High Performance Machine Design Considerations

Abstract

From Formula One race cars to consumer vehicles, the demand for high performing, energy efficient motors is increasing. Technologies including thermal energy recovery systems and electrically assisted turbochargers, along with innovative materials, are allowing automotive manufacturers to meet this challenge.

This article will discuss design considerations and challenges for electric machines and how new materials can help improve their performance and efficiency.

Aaron Williams
Engineering Manager, Machine Applications
Arnold Magnetic Technologies

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Introduction

Every company is under pressure to improve their products. In many cases, that pressure is exerted by two separate entities – the customer that chooses to purchase the product and the regulators that determine what the product must do. Automotive manufacturers are challenged with balancing consumer demand for spacious, powerful and elegant vehicles with the demands from state and federal regulators for safe and fuel efficient vehicles.

Innovative materials are critical to answering this design challenge, and Arnold Magnetic Technologies can help.

Technologies such as hybridization and turbocharging can dramatically improve a vehicle's output power without adding much weight or cost. By improving the drivetrain's power density it is now possible to use a smaller displacement internal combustion engine. The smaller displacement engine is more fuel efficient, but overall system performance matches that of its larger displacement relatives.

Arnold Magnetic Technologies is focused on delivering smaller, more efficient and more powerful products. This requires developing new materials as well as testing these materials in demanding applications. One example of this benchmarking is a high speed motor for a vehicle drivetrain. In the following sections we'll see how Arnold materials improve this machine's performance.

High Speed Machine Design Considerations

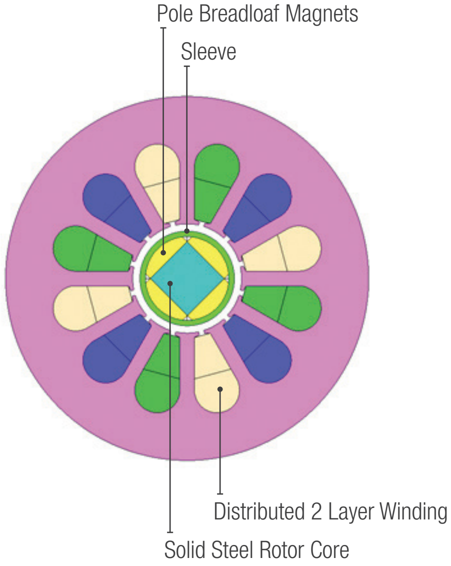
Typically, high speed electric machines will use a Surface Mounted Permanent Magnet topology (SMPM), which offers the following advantages:

- High torque/inertia ratio
- Simple construction
- Highest torque density
- Good torque control
- Common drive topology

For our example, we'll use a four pole SMPM topology with a rated output power of 15kW at 75,000rpm. Since this is an automotive application, we'll assume this machine operates with a 48 Volt DC bus. To keep the design simple, we'll use a 1x1 aspect ratio between the stator outside diameter and the rotor height. The machine is shown in **Figure 1**.

Figure 1 – Typical four pole Surface Mounted Permanent Magnet Machine.

Pole Machine Configuration



Machine Characteristics

Geometry Configuration
12 Stator Slots
4 Rotor Poles
Rotor Magnet OD = 23mm
Stator ID = 30mm
Stator OD = 100mm
Rotor/Stator Height = 100mm

Winding
1 Turn per Coil
2 Parallel Paths
Phase Resistance = 0.0002 Ohms/Phase

Excitation
Rated Current = 470Apk
Switching Harmonics at 10x and 20x Fundamental
DC Bus Voltage = 48 Vdc
Rated Torque = 2.1 Nm
Rated Speed = 75krpm

The design challenges for Permanent Magnet (PM) motors in high speed applications include:

- High centrifugal force on surface permanent magnets
  - A rotor sleeve is necessary
  - Metallic sleeves will have eddy current losses
- Magnet design
  - Trade-off between price, size and quality
  - Risk of demagnetization at normal operating temperatures
- Iron losses in the laminated steel components
  - Must use low loss laminated steel

These challenges can be overcome through the use of innovative designs utilizing high performance materials.

Rotor Configuration for High Speed Operation

The rotor and stator design should be as simple as possible. A simple design has many benefits in terms of manufacturing; however, these have to be weighed against overall performance targets. The four pole design from **Figure 1** will help us understand the tradeoffs between manufacturing and performance.

Minimizing harmonics is critical to achieving high performance. The example machine has relatively low spatial harmonics in the stator and rotor. **Figure 2** shows the flux density on the surface of the rotor sleeve and the Back EMF waveform from the stator.

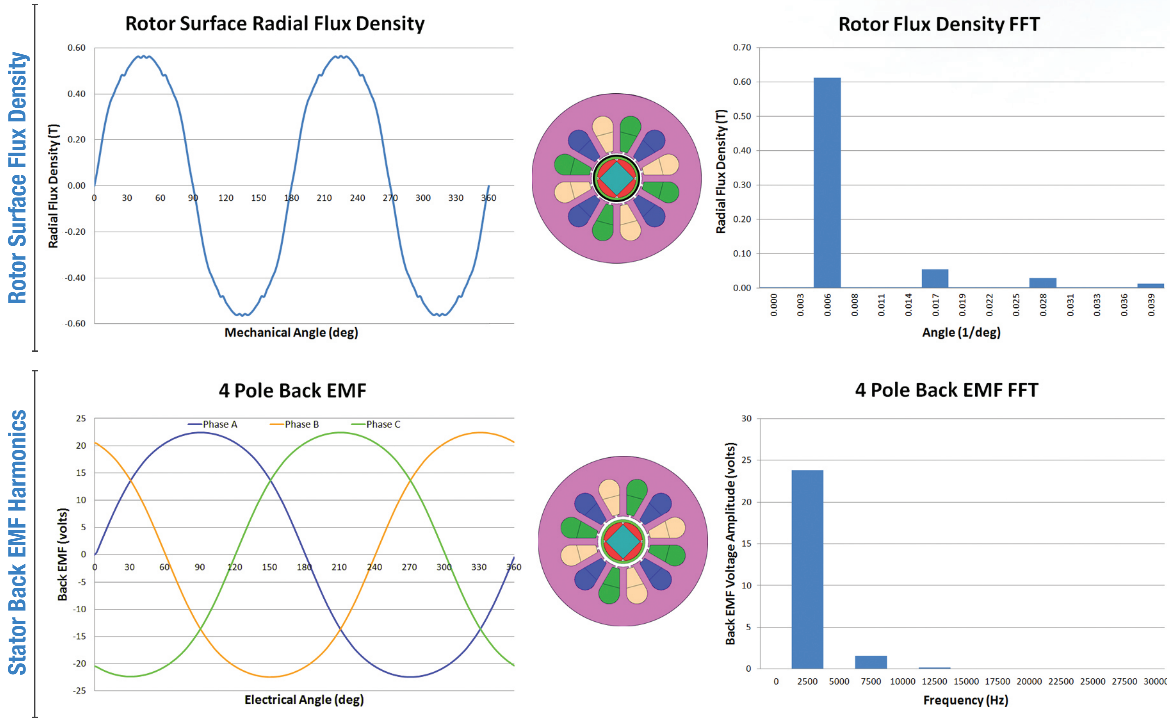


Figure 2 – Spatial harmonics in the rotor and stator.

The stator Back EMF shows some harmonic content. This can be reduced by changing the stator configuration to add more slots and/or change the winding configuration. At this point, we can consider the stator design good enough for this example.

The purpose of the rotor sleeve is mechanical in that it is meant to contain the magnets at high speeds. But its location indicates that it is a part of the flux path between the rotor and stator. If the sleeve is conductive, it will generate eddy current losses.

The primary purpose of the magnet sleeve is to contain the magnets on the rotor, but at the same time you need to consider the sleeve's proximity to the stator's inside diameter. **Figure 3** shows four different air gap thicknesses. For now, we'll ignore the structural requirements of the sleeve and hold the magnet outside diameter constant.

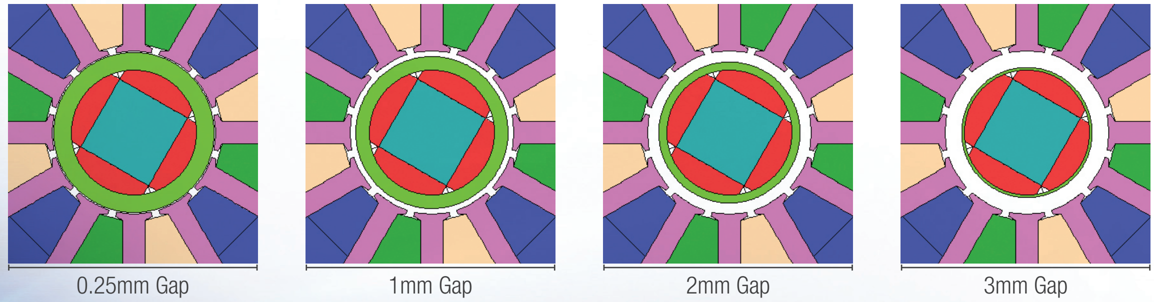
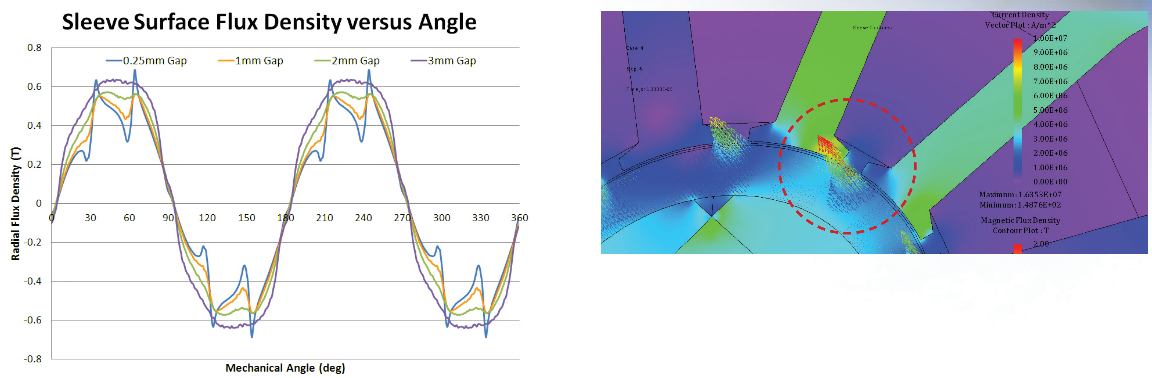


Figure 3 – Four different sleeve thicknesses.

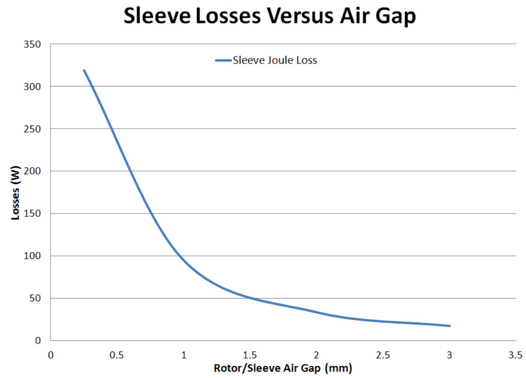
Flux density distortions increase as the sleeve surface moves closer to the stator slots. Higher flux distortions lead to higher eddy current losses, shown in **Figure 4**.

Figure 4 – Air gap flux density on the rotor sleeve surface. Slotting effect highlighted in red.



The flux density distortion is due to the slotting effects. The flux density waveform's amplitude doesn't change much since the sleeve's permeability is close to that of air. But, as shown in **Figure 5**, losses grow exponentially as the gap between the sleeve and stator shrinks.

Figure 5 – Sleeve Eddy Current losses versus sleeve thickness.

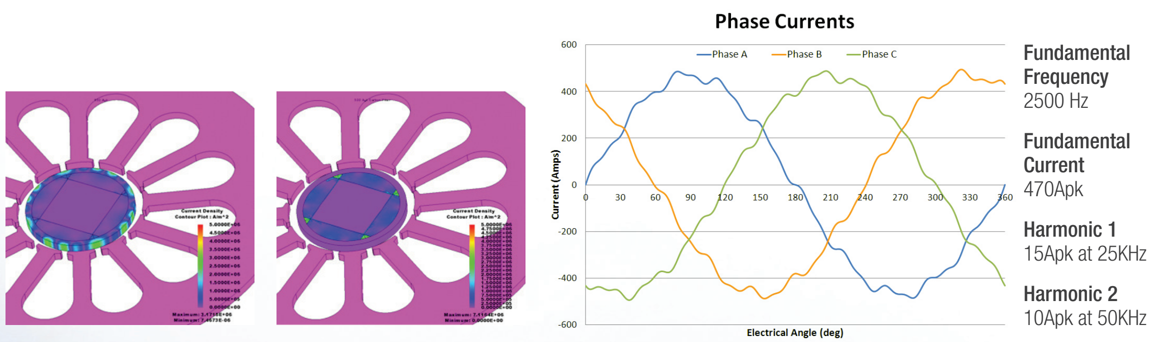


Carbon fiber sleeving like Wraptite can eliminate eddy current losses.

However, by using a non-magnetic material such as Arnold's Wraptite carbon fiber sleeving, you can eliminate these eddy current losses in the rotor sleeve. Using a carbon fiber sleeve means the gap between the sleeve surface and the stator surface is only a function of mechanical tolerance requirements. Carbon fiber is also less dense than steel, so it results in better balance and rotor dynamic characteristics. The low density also provides higher containment capability since it reduces self-induced stresses at high RPM.

It is important to consider total rotor losses when comparing a carbon fiber sleeve to a steel Inconel sleeve. An Inconel sleeve will act like a shield and reduce the losses on the rotor magnets/core. But the carbon fiber sleeved rotor benefits from the magnets/rotor core being further away from the stator slots. **Figure 6** shows the current density in the rotor based on a stator excitation with switching harmonics.

Figure 6 – Current density on the rotor surface with Inconel or Carbon Fiber sleeve.



Current Density with Inconel Sleeve

Current Density with Carbon Fiber Sleeve (higher losses on the magnets)

Stator Excitation Current with simulated switching harmonics.

80% reduction in rotor losses with carbon fiber & laminated magnets.

Shifting the rotor losses from the sleeve to the magnets can increase the magnet joule losses; however, this effect can be reduced by using laminated magnets. The rotor height in our 4 Pole design is 100mm. Instead of using a single magnet in each pole, we can stack fifty 2mm tall magnets to achieve the same height. This stacking will create air gaps within the magnet structure, which will reduce output torque by 1%, but it will also reduce magnet losses by 66%.

The end result is significantly lower losses in the rotor. Using a Wraptite carbon fiber sleeve along with a laminated magnet will provide the necessary structural performance and reduce rotor losses by 80%. A final benefit of switching to carbon fiber is the ability to use a smaller rotor/stator air gap since sleeve loss is no longer a concern.

Magnet Options

The elevated temperatures of a vehicle drivetrain require magnets with superior resistance to demagnetization. In most cases, this necessitates the use of Samarium Cobalt based magnets. The thermal demagnetization for SmCo magnets is much lower than for Neodymium based magnets. (Reversible Temperature Coefficients of .035%/C° for Samarium Cobalt versus 0.10%/C° for Neodymium.) **Figure 7** shows the remnant flux density (Br) versus temperature for different magnet materials and grades. Even though the Neodymium magnet has a higher residual field strength at room temperature, it quickly crosses the SmCo line.

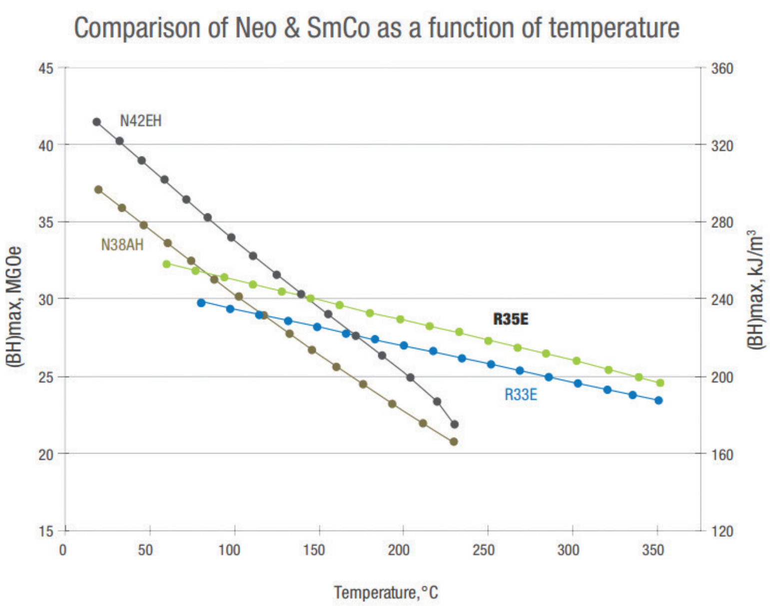


Figure 7 – Magnet remnant flux density versus temperature.

A four pole motor is meant to operate inside a vehicle's engine compartment, which can have an ambient temperature anywhere between -40°C and 125°C. This can lead to temperatures over 180°C inside the machine. Having to design around this temperature range leads to large performance differences in the magnet properties. In other words, a machine operating at room temperature will have more torque than a machine operating at 180°C for the same amount of input current.

The smaller demagnetization value of Samarium Cobalt magnets compared to Neodymium magnets results in much flatter operating characteristics across a temperature range. Temperature stability leads to stable output performance from a four pole machine as shown in **Table 1**.

Table 1 – Output torque versus temperature for Samarium Cobalt or Neodymium magnet rotors.

	Neodymium 38EH Magnets	Samarium Cobalt R35E Magnets
Average torque at 20°C	2.3Nm	2.14Nm
Average torque at 180°C	1.86Nm	1.99Nm

A machine using Samarium Cobalt magnets in the rotor will have a more consistent output torque at different temperatures. This makes the machine's performance more predictable and leads to higher efficiencies across the operating range.

Electrical Steel Options

At the rated speed of 75,000rpm, the four pole machine's fundamental electrical frequency is 2500Hz. At this frequency, joule losses inside the stator electrical steel can be a significant loss driver. In **Figure 1** we saw that the stator had very low harmonic content in its Back EMF waveform which will help reduce iron losses in the stator tooth and back iron. Unfortunately, a typical machine drive will add high frequency harmonics due to PWM switching as shown in **Figure 6**. And the stator slotting effect shown in **Figure 4** will increase iron losses on the stator tooth tips. All these factors contribute to iron losses and must be accounted for.

Figure 8 shows the iron loss density in the stator is most concentrated on the tooth tips and the tooth body.

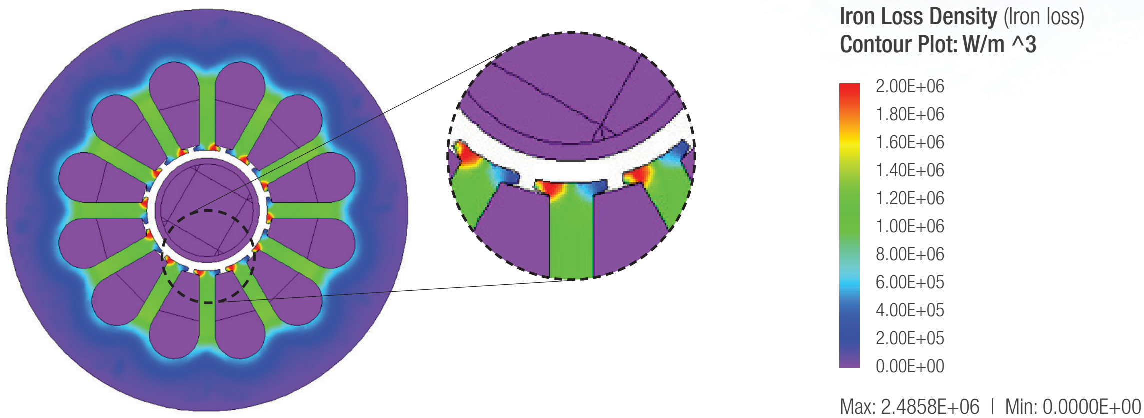


Figure 8 – Iron loss density in the whole stator and on the tooth tips at rated operating point.

Reducing iron losses in the stator requires a low loss lamination steel. Typically, lamination steel thicknesses range between 0.30 and 0.5mm; however, Arnold provides much thinner lamination steels. Arnold's Precision Thin Metals Division manufactures a line of thin gauge non-oriented silicon steel specifically for high frequency motor applications, Arnon® 5 (0.127mm thick) and Arnon® 7 (0.178mm thick). Our non-oriented silicon steel materials reduce losses and increase efficiency by limiting eddy currents.

Typical machines would use a lamination steel similar to a 29 Gauge M19. If the four pole machine used Arnold's Arnon® 5 in the stator, it would reduce its iron losses by 65%. This reduction in losses would lead directly to an increase in efficiency.

Summary

Innovative materials can have a measurable impact on automotive performance. Arnold Magnetic Technologies has an array of materials and manufacturing techniques to help you improve your product's performance. Arnold's carbon fiber sleeving will reduce rotor losses and improve rotor dynamics. Our RECOMA® SmCo magnets have better temperature stability than typical Neodymium magnets. Arnon® thin gauge lamination steel has significantly lower losses as compared to standard gauge electrical steels.

*We can also help you understand how to best utilize these materials in your design. Learn more about Arnold's performance materials at **arnoldmagnetics.com**.*