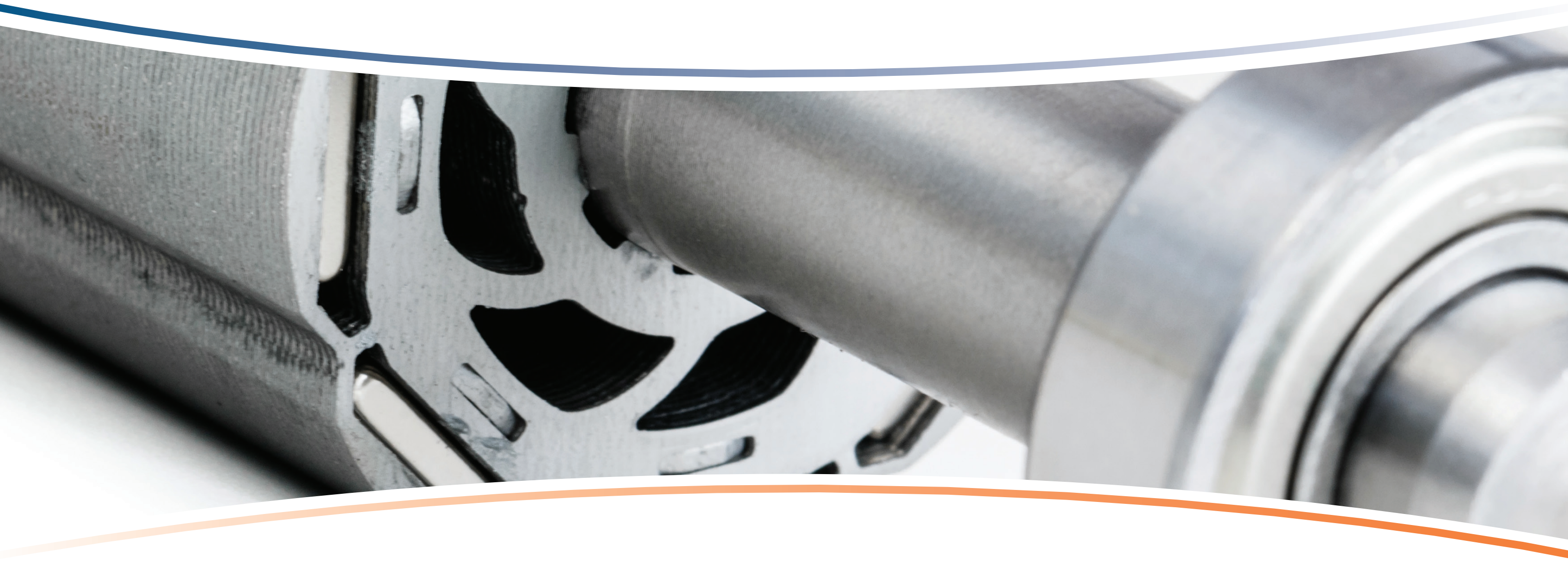

Magnet Retention in Permanent Magnet DC Motors – Part I

Introduction and Overview

For more than 50 years, **Windings** has provided engineered electromagnetic solutions for critical applications in Aerospace, Defense, Automotive and Oil & Gas industries. As a full-service provider, Windings is a leader in the design, test, manufacture and support of custom electric motors, generators and related components including rotors, stators, lamination stacks and insulation systems.

From Induction to Permanent Magnets

For decades, alternating current induction motors (ACIM) have provided the driving force for commercial and industrial applications. These asynchronous motors feature simple and robust designs, require little maintenance, function reliably in a range of uses, require very simple electric starters/contactors to operate, and are inexpensive to manufacture. Asynchronous rotors are cast; the magnetic field necessary to oppose the electromagnetic field generated in the stator winding is induced in the rotor. No permanent magnets are used. But ACIM have limitations: Single phase ACIM have low starting torque, are relatively inefficient under lighter loads, and are acceleration-limited due to inherently high rotor inertia.

As demand increased for higher motor acceleration, power density, and overall efficiency, motor manufacturers have turned to synchronous motor designs. Permanent magnet synchronous motors (PMSM) incorporate permanent magnets to supply the necessary opposing magnetic field. This significantly increases torque density and efficiency, particularly during acceleration, by eliminating the extra current required to induce the magnetic field.

Initially, PMSMs were configured with permanent magnets adhered to the inside of the motor housing and electromagnetic windings fixed to the rotor. This configuration, commonly referred to as a brushed DC motor, uses carbon brushes and a copper commutator to feed electrical current to the rotor windings. Brushed DC motors share the ACIM benefits of simple and robust designs, simple electric starters/contactors for operation, and low manufacturing costs. They also share the drawback of limited acceleration due to high rotor inertia and have higher maintenance requirements due to constant wear on the carbon brushes during operation.

Continuing customer demand for higher acceleration, as well as for point-to-point positioning and more accurate position control, spawned the development of brushless DC (BLDC) motors. An inversion of the brushed DC configuration, BLDC motors feature permanent magnets mounted to the rotor and electromagnetic windings fixed to the inside of the motor housing. Locating the permanent magnets on the rotor significantly reduces rotor inertia, enabling higher acceleration. The downside to this approach is the need for a rotor position feedback device and complex external electronics to track rotor position and manipulate current in the stator windings to produce the desired motion output. Higher performance came with higher overall system cost and complexity, and concern over magnet retention—especially at high rotational speeds.

Properties of Magnetic Materials

Permanent magnet material selection significantly affects the overall performance of a BLDC motor; it is one of the most critical decisions an engineer makes during the design process. Magnetite, a naturally occurring iron ore, has the highest magnetism of any mineral, but has limited magnetic strength. Ceramic ferrites—alloys of iron oxide with barium, manganese, nickel, or zinc—can be magnetized; and aluminum, nickel, and cobalt (alnico) alloys have even stronger magnetic properties.

In the 1960s, scientists at the US Air Force Materials Laboratory alloyed yttrium and cobalt to create the first rare earth magnets, stronger than even alnico. Further research resulted in combinations of neodymium and samarium–cobalt. These component minerals are called rare earth not because they are scarce, but because they are diffuse and difficult to mine in quantity.

In addition to cost, rare earth magnets have two serious drawbacks: They are brittle and vulnerable to corrosion. To reduce the risk of damage or disintegration, these magnets are often plated or coated with more durable materials such as nickel-copper-nickel. Also, at extremely high temperatures, even rare earth magnets can become demagnetized.

Despite these limitations, rare earth magnets are the key to high power density and efficiency in electric motors. No other material helps generate as much output with the same energy inputs. So holding those magnets in place becomes a critical consideration for design engineers. To optimize performance, the designer must keep the magnets as close as possible to the stator windings; minimizing the air gap between the rotor and stator will maximize torque. The drawback is that as the air gap decreases, manufacturing difficulty increases in a non-linear fashion.

Surface and Interior Mounting

Stricter government standards for electric motor efficiency have put tremendous pressure on ACIM manufacturers. Initial efforts to increase efficiency were focused on magnet wire material and rotor designs, followed by the use of external variable frequency drive electronics to control acceleration and minimize inrush current during startup. More recently, ACIM designers have incorporated permanent magnets in rotor designs to further boost electrical efficiency. These modern ACIM configurations embed the permanent magnets into a stack of magnetic steel laminations bonded to the rotor. This configuration is called an interior permanent magnet rotor. Because the magnets are captured within the rotor lamination stack, there is little concern over magnet retention.

Unlike the ACIM configuration, permanent magnets in a BLDC motor are bonded to the outside of the rotor, a configuration called a surface permanent magnet rotor. Surface mounted magnets need to be held in place with a very strong and reliable adhesive to prevent movement or breakage of the magnets during operation, complicating design requirements and adding to manufacturing costs—but surface magnet rotors offer higher performance characteristics than interior magnet rotors.

Evolution of Design

In the publication *IEEE Transactions on Industry Applications* in 1996, authors Michael W. Degner, Richard Van Maaren, Azza Fahim, Donald W. Novotny, Robert D. Lorenz, and Charles D. Syverson outlined the problems of magnet retention on high speed rotors:

> *"The advent of high-energy product, rare-earth permanent magnet materials has brought about a resurgence in the use of permanent magnets to provide the field excitation for electric machines. The rare-earth permanent magnet materials allow machines of very high efficiency and energy densities to be built. The use of permanent magnets to provide the field excitation in an AC generator reduces the size and complexity of the generator. The slip rings and field excitation no longer have to be provided, and the high energy density of the permanent magnets allows the size and weight of the alternator to be reduced. One of the most important issues in the design and manufacturing of any permanent magnet machine is the method used to hold the magnets in place and to prevent them from flying off during operation due to centrifugal forces."*

The authors clearly describe the options design engineers had at the time:

> *"Gluing or banding the magnets in place increases the cost and complexity of the manufacturing process, whereas, burying the magnets increases the magnet leakage flux and the complexity of the magnetic design and model."*

At higher performance levels, adhesive alone was not enough to retain the position and integrity of surface mounted magnets for the expected life of the motor. Motor designers gradually took a "belt and suspenders" approach to magnet retention and started wrapping the rotor assemblies, known as "roving," with various materials to secure the magnets in place should the glue bond fail. Common materials used for banding or roving included fiberglass, Kevlar, and Inconel. These materials provided added protection and in many cases extended the life of the motor, but they were still vulnerable to failure in demanding applications involving high speeds or high temperatures. The authors went on to recommend the latter method, a buried magnet design:

> *"A major problem in the design and manufacturing of surface mounted permanent magnet machines is reliably holding the permanent magnets in place at high speeds.*

> *This paper evaluates a unique rotor lamination design for a high pole number, permanent magnet alternator. This buried magnet design, which is capable of reliably holding the permanent magnets in place at high speeds, offers both easier and cheaper assembly when compared with the methods currently used in surface mounted permanent magnet machines. Finite element analysis is used to compare the buried magnet design with equivalent surface mounted designs and shows that the performance of the alternator is not significantly affected by the iron over the magnets."*

Finally, the authors suggest possible design improvements to reduce lamination complexity:

> *"Another possibility … is the use of a solid 'can' made of either magnetic or nonmagnetic material to surround the surface mounted magnets and hold them in place. A magnetic 'can' of course increases the potential for leakage flux and core losses due to its high permeability and low resistance, but it is cheaper and mechanically stronger than many of the nonmagnetic options. To prevent the magnets from becoming loose at high speed the 'can' or banding have to be pre-loaded when put in place. The pre-loading can be achieved by the use of thermal expansion and cooling in the case of a 'can,' or the stretching of the banding as it is applied over the permanent magnets."*

This recommendation pointed the way for much of the development that has happened since. Here is a brief description of some of these retention methods:

Magnet Retention Slots

In 2001 and 2002, inventors John Weiglhofer, Stewart Peil, and Pieter Van Dine of the Electric Boat Corporation filed patent applications for two methods of retaining permanent magnets in high speed rotors. Both used channels in the rotor surface to keep the magnets in place. The first, U.S. Patent 6492754, was titled "Magnet retention channel arrangement for high speed operation." The second, U.S. Patent 6548932, was titled "Nonmagnetic magnet retention channel arrangement for high speed rotors." Apart from the difference in magnetic properties of the channel material, the two designs had very similar descriptions.

In 2008, Hamilton Sundstrand (now part of Collins Aerospace) filed a patent for retention of permanent magnets in rotors. Titled "Magnet retention system for permanent magnet motors and generators," it described a design with slots in the rotor that held the flanged lower edges of permanent magnets. Each retention slot had a base that extended axially into the rotor flange, a pair of side walls that extended from the base, and a pair of lugs that projected from the side wall to hold the magnet both radially and tangentially. A spring pre-loaded axial retention ring also helped keep each magnet in place.

Magnet Retention Wedges

In 2015, inventors Petri J. Maki-Ontto, Fredrik Boxberg, and Esa H. Vikman, representing the Ingersoll-Rand Company, filed a patent application for a design that uses wedges to hold permanent magnets in place. The function is similar to that of the channels and slots listed above. Titled "Fixation System for a Permanent Magnet Rotor," the design was described as follows:

> *"A fixation system that is structured to secure one or more permanent magnets to a rotor core. The fixation system may include one or more retention wedges that exert an interference or press fit against the permanent magnets to secure the permanent magnets to the rotor core. At least a portion of the retention wedges may be secured within axially extending channels in the rotor core. Additionally, the permanent magnets may be separated from each other by eddy current shields, which may also be retained in position by the retention wedges. The fixation system may also include a magnet pressure or fixation sleeve that exerts a radially inwardly directed force against the magnets and is free from direct contact with the retention wedges."*

Magnet Retention Sleeves

Engineers were already experimenting with encapsulating sleeves when Degner et al made their recommendation. Manufacturers have tried wrapping permanent magnet rotors in materials that range from nonmagnetic alloys to carbon fiber, with varying degrees of complexity and cost.

Robert Cole, representing the A.O. Smith Corporation, was granted U.S. Patent 4,855,630 with the title “Permanent Magnet Rotor with Magnet Retention Band” in 1989. He described the design, in part, as follows:

> *“A rotor structure for a dynamoelectric machine including a magnetic core having a cylindrical outer surface. Equicircumferentially spaced permanent magnets are secured to the face of the core with gaps therebetween on diametrically opposite locations of the core. The outer surfaces of the magnets define a cylindrical surface. A retention band encircles the magnets. The band has a width substantially less than the width of the magnets including opposite ends overlapped and aligned with a securement gap.”*

This is similar to more recent sleeve designs; the most significant difference has been the materials chosen with each iteration. In 2019, Co Huynh of Calnetix Technologies described the current state of material options this way:

> *“There are two primary technologies of magnet retention in high speed permanent magnet machines, namely high-strength non-magnetic metal sleeve and a proprietary advanced graphite-composite sleeve. Each offers unique advantages to the system and motor/generator performance. The metal sleeve can be designed to provide some stiffness to the rotor structure. It also acts to effectively shield the magnets from stator’s harmonic currents. Eddy currents generated in the metal sleeve due to [the] stator’s harmonic currents and stator slotting impede high frequency fields from penetrating the magnets and generate losses. Most of the absorbed energy in the metal sleeve readily dissipates to the cooling medium in the airgap and the rest is conducted to the magnets and/or end supports. Carbon fiber sleeves are significantly stronger and lower density than their metal counterparts thus allow the use of more magnet mass or thinner sleeve for similar magnet volume. The result is smaller magnetic gap and better magnetic performance with carbon fiber sleeve. However, they do not provide any harmonic filtering. Moreover, due to their low thermal conductivity they act as thermal barriers to heat generated in the magnets. Rotor loss reduction and management techniques such as segmenting magnets or conductive layer shielding can be employed to enhance system performance when using carbon fiber sleeves.”*

Summary

In the time between Robert Cole’s patent and the state of the industry described by Co Huynh, permanent magnet motors have become ubiquitous in advanced machines. As engineers design equipment for demanding environments, they value the high torque, high efficiency, and low maintenance requirements of permanent magnet motors. Magnet retention remains a challenge, particularly as performance demands continue to escalate.

For now, leading manufacturers will offer metallic sleeves in materials such as 300 CRES stainless steel, A286 iron-nickel-chromium alloy, and Inconel superalloys—and in thermoplastic, thermoset, and high-strength carbon fiber, according to the requirements of each machine design.

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