.38$ T, 2.54-cm-wide
amorphous iron)

Machine Parameter	$l_{gap} = 1.5$ cm		$r_1 = 4.5$ cm	
	$B_{gap} = \frac{1}{2} B_r$	$B_{gap} = \frac{3}{4} B_r$	$B_{gap} = \frac{1}{2} B_r$	$B_{gap} = \frac{3}{4} B_r$
	$V_{in} = 180$ #1	$V_{in} = 90$ #2	$V_{in} = 180$ #3	$V_{in} = 90$ #4
P_{Cu}/P_{out}	0.021	0.021	0.009	0.009
$B_{pk, iron}$	0.93 (T)	0.89 (T)	1.30 (T)	1.29 (T)
L (mH/phase)	19	4.8	4.3	1.1
R (Ω /phase)	3.8	0.95	1.6	0.52
N /pole/phase	310	155	207	103
Wire (AWG)	19	16	17	15
Weight (kg)	9	9	11	11
Cost \$	56	56	65	65

efficiency that can be obtained with only a moderate increase in machine cost.

A machine similar to this design but utilizing standard tape-wound iron has been built [6]. While running as a 10 kW ac generator with a similar air gap flux density, this larger machine had predicted iron losses of 0.6% and measured copper losses of 8%. However, larger machines typically have lower per-unit losses, and that machine was designed for compact size.

The possibility of a rare earth magnet design machine was also examined in this study [7]. In this case, an increase in pole number is desirable to reduce the peak iron flux. This machine was somewhat smaller but twice as expensive. Rare earth should apparently be reserved for larger machines or special applications where the small size is mandatory.

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 (<i>l</i> × <i>d</i>)	3.2" × 6.5"	8" × 7"	12" × 7"
Cost (\$)	56 ⁴ /171 ⁵	20 ⁴ /45 ⁶	170 ⁷

¹Design machine #1 assuming windage and iron losses are < 6%

²0.5-hp, 1725 r/min, three phase, 230 VAC, open-drip-proof, rigid mount, NEMA 56 frame, general purpose

³0.5-hp, 1800 r/min, 180 VDC, totally enclosed non-ventilated, rigid mount

⁴Materials cost

⁵Materials cost with current price for 1-in-wide amorphous iron

⁶Total manufacturer's cost

⁷Average list price

CONCLUSIONS

This paper has presented a novel axial field permanent-magnet synchronous machine that utilizes an amorphous iron 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. Although 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 higher efficiencies, for a small machine, are possible and at a competitive cost when an electronic drive is already a system requirement. With these encouraging results, the use of amorphous iron tape-wound 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, although fractional hp machines are the focus of this work, larger machines of this construction are also possible.

ACKNOWLEDGMENT

The authors wish to thank D. 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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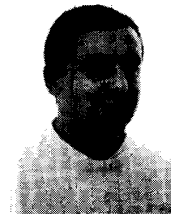
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