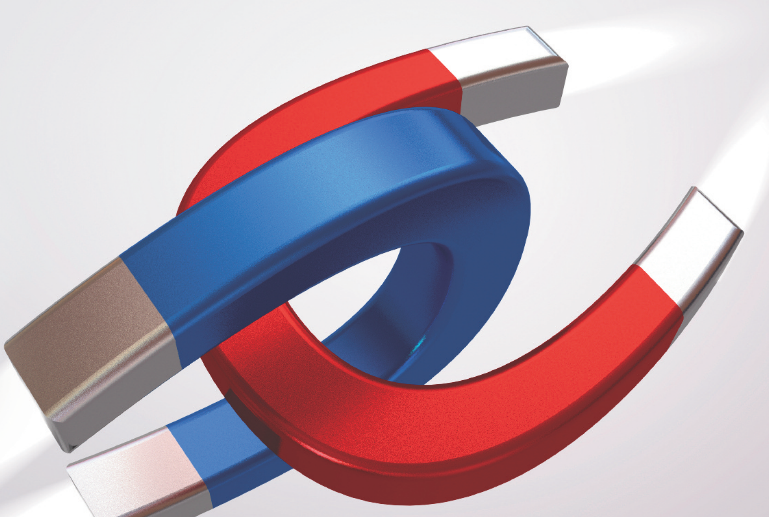
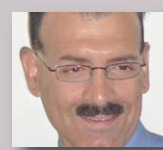


Magnet choices can have permanent benefits

Using advanced permanent magnet materials can result in smaller, lighter and more efficient motors. But, as Dr Sab Safi of SDT-Drive Technology* explains, there are many factors to consider when choosing PM materials.



Permanent magnets have been a key component of motors since the first experiments on rotating electromagnetic machines by Faraday and Barlow in the early 19th century. The development of practically useful permanent magnet (PM) motors began in around 1900 and improvements since then have been driven mainly by the development of better magnet materials.

In the past decade, however, interest in PM machines has been increasing as a result of advances in power electronics and their control. Today, PM machines are used in a wide variety of applications, from motors in watches to direct-driven windpower generators and ship propulsion drives.

The single most important advance in PM motor technology was the introduction of stronger magnet types, known as rare-earth materials, in the mid-1970s. Samarium-cobalt – and, to a lesser extent, neodymium – have replaced aluminium-nickel-cobalt (Alnico) and ferrite materials in many motors. The magnetic characteristics of PM machines depend on the properties of the magnet material used. A basic knowledge of the PM materials is thus essential.

Understanding PM materials begins with an understanding of hysteresis loops. These loops (or B-H curves) describe the cycling of a magnet in a closed circuit as it is brought to saturation, demagnetised, saturated in the opposite direction, and then demagnetised again, under the influence of an external magnetic field (see Fig 1).

The second quadrant of the B-H curve, commonly referred to as the "demagnetisation curve", describes the conditions under which permanent magnets are used in practice and shows the most important characteristics of the relation between Br and –Hc – the points at which the curve intersects the B and H axes. Br is the residual induction or the remaining magnetism retained by the material when the magnetising field is zero. HC (the coercive force) is the point at which the magnet becomes demagnetised under the influence of a strong externally applied magnetic field (created by a coil), opposite to the magnetisation direction.

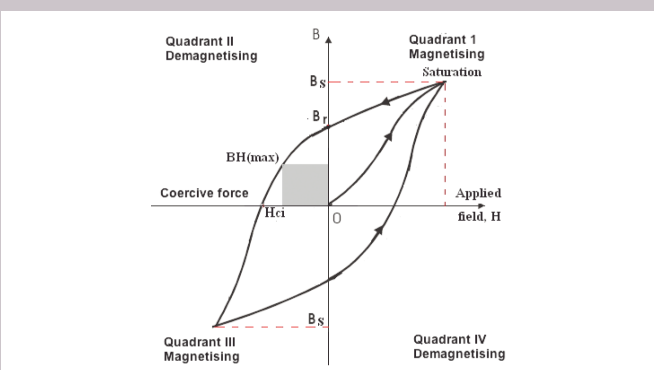


Fig 1: The hysteresis loop (B-H curve) for permanent magnet materials

It can be shown that when a piece of PM material is part of a magnetic circuit, the magnetic field generated in an air-gap in the circuit is proportional to B x H x volume of the magnet. To obtain a given field with minimum magnet volume, B x H must be maximum. The maximum BH value is useful when comparing the characteristics of materials.

> Magnetic history

The original PM materials were steels but these have been superseded by better and more stable materials, including barium ferrite (also called ceramics), Alnico, samarium-cobalt (SmCo), and the bonded rare-earth material, neodymium-iron-boron (NdFeB).

Alnico alloys were used in PM machines from the mid-1940s until about 1970. They have high magnetic remanent flux and low temperature coefficients, but low coercive forces and the extremely non-linear demagnetisation curves.

Ferrites were invented in the 1950s. They have a higher coercive force than that of Alnico, but they have a lower remanent magnetic flux density. They have a low cost and a high electric resistance, not having eddy-current losses in the PM volume.

Rare-earth alloys, developed over the past three decades, have increased energy densities considerably. The first generation of the SmCo PMs had high remanent flux densities, high coercive forces, high energy products, linear demagnetisation curves, and low temperature coefficients. Their only disadvantage was their high cost, due to the limited supplies of samarium and cobalt.

A second generation of rare earths is based on the much more abundant neodymium (Nd) and iron. Although NdFeB magnets have better properties than SmCo, their demagnetisation curves are temperature-dependant and they are susceptible to corrosion. The maximum BH values that can be achieved with rare-earth alloys are 4–6 times greater than those of Alnico or ferrite.

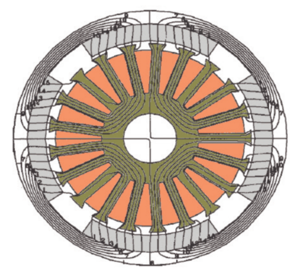


Fig 2: Finite element analysis can reveal details of PM motor performance

Fig 3: The relative sizes of similarly rated ferrite (left) and rare-earth (right) permanent magnet motors.

> No copper losses

Advantages of using PMs on the rotor instead of coils include: the absence of copper losses resulting from currents flowing through coils; the avoidance of windings and copper wires; and simpler, cheaper and more compact field assemblies with fewer parts. The disadvantages are that there is little or no field control, and the materials may be difficult to machine and can cause demagnetisation problems. The choice of magnets is important because they have a powerful influence on the performance of the motor.

Typical properties of PM materials commonly used in electric machines are listed in the table. Each material offers one or more reasons to consider its use. There are obvious design and performance tradeoffs involved in selecting PM materials, including the shape of normal curve and the operating temperature.

Permanent magnets demagnetise when they become too hot or when a strong reverse field is applied. The latter occurs when a stall current is supplied to a PM motor. As the temperature rises, the remanence decreases and the coercivity changes in a positive or negative direction, depending on the type of material.

In principle, the magnets should:

- have a high remanence (Br), to achieve high magnetic motive forces;
- have high coercivity (Hc), to avoid demagnetisation when reverse fields are applied;
- not be affected by high temperatures;
- have a low mass; and
- be inexpensive.

> Design factors

Size effect To produce sufficient torque and/or forces in small machines, it is advantageous to use PM materials to produce the field, because the their flux density is independent of their size. Magnet excitation tends to be used for machines having smaller pole sizes, although the upper economic limit has moved upwards as PMs have come down in cost while the price of copper has increased. Leakage, defined as the ratio of the total flux of the circuit to the flux across the air gap, is used in calculations to take this into account. This factor is usually at least 1.5.

Demagnetisation This can be caused by: ageing; exposure to high temperatures; disassembly; and too high an armature mmf. Designers can avoid the problem by: using special "keepers" when the rotor is removed; magnetising PMs after assembly; and designing for a particular operating point.

When designing small motors with powerful rare-earth materials, engineers need to take account of the high flux density using appropriate geometries or sizes for the slots, teeth, magnet thicknesses and angles, and so on.

For example, SDT Drive Technology* has developed a four-pole brushed DC motor with rare-earth materials. The magnetic circuit was analysed using both analytical and finite element methods (FEM), which can give information on the smallest details on motor's properties. Fig 2 shows an example of a mesh-positioned diagram produced using a two-dimensional finine element analysis method. This solution is satisfactory for highly symmetric situations, particularly for rare-earth motor designs.

These results made it possible to provide a brush-type motor up to the 75A, 500W, 6,000 rpm (80mm frame size) with a four-pole field system using rare-earth magnets. This design led to rare-earth magnet motors that are smaller and lighter than comparable motors with iron magnets (see Fig 3). Alternatively, motors using rare-earth magnets can be more powerful and efficient than motors of a similar size based on ceramic ferrite magnets.

In developing and designing rare-earth motors, identifying possible solutions is an important part of the design process. For the design described above, the following possible solutions have been identified:

- Heating, noise and cogging could be high when using a high-energy magnet material like NdFeB, but can be reduced by appropriate design choices.
- The choice of proper slot/tooth ratios and skewing can be effective in reducing torque ripple.
- The magnetic losses experienced in a motor are always a critical part of the performance characteristics in a new design. They are made up of hysteresis and eddy-current losses and are primarily found in steel. The amount of these losses depends on the flux-density level and the frequency of change of flux direction in the steel. In view of the high operating levels of flux-density when using NdFeB magnets, adjustments to the design are necessary to keep these losses under control.

Key characteristics of PM materials

Material	Advantages	Disadvantages
Ferrite	Low cost	Low residual flux density
Alnico	Low cost; high residual flux density	Easily demagnetised
Samarium cobalt	High residual density; high temperature operation	Expensive
Neodymium iron boron	Very high residual flux density	Low maximum operating temperature

Replacing one magnet material with another can achieve higher performance, lower costs, or faster production times. However, the following points need to be taken into account:

Magnet materials are not always interchangeable. Magnets have different strengths and characteristics. Take each property of the original material and determine if the new material can meet those properties, and if not, how it will affect the design.

Magnets have particular operating points. This is determined by their shape and type of material. The operating point will determine how the magnet will perform. At the optimum operating point, the magnet will operate at its maximum energy product.

Service temperature must be carefully considered. Even if you use a more powerful magnet, if the service temperature is high, you may have a weaker magnet. An example is substituting SmCo with NeFeB. This has been done successfully in many designs, providing significant savings. However, careful analysis is needed because SmCo has a much lower temperature coefficient than NdFeB. D&C

*** www.sdt-safidrivetechnology.co.uk**