Analysis of a Continuous Halbach Array Permanent Magnet Motor for Electric Vehicles

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***Abstract*—Permanent magnets spirals with continuously varying magnetization directions to replace Halbach arrays have recently been developed. Ideal sinusoidal fields with the desired polarity are created in the machine airgap. In this paper we propose to compare a motor initially designed with a conventional discrete Halbach array with the innovative continuous Halbach array magnets. The continuous Halbach array comprises bonded magnets manufactured from anisotropic powder aligned and compacted without a bonding agent. The paper focuses on the impact of using these magnets on the performance of a motor designed for electric vehicle applications using 2D and 3D FEA simulations. The baseline motor is a 50-kW outrunner motor designed for light duty electric vehicles**

I. Introduction

High power density permanent magnet motors often utilize Halbach array permanent magnets. These machines are usually designed to operate at high speed in order to achieve the maximum power density, and therefore the permanent magnets need to be highly segmented in order to minimize the Eddy current losses and associated heating. Furthermore, discrete Halbach array magnets with multiple segments per pole are employed to achieve high performance. During assembly, there are gaps between adjacent magnet segments which lead to performance degradation. The difficulty and cost of manufacturing Halbach arrays is a major pain point; the assembly requires handling of many permanent magnets and the need for expensive tooling to force magnets with different magnetization directions into close proximity.

An innovative method to make Halbach array permanent magnets with continuously varying magnetization patterns was recently developed providing ease of assembly and cost effective manufacturing [1-2]. This technology is called the PM-360 enabled by the PM-Wire manufacturing process, a powder-in-tube process developed at the Advanced Magnet Lab. This paper evaluates the performance of a motor designed with the PM-360 permanent magnets. The magnet powders (i.e. MQA powder from NeoMagnequench) used to make the PM-360 anisotropic powder are compacted without a bonding agent. The powder is compacted to over 80% of the NdFeB density leading to a remnant flux density of around 1T at room temperature for the resulting magnets. The motor performance with a PM-360 rotor is compared with a baseline motor design which uses discrete Halbach array permanent magnets with 4-segments per pole.

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II. Baseline motor based on discrete Halbach array magnets

An outer rotor permanent magnet motor designed for 50kW continuous and 100kW peak power is chosen as baseline [3]. The maximum operating speed for this machine is 20,000rpm. The motor has 18-stator slots and 16-rotor poles. Each pole is implemented using 4-permanent magnet circumferential segments, each with a different direction of magnetization. The stator has 18 slots and uses fractional slot concentrated windings.

This machine design uses sintered N-48 permanent magnets. Such magnets have a maximum recommended operating temperature of 80 deg C. In order to minimize the magnet heating due to the permanent magnet eddy current loss at the maximum operating speed point, the permanent magnets are segmented in the axial direction. Including the axial segments as well as the 4 magnet pieces per pole required to implement the Halbach array, the number of discrete magnets in this design exceed 2000.

The manufacturing of the magnets with different magnetization directions and the handling and assembly is expected to be cost prohibitive. The 3D geometry along with the magnet segmentation is shown in Fig. 1. The other design parameters are summarized in Table I. A 2D electromagnetic model was created in COMSOL to analyze the field in the machine and compute the torque. The magnetic flux density and streamlines are shown in Fig. 2.

III. Continuous Halbach array permanent magnet motor

A novel manufacturing method for permanent magnets, PM-Wire allows for inexpensive continuous flux directed Halbach arrays to be developed thus enabling the cost-effective development of very high-power density machines. PM-Wire is an innovative manufacturing process in which a “powder-in-tube process” is used to compact, shape, and magnetize the

Motor Rated Power[kW]	100
Maximum RPM [rpm]	20,000
No. of slots	18
No. of poles	16
Stator outer diameter [mm]	208
Rotor active outer diameter[mm]	242
Stack length [mm]	43
Turns per coil	8

Table I: Motor design specifications

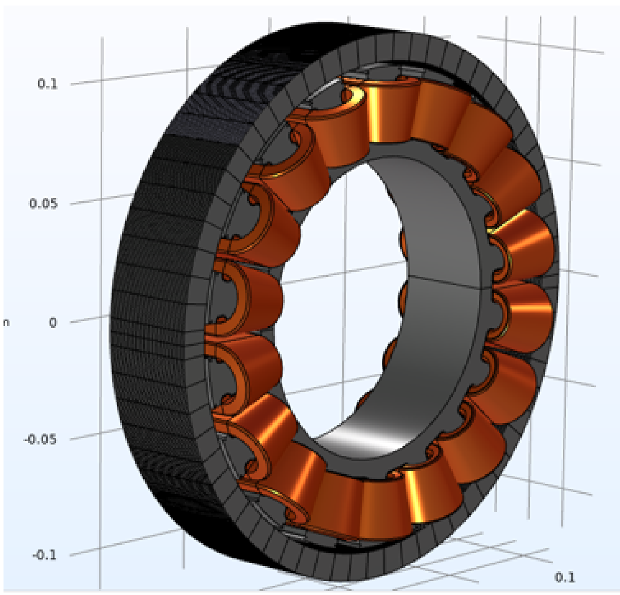

Figure 1: Three-dimensional geometry of the discrete Halbach array motor showing the axial magnet segmentation.

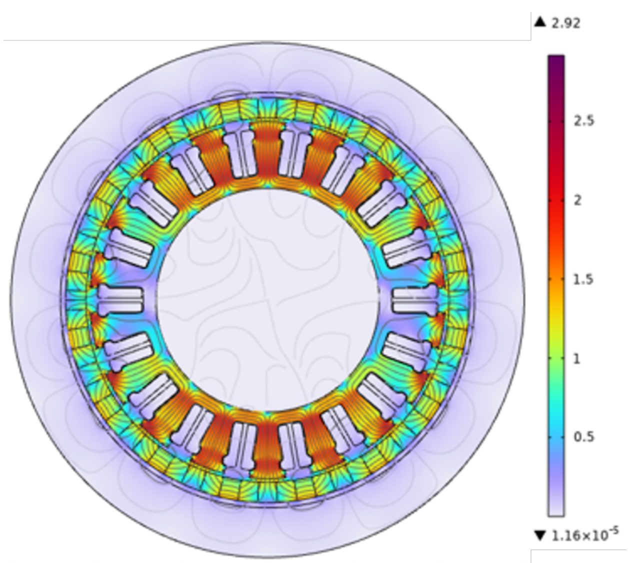

Figure 2: Magnetic field lines obtained from a 2D FEA model developed in COMSOL for the machine with discrete Halbach array magnets.

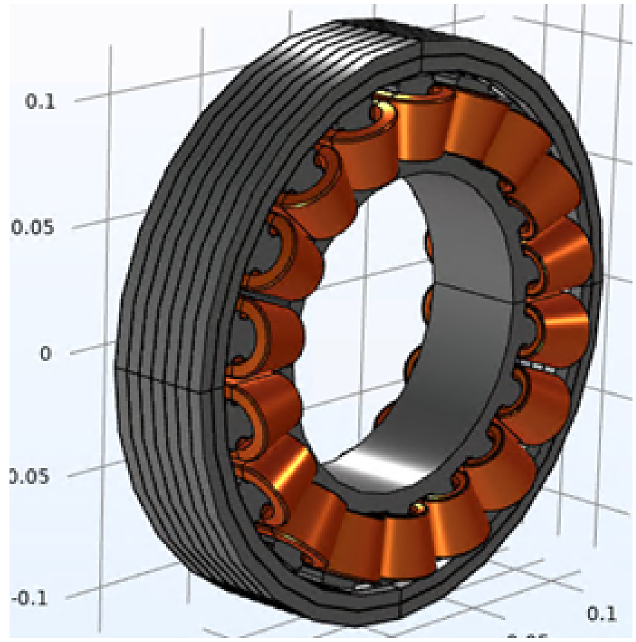

Figure 3: Three-dimensional geometry of the proposed continuous halbach array rotor machine

permanent magnet material in a highly automated and high-rate (mass production) process.

Additionally, the PM-Wire process enables unique flexibility in terms of shape and magnetization direction and configurations that are not possible with current manufacturing processes [2]. Anisotropic powder (MQA-36-19) is used to make the PM-360 rings. It may be noted that the PM-360 magnets use bonded material with high resistivity and therefore would not require axial segmentation.

Using the above process, the external rotor design with the Halbach configuration having 2752 magnets could be replaced by 14 PM-360 rings with continuous flux directed magnetization. A 3D model with the PM-wire rotor is shown in Fig. 3. PM-360 magnets are made with a continuous sinusoidal change of magnetization direction forming magnetic poles and the equivalent of a perfect continuous Halbach array. Figure 4 summarizes the difference in magnetization between the Halbach and the PM-360 configuration.

IV. Performance comparison

The baseline design is based on N48 sintered permanent magnets with Br = 1.3T at simulated operating condition (i.e. 80 deg C) The PM-360 design is based on MQA-36-19 anisotropic bonded magnets with a Br of 0.9T at 80 deg C. Due to the reduction in Br compared to the sintered magnets in the baseline machine, an increase in motor volume for the same output power is expected. However, since the PM-360 design generates an ideal sinusoidal field in the airgap, the gap in performance due to the lower Br of the anisotropic bonded magnets is somewhat compensated. The magnetic fields and the B vector plot for the PM-360 design are obtained from COMSOL and are shown in Fig. 5. It can be observed from

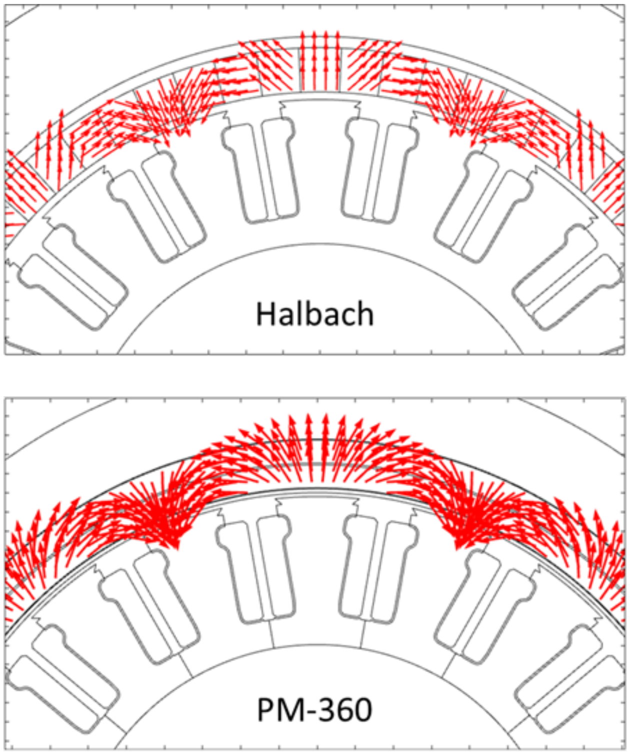

Figure 4: Magnetization comparison between Halbach and PM-360 rotors

these figures that a 16-pole ideal sinusoidal magnetic field pattern is achieved using this technology. It may be noted that the stator cross section remains the same in both designs and only the rotor is modified.

The performance comparison between the two types of machines is summarized in Table 2. It is seen that although the reduction in Br exceeds 40%, the reduction in torque output is only 25% indicating that the PM-360 technology may enable the use of lower cost, lower energy density permanent magnets. Such a performance improvement is in line with expectations. For instance, a 10% performance improvement was calculated using FEA when the discrete Halbach array was replaced with a continuous Halbach array for a motor designed for aeronautic applications [4] . The two motor configurations were also modeled using 3D FEA for validation.

In order to compensate for the reduction in torque output in the PM360 design, the PM-360 ring dimension is increased from 6mmx6mm to 10mmx10mm, leading to an active rotor outer diameter of 250mm, which is only a small increase from the active outer diameter of the N48 magnet-based discrete Halbach array baseline machine. The 8 PM-360 rings are composed of compacted powder inside a 0.25mm non-magnetic jacket.

V. Mechanical analysis

High-speed surface permanent magnet motors require retention in order to keep the magnets in contact with the rotor surface at high speeds as well as to maintain them under

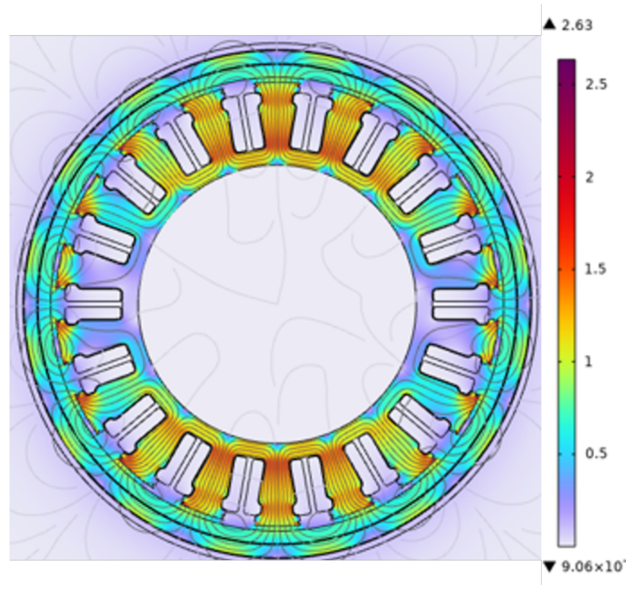

Figure 5: Magnetic field lines obtained from a 2D FEA model developed in COMSOL for the machine with the PM360 magnets

Operating point	Rated	Peak	Top speed
Current [A]	194	388	32
Torque discrete halbach array motor [Nm]	88	164	27
Torque PM 360 motor [Nm]	70	130	22

Table II: Performance comparison between the discrete halbach array and the PM-360 motors.

compression [5-6]. In this work in case of the conventional discrete Halbach array rotor, a carbon fiber wrapping on the outer diameter of the rotor case is required, similar to the high-speed motor discussed in [6]. Considering the fact that the Halbach array is realized from discrete magnets, some magnetic field is present at the back of the array. Thus, the rotor requires a magnetic back-iron which is laminated to minimize eddy current loss. Furthermore, the rotor case is made from high-strength steel to keep the Von mises stress limited. All these aspects together increase the overall diameter

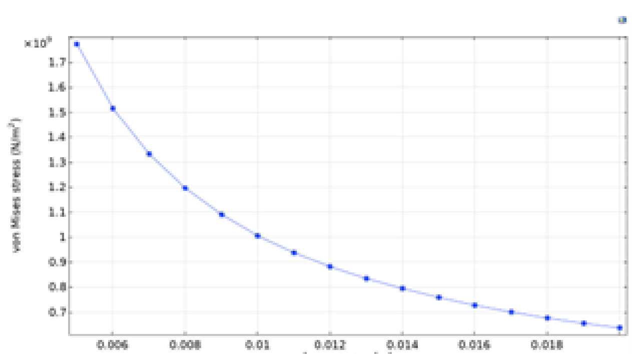

Figure 6: Parametric Study on the peak von misses vs overwrap thickness

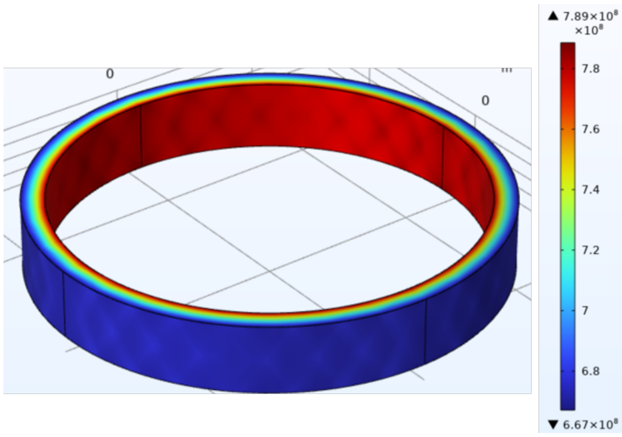

Figure 7: Von misses stress in the overwrap for the PM-360 rotors. The maximum and minimum limits of the scale are 0.8GPa and 0, respectively.

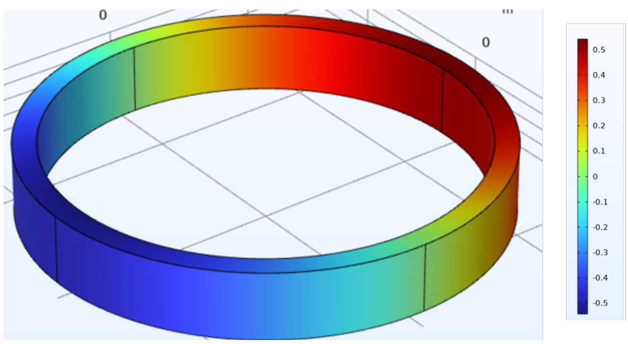

Figure 8: Radial deflections in the overwrap for the PM-360 rotor. The maximum and minimum limits of the scale are -0.5mm and 0.5mm, respectively.

of the motor including the casing and carbon fiber over-wrap.

In case of the PM-360 design, the permanent magnet volume was increased in order to match the torque of the baseline design. This lead to an increase in the machine active outer diameter. The PM-360 design results in a true Halbach array, thus minimum field is present at the back of the PM-360 magnets. Moreover, since the magnet powder is compacted and placed in a hollow steel jacket, no additional rotor casing is required. These aspects simplify the rotor mechanical assembly, thus reducing the overall diameter compared to the baseline discrete Halbach array design. An over-wrap on the steel jacket is used in order to reduce the stress in the rotor to an acceptable level. A 3D stress analysis was carried out to estimate the thickness and safety factor of the overwrap for the PM-360 design. The overwrap used is high modulus carbon fiber named M60J [7] and is commonly used in many industrial and aerospace applications.

A parametric study (Fig. 6) was performed to find the overwrap thickness that is associated with a safety factor of 2.5. Analysis shows a 14 mm overwrap is required with peak von misses stress of 0.8 GPa to hold the PM-360 magnets. The analysis assumes all the stress is taken by the overwrap whereas in reality the jacket of the PM-360 sees some stress as well. Figures 7 and 8 summarize the von misses stress in the overwrap and the radial displacements respectively. The outer diameter of the PM360 motor (with the overwrap) is 278 mm and thus, the overall motor diameter is comparable to the baseline discrete Halbach design.

VI. Conclusion

This paper compares motor performance when a discrete Halbach array rotor is replaced with a continuous Halbach array (PM wire). The discrete Halbach array is based on sintered N48 permanent magnets, while the continuous Halbach array utilizes bonded magnets. The PM-wire creates an ideal sinusoidal flux density in the airgap using very few concentric magnet rings. Even though the magnetic material used to manufacture the PM-wire has a 45% lower remanence, only a 25% reduction in torque output for the same volume is evaluated from 2D and 3D finite element analysis.

Increasing the PM-360 ring height by 40% and therefore the machine active outer diameter led to the same torque as baseline N-48 continuous Halbach design. However, owing to the simplified mechanical assembly of the PM-360 design due to the sinusoidal magnetic field and the rotor construction, the overall outer dimensions of machines are comparable. The PM-wire rotor uses bonded magnets which have virtually no eddy current loss and related heating. The use of this technology greatly reduces the number of discrete magnet pieces which would simplify manufacturing and complexity and eliminate performance degradation which is expected when multiple wedge shaped magnets are assembled together. Additional advantages with respect to magnet containment is seen for the PM-360 design. It is expected that this technology will enable high performance machines with reduced rare earth permanent magnet content

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