By Tony Morcos, President • ACM Magnetics

The Magnetized Tail Wags the Motorized Dog

Increasing the efficiency of the conversion of electrical energy to mechanical energy (motors) and mechanical energy to electrical energy (generators) is a powerful and necessary tool for meeting the ever-growing energy demands on planet Earth. Because permanent magnets, steel and copper are the fundamental ingredients of electromechanical energy conversion, these materials deserve a closer look. As a designer of electromagnetic devices, I use these materials as components to manipulate electric and magnetic fields to create motion, harness motion, sense motion or prevent motion. I am always trying to think of ways to integrate these materials in new and more efficient configurations to best utilize their strengths while minimizing the effects of their weaknesses. I find the biggest limitation to my creativity is that available magnet shapes dictate the magnetic circuit designs for permanent magnet motors, generators and sensors — not vice versa. With few exceptions, the rule is current manufacturing techniques provide a very limited number of shapes and range of sizes for permanent magnets. It is the exceptions to the this rule that provide a new window of opportunity to think outside the box.

The magnetic circuit designer typically employs either sintered ferrite or sintered NdFeB as a first choice, because these magnets provide the most magnetic flux per unit cost. The high "flux per bucks" of both sintered ferrite and sintered NdFeB is because both are fully dense and are anisotropic, meaning they provide maximum properties along a given axis of orientation. Unfortunately, the manufacturing of anisotropic sintered magnets severely limits the available sizes and shapes of such magnets for the following reasons. The pressing process limits the shapes of sintered magnets to disks, donuts, block, arcs or rings. The orientation process, where the magnetic particles are pressed under the presence of an aligning magnetic field, limits the pole configurations on these simple magnet shapes. The high-temperature sintering and annealing processes severely warp and deform the pressed magnet, so that these simple shapes must still be machined to final dimensions, usually via grinding with a diamond wheel. Magnet size is limited by press tonnage, and large blocks of sintered NdFeB have the added complication cracking because of a coefficient of thermal expansion (CTE) mismatch parallel and perpendicular to the magnetic axis of orientation. Therefore, large sintered magnet blocks or arcs for large machines must be pieced together from smaller pieces, either before (preferably) or after magnetization.

The size and shape limitations of sintered magnets severely limit the geometric configurations of permanent magnet devices. Most permanent magnet motors employ sintered magnet arcs with a simple magnetization pattern that is difficult to tailor. The most useful magnet shape for permanent magnet motors is a radially-oriented ring. Unfortunately, this shape and orientation of magnet is the most difficult type of anisotropic sintered magnet to manufacture. Expensive tooling is required to produce such rings, severely limiting the options of the motor designer when developing the product. The typical alternative to radially oriented rings is to approximate the ring with a series of arc segments. This is a labor-intensive process, with a myriad of assembly complications, especially when trying to piece together pre-magnetized arcs.

Fortunately, there are other permanent magnet material options available to allow greater design flexibility for permanent magnet devices. These alternate magnet choices tend to have lower magnetic properties because they are "bonded" (i.e., not fully dense) and they are (sometimes) isotropic, with no preferred direction of orientation. Below, I present a few such bonded magnet options, in order from lowest to highest magnetic flux density.

Flexible ferrite magnets are a versatile tool, with capabilities far beyond holding your refrigerator door closed. Available in strips and sheets of various thicknesses, these magnets are typically anisotropic through the thin direction. Such magnets are well suited for the emerging market to replace low-efficiency single-phase FHP induction motors with more efficient permanent-magnet DC motors. They can be easily magnetized with relatively inexpensive equipment, and their mechanical properties allow them to be shaped into varying diameters to produce a radially-oriented ring. With flexible ferrite magnets, a family of permanent magnet DC motors of varying diameters and outputs can be developed using a single roll of flexible ferrite material.

Injection-molded (IM) ferrite is another powerful tool for the magnetic circuit designer. This type of magnet is typically anisotropic, with the material aligned and magnetized during the molding process. The injection molding of ferrite permanent magnets is a net-shape process, producing tight tolerances with no secondary operations necessary. This material allows complex shapes and pole patterns, the capability to produce thin-walled rings and vary small magnets which may not be possible with other magnet materials. Permanent magnet pump rotors, which incorporate mechanical features of the impeller into the rotor magnet, are a good example of an "outside the box" application for this material. As I stated in a previous article, several clever generator designs employ IM ferrite permanent magnets to boost the output of what would typically be a non-permanent-magnet machine.

Rubber-bonded flexible NdFeB magnets pack a considerably greater magnetic wallop than their ferrite counterparts, while still providing the mechanical properties which allow them to be shaped into varying diameters to produce a radially-magnetized motor ring. Flexible NdFeB magnets, like all other types of bonded NdFeB, are truly isotropic. This means that magnetic pole patterns are limited only by the magnetizing process, and not by the manufacturing process. Rubber-bonded NdFeB magnets have the unique combination of being isotropic and mechanically flexible, which provides the unique opportunity to simply fabricate motor rings with near-perfect Halbach magnetization, allowing for very high-efficiency permanent magnet motors.

Likewise, injection-molded NdFeB magnets provide the same advantages of injection-molded ferrite with considerably higher magnetic properties. Because bonded NdFeB is isotropic, the injection mold tooling for NdFeB is much simpler than that for anisotropic IM ferrite. There are several brushless permanent magnet motor and generator topologies which shoot molded NdFeB into imbedded cavities in the rotor assembly, with magnetization in directions that would be difficult or impossible to achieve with an anisotropic magnet. These hybrid magnetic circuit designs are capable of producing extremely high efficiencies over a wide speed range, making injection-molded NdFeB a strong candidate for both wind turbine generators and hybrid electric vehicle drives.

While sintered ferrite and sintered NdFeB magnets will continue to be the workhorse materials for most permanent magnet motors, generators and sensors, the limitations on the available sizes and shapes of such magnets shackle the magnetic circuit designer. The bonded magnet alternative I describe above provide the designer valuable tools to more effectively harness the strengths of copper, steel and permanent magnets to energize the world.

Tony Morcos has more than 25 years of experience in permanent magnet manufacturing and electric motor/electromagnetic device design and manufacturing. Mr. Morcos has a B.S. and M.S. in Electrical Engineering from the University of Dayton. He can be reached at tonymorcos2@nc.rr.com.