Project title: Advanced Motors
Company: IAP Research, Inc. **PI:** Bhanumathi Chelluri
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Project Summary

Transportation energy usage is predicted to increase substantially by 2020. Hybrid vehicles and fuel cell powered vehicles are destined to become more prominent as fuel prices rise with the demand. Hybrid and fuel cell vehicle platforms are both dependent on high performance electric motors. Electric motors for transportation duty will require sizeable low-speed torque to accelerate the vehicle. As motor speed increases, the torque requirement decreases which results in a nearly constant power motor output.

Interior permanent magnet synchronous motors (IPMSM) are well suited for this duty.[1,2,3] These rotor geometries are configured in straight lines and semi circular arc shapes. These designs are of limited configurations because of the lack of availability of permanent magnets of any other shapes at present. We propose to fabricate rotors via a novel processing approach where we start with magnet powders and compact them into a net shape rotor in a single step. Using this approach, widely different rotor designs can be implemented for efficiency. The current limitation on magnet shape and thickness will be eliminated. This is accomplished by co-filling magnet and soft iron powders at specified locations in intricate shapes using specially designed dies and automatic powder filling station. The process fundamentals for accomplishing occurred under a previous Applied Technology Program titled, "Motors and Generators for the 21st Century". New efficient motor designs that are not currently possible (or cost prohibitive) can be accomplished by this approach. Such an approach to motor fabrication opens up a new dimension in motor design.

Feasibility Results

We were able to optimize a IPMSM rotor to take advantage of the powder co-filling and DMC compaction processing methods. The minimum low speed torque requirement of 5 N-m can be met through an optimized design with magnet material having a Br capability of 0.2 T. This level of magnetic performance can be met with a variety of bonded magnet compositions.

The torque ripple was found to drop significantly by using thinner magnet segments. The powder co-filling and subsequent compaction processing allow for thinner magnet structures to be formed. Torque ripple can be further reduced by using skewing and pole shaping techniques. The techniques can be incorporated into the rotor during the powder co-filling process.

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[1] Honda, Y.; Murakami, H.; Kazushige, N.; Higaki, T.; Morimoto, S.; Takeda, Y.; "Optimum Design of a Multilayer Interior Permanent Magnet Synchronous Motor Using Reluctance Torque", Electrical Engineering in Japan, Vol. 127, No. 1 1999

[2] Vaez-Zadeh, S; Ghasemi, A.R.; "Design optimization of permanent magnet synchronous motors for high torque capability and low magnet volume", Electric Power Systems Research 74 (2005) 307-313

[3] Staton, D.A.; Miller, T.J.E.; Wood, S.E.; "Maximising the saliency ratio of the synchronous reluctance motor", IEEE Proceedings-B, Vol. 140, No. 4, July 1993, 249-259

INTRODUCTION

Transportation energy usage is predicted to increase substantially by 2020 as shown in Figure 1. Hybrid vehicles and fuel cell powered vehicles are destined to become more prominent as fuel prices rise with the demand. Hybrid and fuel cell vehicle platforms are both dependent on high performance electric motors.

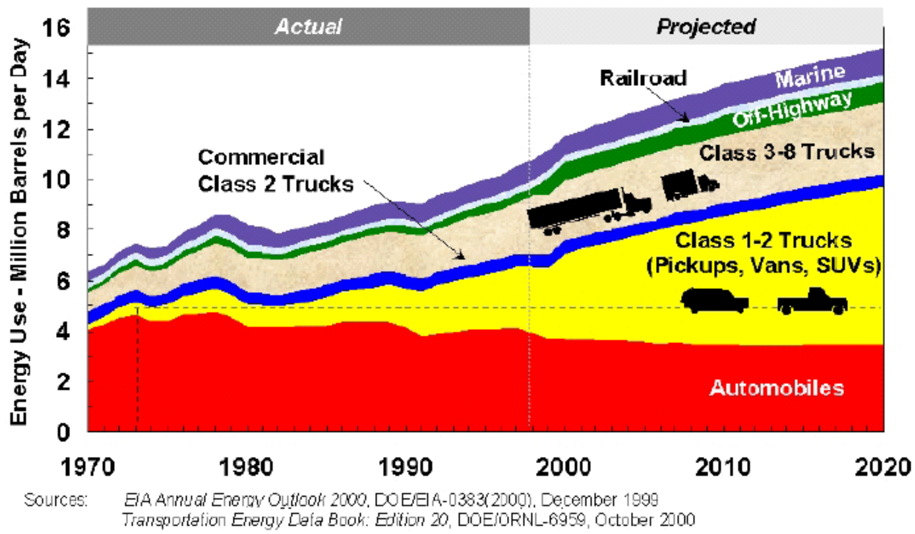

Figure 1. Transportation energy use is expected to increase by nearly 40% from 1998 to 2020.

Electric motors for transportation duty will require sizeable low-speed torque to accelerate the vehicle. As motor speed increases, the torque requirement decreases which results in a nearly constant power motor output.

Interior permanent magnet synchronous motors (IPMSM) are well suited for this duty.[4,5,6] Figure 2 shows some of the typical rotor geometries for IPMSM motors. These rotor geometries were configured as shown in Figure 2 in straight lines and semi circular arc shapes. These designs are of limited configurations because of the lack of availability of permanent magnets of any other shapes at present. We propose to fabricate rotors via a novel processing approach where we start with magnet powders and compact them into a net shape rotor in a single step. Using this approach, widely different rotor designs can be implemented for efficiency. The current limitation on magnet shape and thickness will be eliminated. This is accomplished by co-filling magnet and soft iron powders at specified locations in intricate shapes using specially designed dies and automatic powder

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filling station. The process development for accomplishing this has occurred under a previous Applied Technology Program titled, “Motors and Generators for the 21^{st} Century”. New efficient motor designs that are not currently possible (or cost prohibitive) can be accomplished by this approach. Such an approach will open up a new dimension in motor designs.

IAP has patented a powder processing technology [6,868,778] that is directly applicable to the fabrication of these motors. Using this powder filling technology, the cross sections of the magnet and flux paths can have irregular shapes. The designs shown in Figure 2 are composed of straight line and simple arcs. In Phase I, we performed an analytical study to determine the performance enhancement possible by using magnet and flux path structures created directly from powder using the DMC process. In future efforts, we will build and test rotors to confirm and improve upon the performance predicted in Phase I.

The powder loading system IAP has developed allows for the loading of multiple powders. We anticipate using a non-ferrous stainless steel (SS) powder for bridging structures within the rotor. These SS bridging structures will increase the structural strength of the rotor without creating magnetic shorts between flux guides.

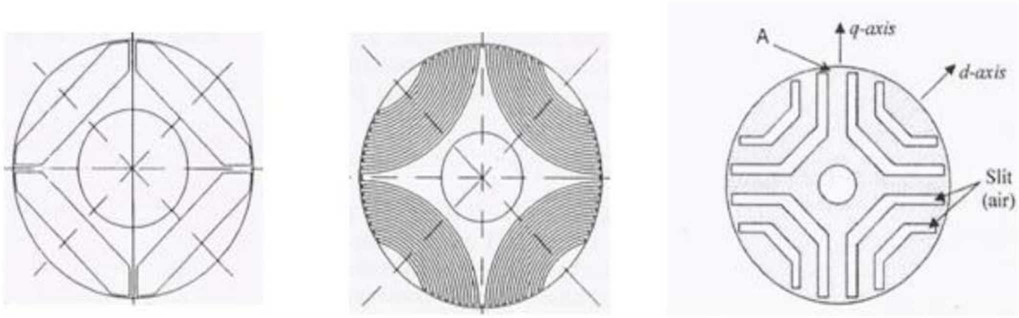
We have experience building permanent magnet motor structures by combining our powder loading and compaction technologies. Figure 3 shows one stator and three rotor components made using these techniques. All of these parts are made with isotropic neodymium iron boron (neo) powder for the magnets and composite iron for the soft magnetic portions. The stator shown in Figure 3(a) has skewed magnets. The skew was put into the part during the powder loading stage. Loading incompressible powder into this region created the void space next to the demagnetization shunt. The rotor shown in Figure 3(b) has isotropic neo magnets. The powder-loading tool determines the magnet widths. The two ring rotors shown in Figure 3(c) were compacted directly onto the rotor shafts.

The rotors in Figure C-3(c) were tested by MOOG Components Group. Through material development and the high density DMC process, the motor’s torque coefficient was increased by 33%. MOOG estimated that this performance improvement could be converted into a 12% mass reduction through a motor redesign. DMC processing of these rotors lead to a 100% increase in rotational speed.

The principle of powder compaction using the DMC process is shown in Figure 4. In this approach the powder is placed in a conductive container (armature), which is then placed in the bore of a high field coil. The coil is pulsed with a high current to produce a magnetic field in the bore, which, in turn, induces currents in the armature. The induced currents interact with the applied magnetic field to produce an inwardly acting magnetic force that collapses the tube thus compacting the powder. The duration of the pressure application is very short (< 1 millisecond).

Using the DMC compaction process on commercially available composite iron dramatically improves the magnetic saturation and permeability. Figure 5 compares the B-H curve for a plain steel lamination, conventionally compacted iron, and DMC compacted iron. The improved density allows the DMC compacted iron to nearly reach the magnetic saturation capability of the laminate. The air spaces between the individual iron particles lead to the decrease in magnetic permeability. During Phase I, we introduced nano material to the composite iron[7]. Our goal was to reduce the air gaps and thereby increase the magnetic permeability. Some increase in saturation flux density was also expected. Our limited Phase I efforts did not result in a significant performance change in the composite iron. Future efforts will focus on demonstrating improved motor performance through prototype testing utilizing commercial soft magnetic composite materials.

[7] Patent pending



(a) (b) (c)

Figure 2. A variety of IPMSM motor rotor geometries have been used in high performance applications.

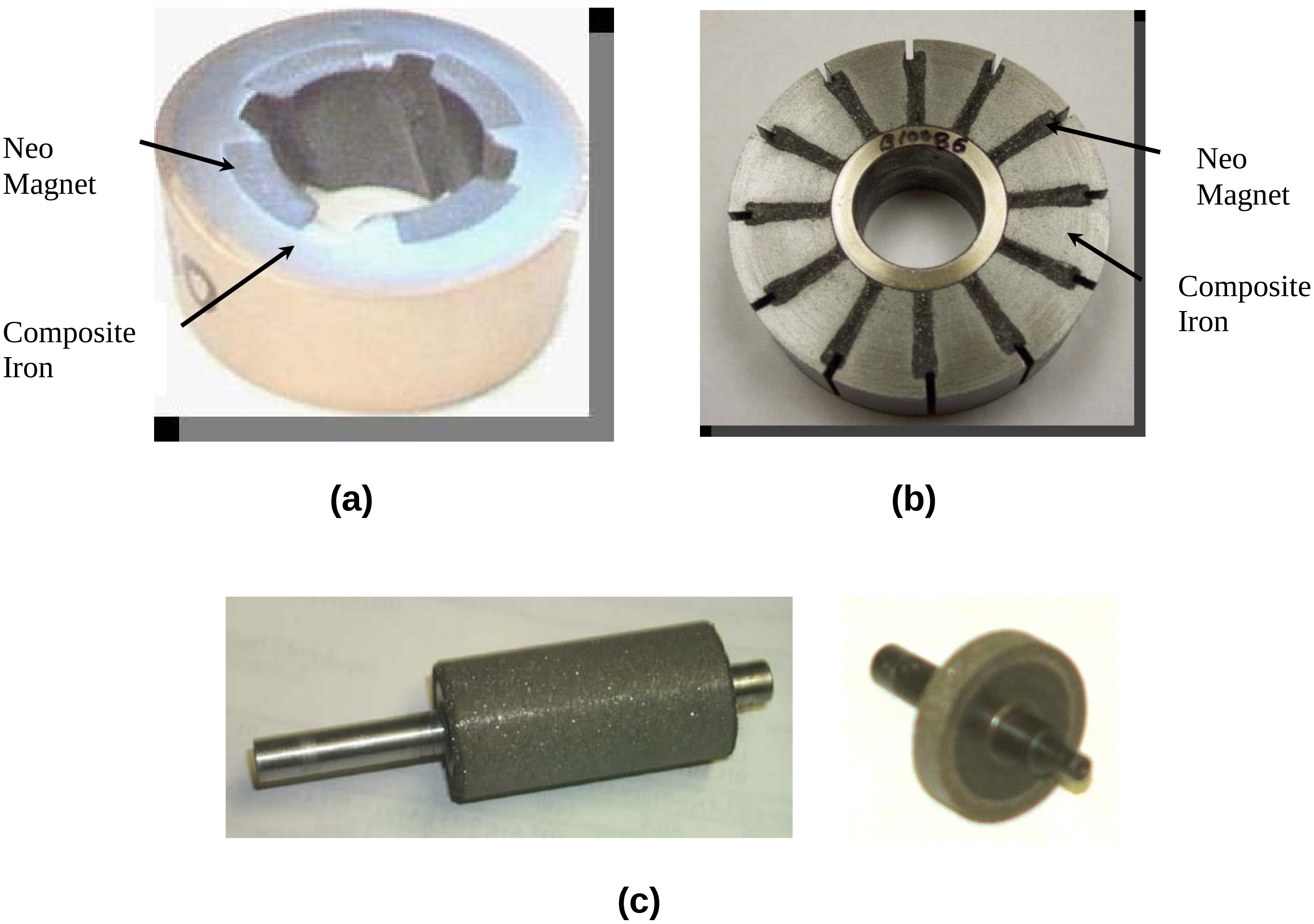


Figure 3. Dynamic Magnetic Compaction (DMC) was used to fabricate these magnetic structures.

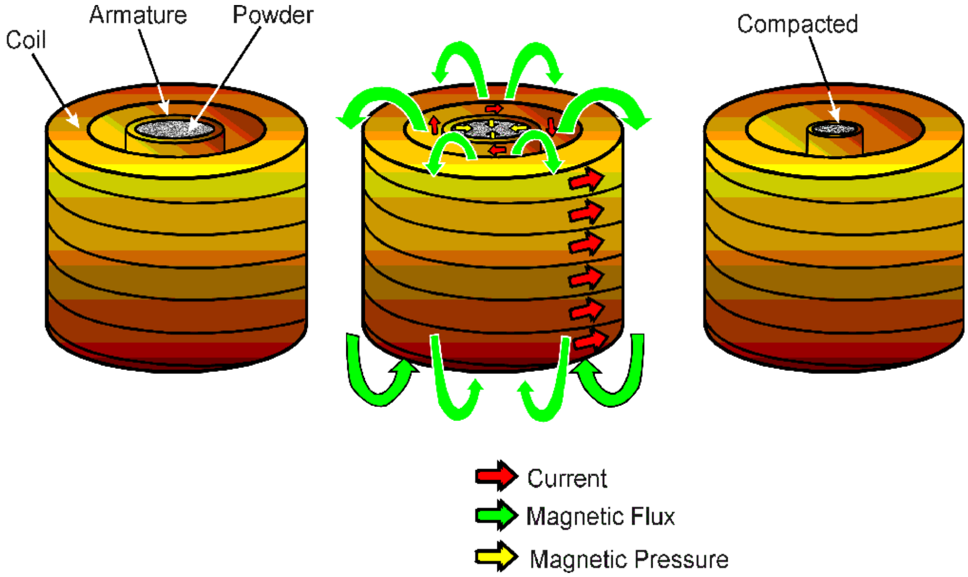
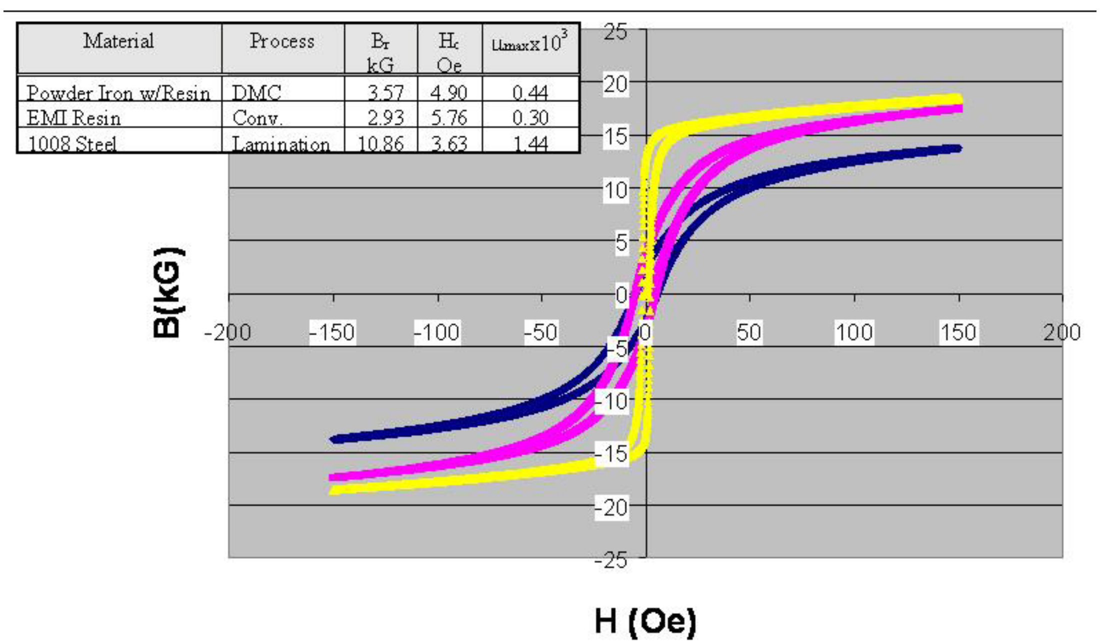


Figure 4. Principle of DMC Process.



Material	Process	B_r kG	H_c Oe	μ_{max} x 10^3
Powder Iron w/Resin	DMC	3.57	4.90	0.44
EMI Resin	Conv.	2.93	5.76	0.30
1008 Steel	Lamination	10.86	3.63	1.44

Figure 5. High density composite iron has nearly the same saturation flux density as a steel lamination. (Yellow = Laminate, Pink = DMC, Blue = Conventional Pressing)

Soft Magnetic Material Development

Typical soft magnetic composite (SMC) material has a magnetic permeability of about 250. We have produced SMC material with magnetic permeability exceeding 400 using the DMC compaction process. The permeability is a function of air gaps in the material. The sintered /wrought materials have permeability in the range of > 5000 due to not having a large volume of porosity. However in powder compacted materials, permeability is limited by porosity in the compact. Figure 6 shows the permeability in composite iron material at various density levels. As the density level is increased, permeability also increased. The scatter in the points is due to variations in coating thickness and type of coating. As compared to wrought material values which are 8000 for M-19 steel and 5000 for cold rolled magnetic lamination (CRML) steel, the powder values are fairly low at less than 500.

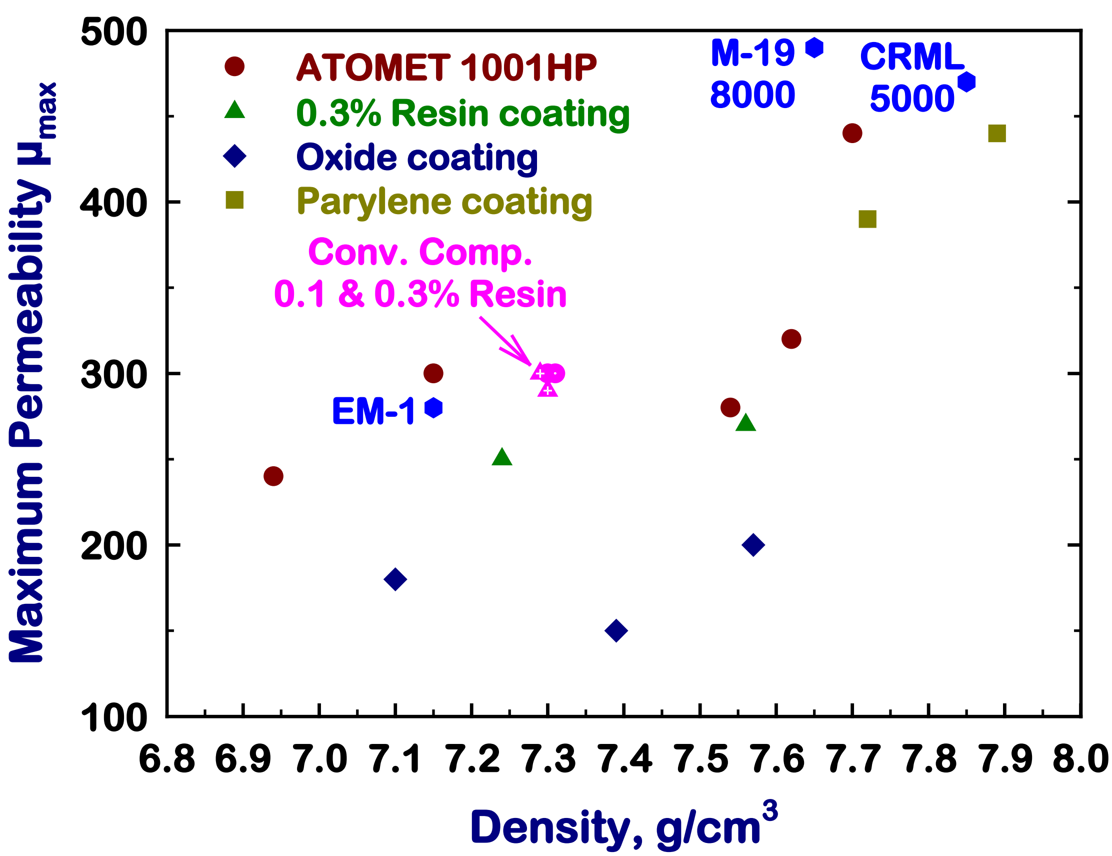


Figure 6. Comparison of permeability of various materials at different density values.

In Phase I, the innovative idea was used to disperse nano iron powder into micron size powders so that the porosity in the micron size powders will be occupied by nano particles. Such powder mixes were DMC compacted into standard toroids for magnetic measurements according to ASTM standard. The pink curve shows composite iron B-H curve and yellow curve shows with 4 vol % blended nano Fe in composite iron sample. Samples without nano iron addition showed a maximum permeability of 289 and the samples with nano iron had a 206 maximum permeability. This is in the range expected from Figure 2 for the density range. Due to limitation of compaction pressure available for the test, we could not compact the powders with nano iron to a very high density in the range of 7.6-7.7 g/cc to see the effects of closing the air gaps. Thus we conclude the result of adding nano iron powders did not give rise to an increase in permeability as expected at the density values achieved.

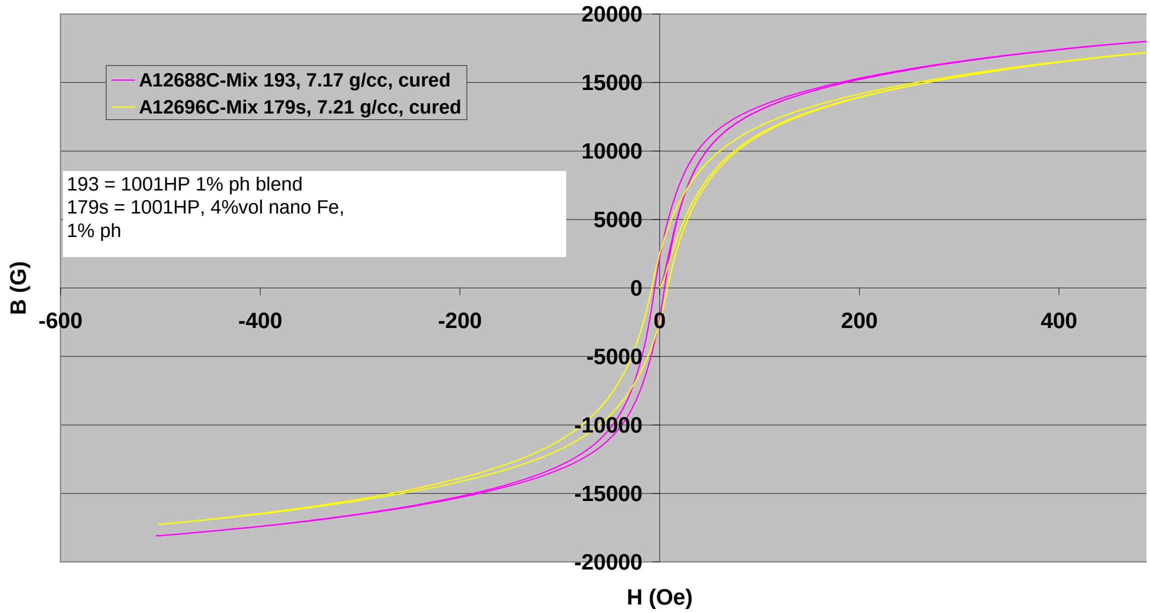


Figure 7. Comparison of B-H curve of Iron with and without nanopowder addition.

Motor Design Optimization for DMC Processing

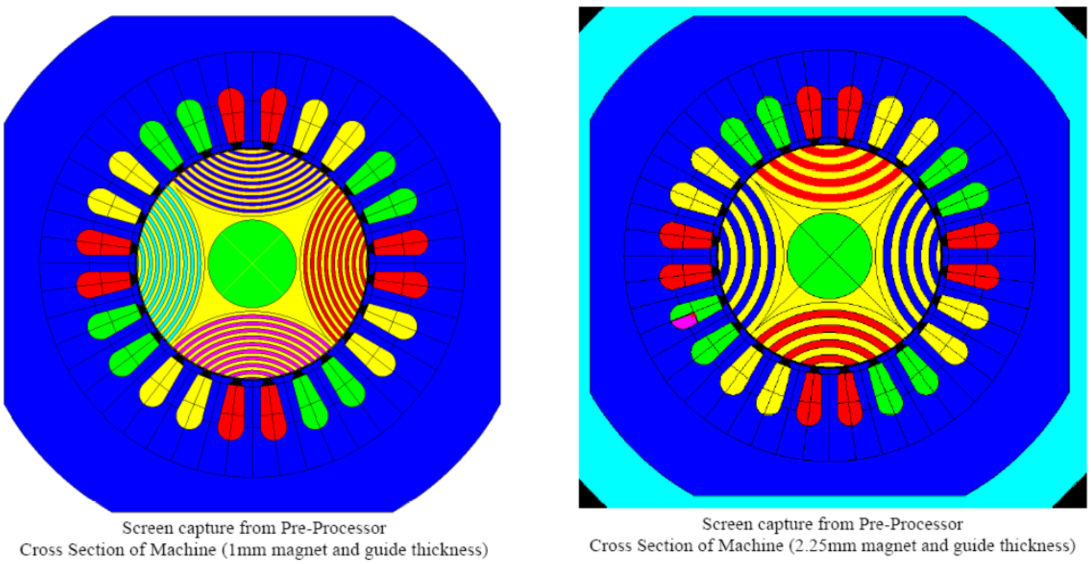
Interior permanent magnet synchronous motors (IPMSM) are well suited for transportation duty. They can provide the required low-speed torque needed to accelerate the vehicle. As the vehicle reaches the desired speed, the required motor torque decreases resulting in a nearly constant power motor output.

One of our goals in Phase I was to optimize an IPMSM motor rotor for DMC processing. A 4-pole multi-barrier rotor was chosen for the optimization effort. Dan Ionel of the AO Smith Corporation provided the stator design used for the motor optimization effort. Dave Staton from Motor Design Ltd. used FLUX FEA software to calculate low speed performance and perform the optimization. Field weakening performance was predicted using SPEED PC-BDC software. B-H curve data for both the soft and hard magnet materials we have produced using DMC processing was used for modeling.

Figure 8 shows the rotor topologies investigated. Two magnet and flux guide thicknesses were investigated, 1 mm and 2.25 mm. The motor optimization was carried out with the following performance requirements:

- the Phase I motor is targeted at 5 HP (3700 W), and
- provide a minimum low speed torque of 5 N-m.

The optimization objective was to minimize the amount of magnet material required. The magnet Br is adjusted from 0.1 to 0.779 to represent the use of less magnet powder in the design. The optimum design will achieve a 5 N-m torque requirement with the minimum amount of magnetic material.



(a) (b)

Figure 8. The 1 mm thickness design has 9 magnets per pole while the 2.25 mm thickness design has 4 magnets per pole.

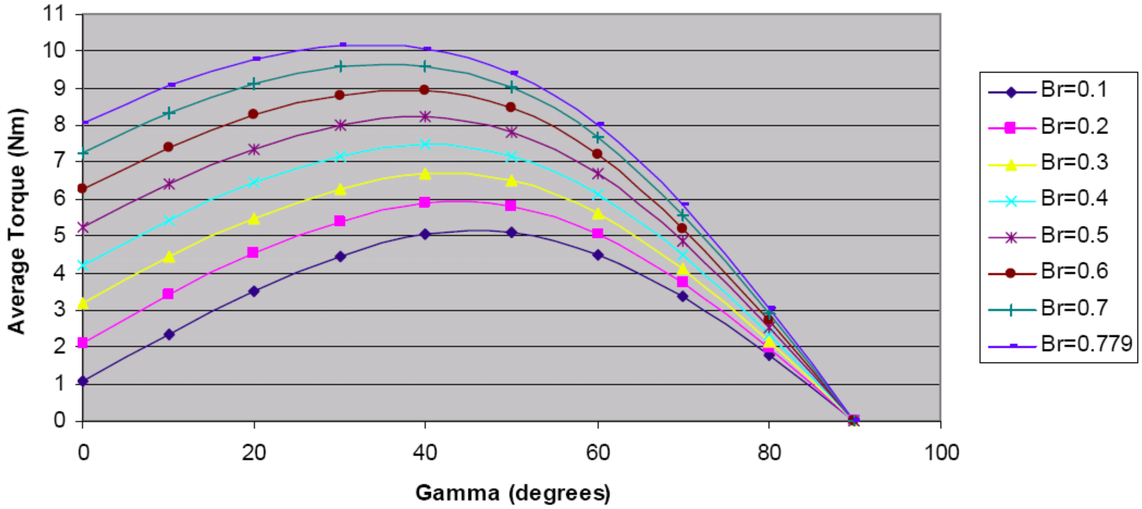
Figure 9 shows the average torque achieved for each magnet/guide thickness and Br set-point. In each case the same geometries were used. The Br capability of the magnet was varied from 0.1T to 0.779T in 0.1T increments. Gamma was varied from 0 to 90 electrical degrees in steps of 10 degrees. The average torque is only slightly reduced by the magnet/flux guide thickness increase. A 5 N-m torque requirement can be met with a magnet Br of 0.2 T.

Figure 10 shows the torque ripple for the same cases as in Figure 9. The torque ripple nearly triples by increasing the magnet/flux guide thickness from 1 mm to 2.25 mm. The torque ripple with a 1 mm magnet/flux guide thickness is still sizeable at 36% of the rated torque. Torque ripple reduction strategies such as skew, offsetting the poles, and airgap profiling will be investigated in follow-on efforts. Figure 11 shows how the co-filling technique can be used to create skew in the magnetic structure. This same technique will be used in new designs to skew the rotor poles thereby reducing torque ripple. Figure 11 also a co-filled component with a 1 mm thick magnet section.

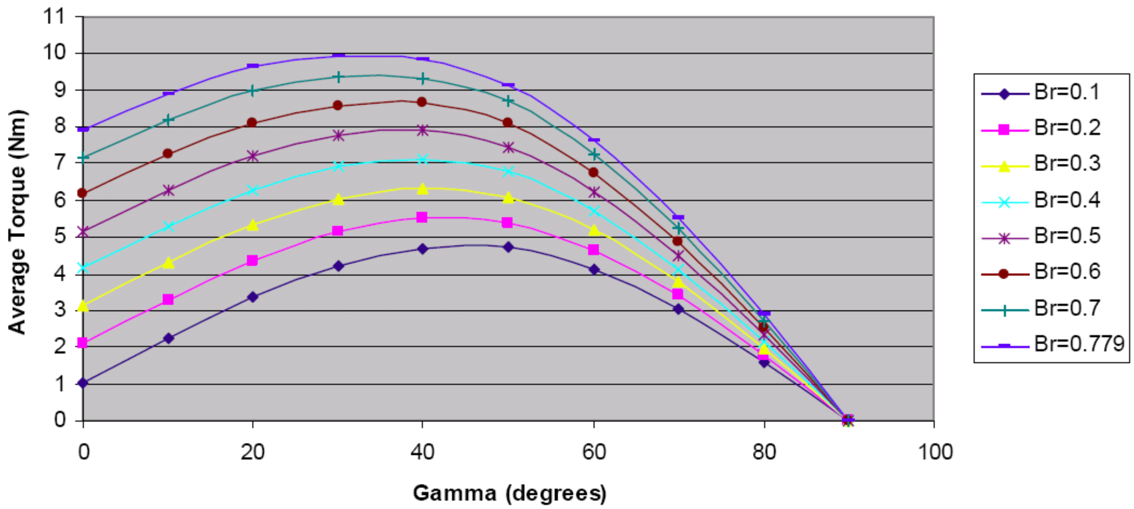
The performance of the 4 magnets per pole rotor was evaluated using SPEED PC-BDC software. Figure 12 shows the torque versus speed characteristics for the optimized motor. The torque remains constant from 1,000 to 12,000 rpm. Torque then decreases linearly until 32,500 rpm. Above 32,500 rpm the torque remains constant.

The output power versus speed is shown in Figure 13. The power increases linearly with speed until 12,000 rpm. Above 12,000 rpm, the output power remains flat within ±14%.

The performance characteristics of this subscale motor are consistent with those needed for hybrid electric vehicles. In future efforts, we plan to build and test prototype motors to confirm and further develop the motor design and fabrication technologies.

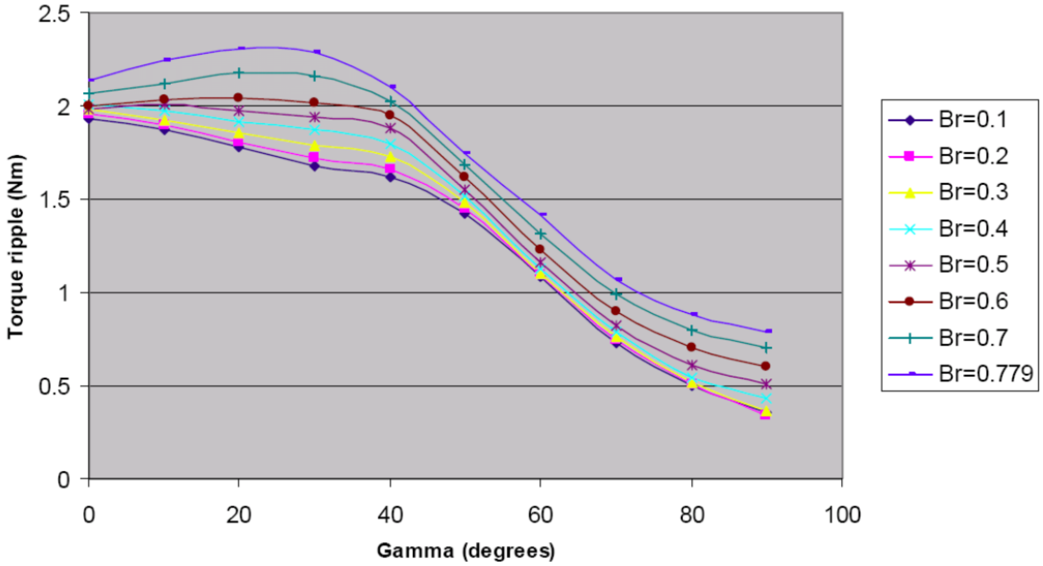


(a) 1mm magnet/flux guide thickness



(b) 2.25 mm magnet/flux guide thickness

Figure 9. Average torque is insensitive to magnet/flux guide thickness.



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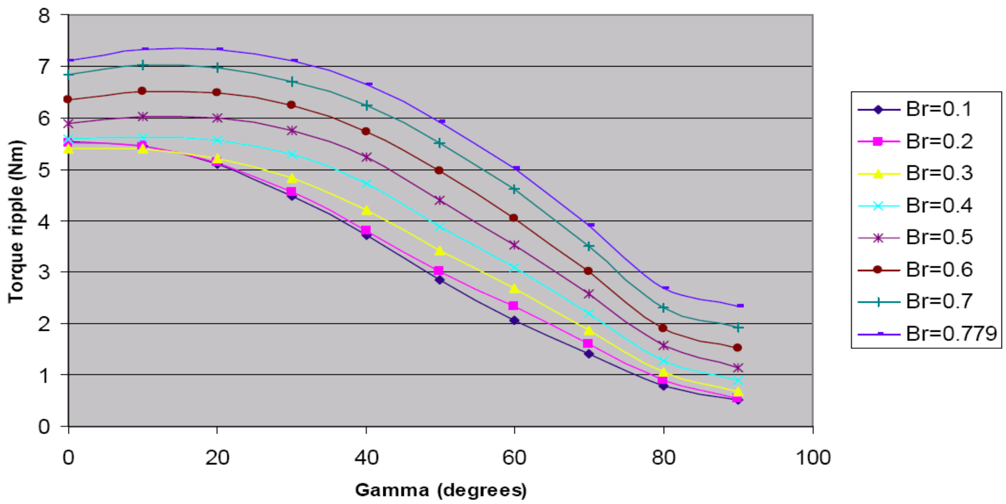

(b) 2.25 mm magnet/flux guide thickness

Figure 10. Increasing magnet/flux guide thickness sharply increases ripple torque.

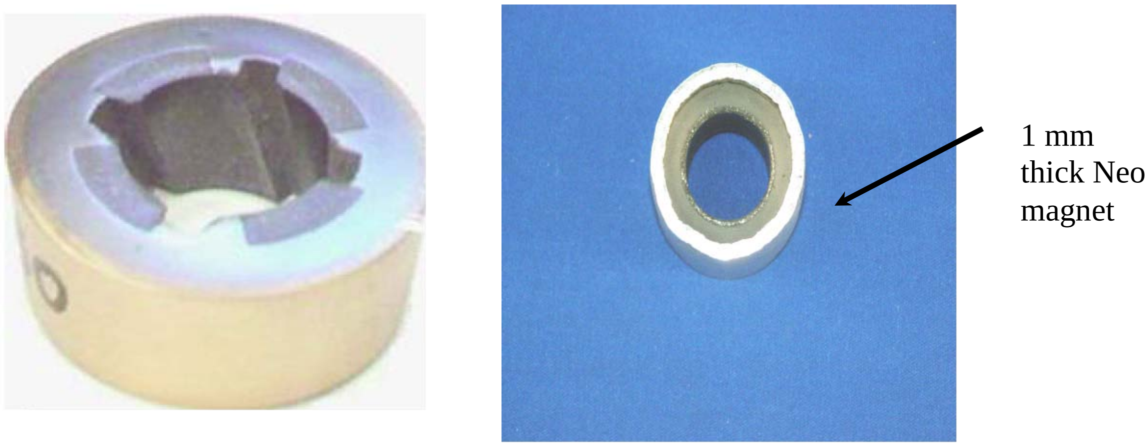

Figure 11. The skew of the magnetic poles is created during powder filling. The 1 mm thick Neo magnet and composite iron were co-filled and compacted together.

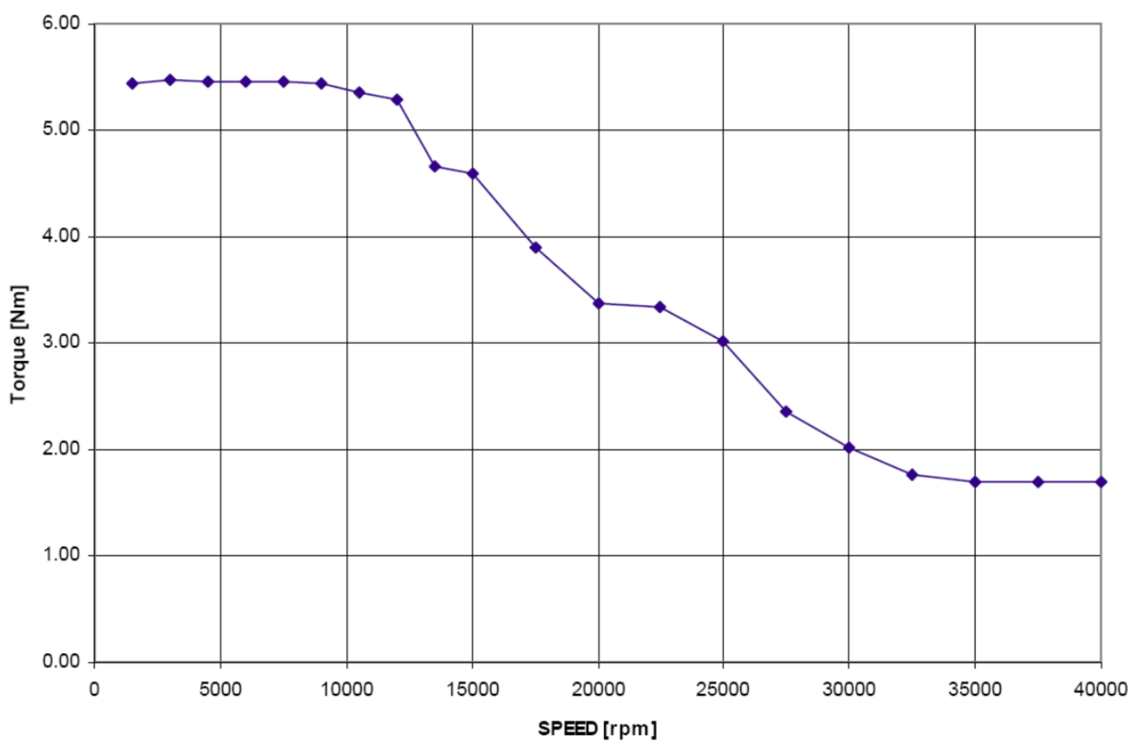

Figure 12. This motor produces high torque at low speeds.

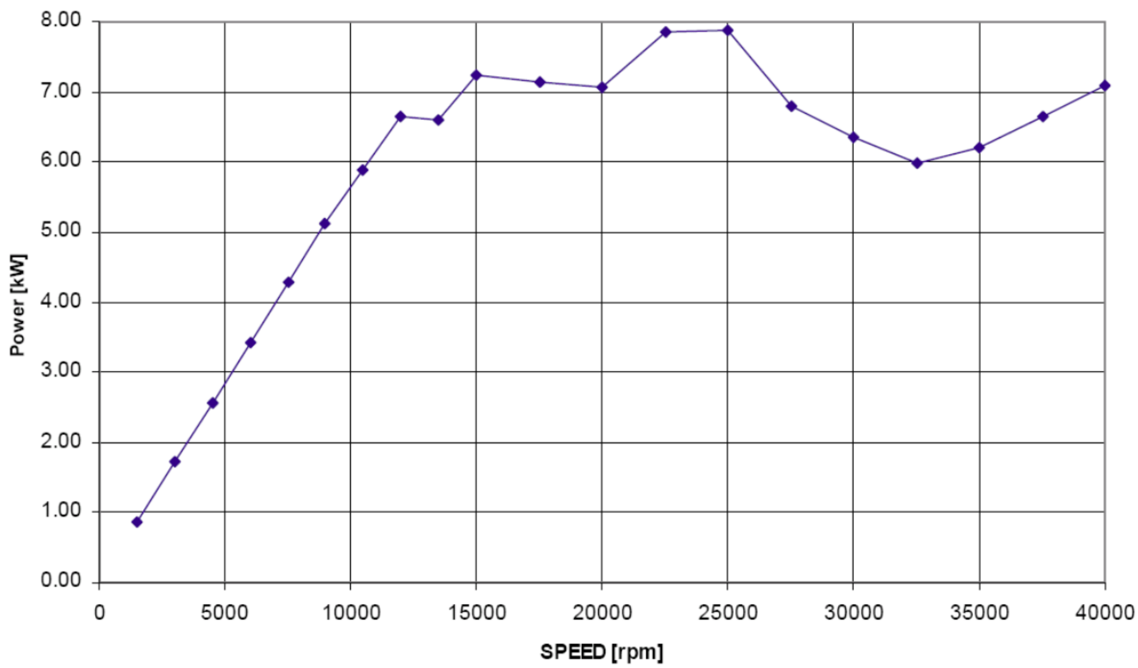

Figure 13. Motor power plateaus above 12,000 rpm.

PROJECT SUMMARY

We were able to optimize a IPMSM rotor to take advantage of the powder co-filling and DMC compaction processing methods. The minimum low speed torque requirement of 5 N-m can be met through an optimized design with magnet material having a Br capability of 0.2 T. This level of magnetic performance can be met with a variety of bonded magnet compositions.

The torque ripple was found to drop significantly by using thinner magnet segments. The powder co-filling and subsequent compaction processing allow for thinner magnet structures to be formed. Torque ripple can be further reduced by using skewing and pole shaping techniques. The techniques can be incorporated into the rotor during the powder co-filling process.

WORK IDENTIFIED FOR FUTURE DEVELOPMENT EFFORTS

Our technical objectives for the next step in motor development are listed below as questions.

1) Which powder magnet material is best for use in multi-barrier permanent magnet rotors? The magnet material needs to provide the desired flux, resist demagnetization, and provide sufficient mechanical strength for 25,000 rpm operation.
2) Can we build and properly magnetize the multi-barrier permanent magnet rotors? The magnet and composite iron materials will need to flow well to properly fill the DMC cassette.
3) Do DMC processed multi-barrier permanent magnet rotors perform as modeled? Is the torque ripple as high as predicted?
4) Will skewing of the rotor adequately reduce the torque ripple?
5) Can an IPMSM designed for DMC processing meet projected hybrid electric vehicle performance and cost goals?