Promising Applications of Neodymium Boron Iron Magnets in Electrical Machines

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Abstract

Neodymium Boron Iron (NdBFe) magnets have high energy product with suitable magnetic and physical properties for applications in electrical machines. The design aspects of permanent magnet machines using NdBFe magnets are presented. The ranges of applications cover both generators and motors up to 200 kW ratings. The exciting combination with micro-computers and power electronics makes the permanent magnet motors truly attractive for drives requiring smooth synchronous operation, constant torque and constant power characteristics.

Introduction

Developments in metallic permanent magnets have taken place in quantum steps with the introduction of new families of magnets. The production of semi-hard and hard permanent magnets has been increasing steadily. These magnets are widely used in various fields of electrotechnology. Of all these materials Alnico, ferrites and Samarium-cobalt magnets have had major impact. Figure 1 shows the historical development of maximum energy product of commercial permanent magnets. It is evident that a nearly-exponential increase is occurring with the introduction of the new ternary compounds containing Nd, B and Fe. These exhibit remarkable magnetic and physical properties, promising extensive applications in electro- mechanical energy conversion devices.

Since early times, 600 B.C., engineers have been attempting to increase the magnet's ability to produce a magnetic field and have been using magnets in an ever-increasing number of applications. Table 1 contains a brief chronology of the milestones in magnet development.

Table 1 — Permanent Magnet History

Appropriate Dates	Events
< 600 BC	Natural lodestone discovered (It was placed on floating wood as primitive compass)
1600	Systematic experimentation on permanent magnets by Gilbert
1750	Powered iron oxide magnet
1825	Electromagnet
1900	Permanent magnet motor (Edison)
1935	Commercial Alnico (Isotropic)
1940	Alnico V (Anistropic)
1957	Commercial barrium ferrite
1974	Commercial Samarium Cobalt
1984	Neodymium Boron Iron

Three basic magnetic parameters are of critical importance for permanent magnet applications in machines. These are: residual flux density B_r, coercive force H_c and maximum energy product(BH_{max}). It is the value of B_r which primarily determines what magnet area perpendicular to the main flux path is required to maintain the air gap operating flux. The coercive force H_c gives a first-order measure of the magnet's resistance against demagnetization during short-circuit, starting, etc. The

(BH_{max}) product is inversely related to the total magnet volume required for a given application. Table 2 contains pertinent properties of several permanent magnet materials.[1]

Table 2 — Properties of Permanent Magnets

Material	B_r (T)	H_c (KA/m)	BH_{max} (kJ/m^3)	Cost ($/kg)*	Remarks
Alnico V	1.280	51	44	35	Brittle and hard to machine
Ferrites	0.385	235	28	5	Brittle and hard to machine
Mn-Al-C	0.560	239	61	15	Ductile, machinable
$SmCo_5$	0.87	637	146	100	Brittle and hard to machine
$Nd_{15}B_8Fe_{77}$	1.23	881	290	55**	Machinable, 150° limit

* Estimated unit cost [1,10] **Anticipated unit cost [14]

A most important property for successful applications of permanent magnets in electrical machines is the linearity of the demagnetization curve in the second quadrant.

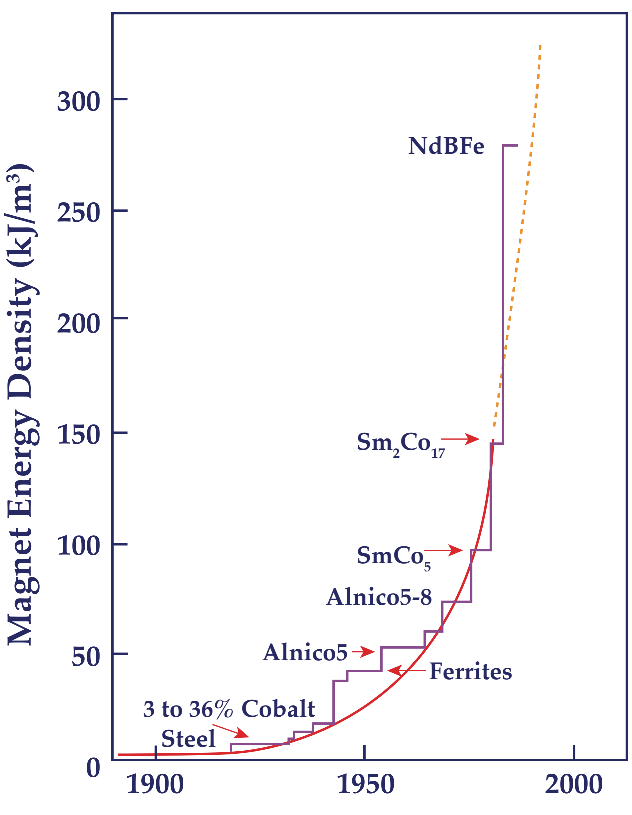

Figure 1 — Increase in maximum energy product (BH_{max}) maximum for commercial permanent magnet materials

Figure 2 shows the 2nd quadrant of the *B-H* curves for several permanent magnet materials. For the ferrities, samarium cobalt and neodymium boron iron, it is noted that the demagnetization curve is essentially linear over the whole of the second quadrant. When such materials are subjected to a demagnetizing field within this linear range, the recoil characteristic is nearly identical with the demagnetization curve and there is no loss of residual magnetism. It is only if demagnetization is carried into the curved portion that permanent loss of magnetization occurs. The relative recoil permeability of these materials in the linear region is little greater than unity. For the neodymium iron material, it is about 1.05. In contrast, the Alnico V material has no substantial linear position and loses permanent magnetism for any reverse field. Its recoil line is however reasonably linear with a relative permeability in the range 3.5 to 5.

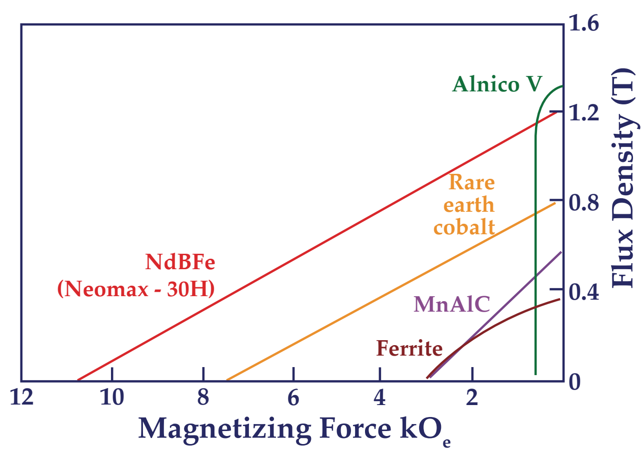

Figure 2 — Second Quadrant *B-H* Characteristics of Magnet Materials

Permanent magnet motors may experience severe demagnetizing fields during starting and synchronizing or as a result of stator short circuits. The design must be such that the demagnetization is limited to the linear part of the *B-H* characteristics.

Cost and security of supply of raw materials are two major constraints on the application of newer magnetic materials in commercial machines. For samarium cobalt, the cost is relatively high (Table 2) and the future security of supply of both samarium and cobalt is questionable. The iron-based neodymium boron materials offer both a lower cost (comparable with Alnico's per unit weight) and plentiful material supply. Large scale application, as in the automotive industry, is therefore conceivable. Such magnets meet the dream of electric machine designer like Merril[2] who wrote in 1955 that

> "if the course of future research produces a magnet of greater energy ... an ideal magnet would retain the residual value of 12.6 KG and extend the coercive force, ... the improvement in output; power factor and efficiency of the permanent magnet motors could be remarkable."

At the present time, the major limitation on the application of neodymium iron magnets is the limited temperature tolerance. While the Curie temperature is about 300°C, operation must normally be limited to about 150°C because of the relatively high temperature coefficient of residual flux density above that temperature.

Applications

The scope for application of NdBFe magnets in electrical machines is potentially very large, particularly in the areas of aircraft alternators, pilot exciters for commercial generators, dc motors and synchronous motors of either the line start or inverter fed variety. The application of permanent magnets in 400 Hz aircraft generators is well established. A major advantage of the use of NdBFe magnets in these generators would be a further improvement in the power-to-weight ratio.

Ferrites are extensively used in motors for the automotive industry and in general control applications. Since the unit cost of NdBFe material is still significantly higher than that of ferrite, use of the former will depend on the cost savings which can result from reduction in overall material content.

Permanent magnet generators up to 200 kW ratings are used commercially as pilot exciters for large turbo and hydraulic generators.[3,4] Early design using Alnico magnets had long salient poles of magnet material fitted with iron pole pieces to control the degree of demagnetization. With the higher energy product magnet materials now available, the typical design of these permanent magnet exciters is the circumferential flux type shown in Figure 3. The magnets are magnetized in the short circumferential direction and the flux is delivered to the air gap by iron poles mounted on a non-magnetic cylinder. This design is particularly appropriate for low speed machines requiring a large number of poles.

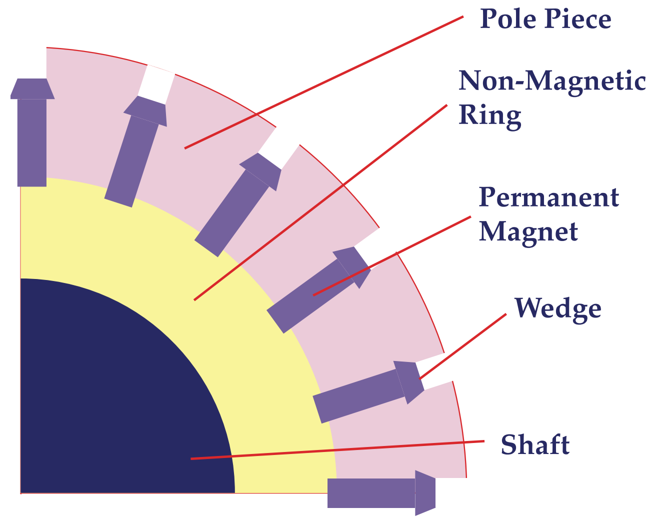

Figure 3 — Cross-section of One Quadrant of Circumferential-Flux Type Rotor

If NdBF magnets were used in this design the magnets could extend up to near the air gap without danger of demagnetization during a stator short circuit. Because of the high flux density of the magnetic material, the length of the arc of each pole piece could be approximately twice the radial depth of each magnet. In contrast, if ferrite magnets were used, the pole arc must usually be considerably less than the magnet depth.

The literature contains a wide variety of permanent magnet machine designs created to make optimum use of specific magnet materials.[3,4,5,6,7,8,9,10,11] Since earlier materials were lacking either in available flux density or in usable demagnetizing field, considerable geometrical ingenuity was often required. With the introduction of NdBFe magnet materials, some of these designs can be both simplified and optimized as will be seen in the following sections.

Line-Start Permanent Magnet Synchronous Motors

An area receiving considerable attention is the development of permanent magnet synchronous motors for use in applications previously supplied by induction motors. The major advantages sought are the improved power factor with resultant reduction in stator copper loss and the improved efficiency resulting from synchronous operation with no rotor slip losses. Such motors normally operate only ac line frequency and must be capable of a smooth start and acceleration. They must also have the ability to synchronize a high inertia load.

To accomplish this a cage design is employed with the magnets imbedded in the rotor iron.

Two typical rotor designs are shown in Figure 4. In Figure 4(a), radially directed arc shaped magnets are fitted into slots below the cage winding. In addition, circumferentially-directed magnets are fitted near the rotor surface separating the radial magnets. Some magnet flux is lost in the saturated iron bridges around these magnets but a large proportion is directed across the air gap. In Figure 4(b), the arrangement is similar except that essentially straight magnets are used, usually incorporating the circumferential magnet sections at their ends.

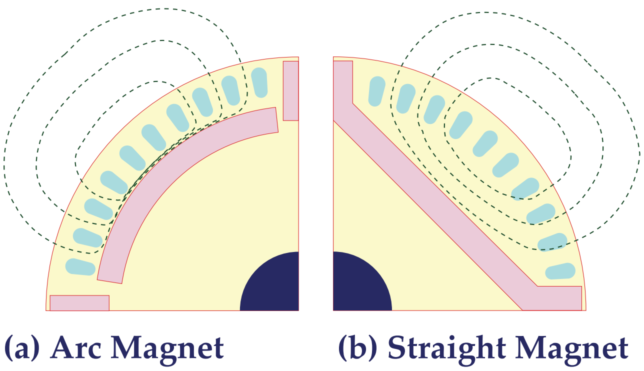

Figure 4 — Rotor Segments of Permanent Magnet Synchronous Rotors with Squirrel-cages

A typical torque-speed characteristic during starting is shown for this of motor in Figure 5. The squirrel cage provides the expected induction motor torque characteristic.

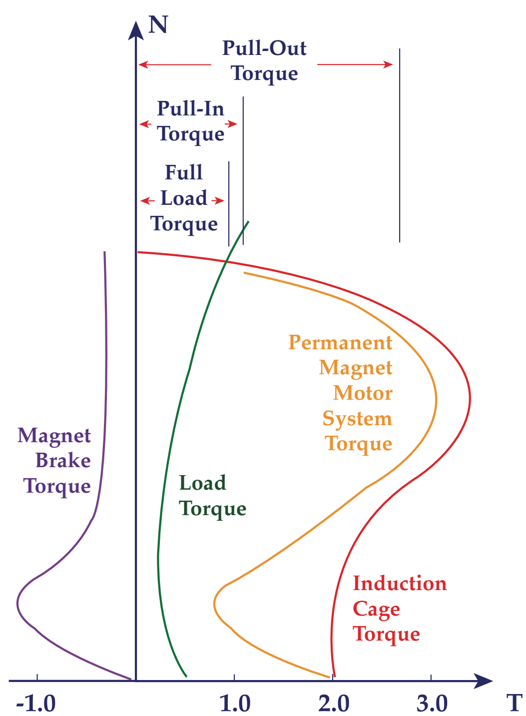

Figure 5 — Permanent Magnet Motor Torque Components

The magnet system, however, provides a braking torque similar to what might be expected from a permanent magnet motor with shorted stator winding. The stronger the magnet field, the greater is the braking torque. Design must therefore ensure that the total torque at low speed is adequate to accelerate the anticipated load.

As the motor approaches synchronous speed, the motor must develop adequate synchronizing torque from the permanent magnet field to pull the load into synchronism. For a given design, there will be a maximum load inertia which can be accommodated. A detailed analysis of the transient performance is required to evaluate this property.

Neodymium boron iron magnets are particularly suited for application in such designs. The thickness (ℓ) of the radially-directed magnet can be made several times that of the air gap(g). To a first approximation the operating point of the magnet is then given by:

$$B_m = \frac{\ell}{\ell + g} B_r \quad (1)$$

The gap flux density B_g will be lower than magnet flux density B_m due to both leakage and rotor curvature. If the iron-bridge leakage paths are small and the magnet is reasonably near the rotor surface, a gap flux density in excess of 0.8T can be achieved. This is potentially larger than would occur for induction motors, providing the prospect of greater torque per stator ampere from a given frame size.

Motors of the types shown in Figure 4 have considerable saliency torque in synchronism as well as the magnet-produced torque. In contrast with ordinary salient-pole synchronous machines, the direct-axis reactance of these permanent magnet motors is normally much less than the quadrature axis reactance. This arises because of the high reluctance of the magnet in the direct axis. The quadrature axis reactance may be similar to that for an induction motor but may be subject to considerable saturation in the design of Figure 4(a), because of the constrained space between the cage winding and the magnet. The direct-axis reactance is also nonlinear, particularly for the condition where the direct-axis stator mmf is directed so as to increase the gap flux density and is of such a magnitude as to bring the iron bridges between the magnets out of saturation. For this condition, the saliency and its resultant torque is considerably reduced.

A 25 hp, 3-phase, 4 pole, 60 Hz 208V induction motor stator frame was recently used to test two rotor designs using NdBFe magnets. The standard aluminum cage was left largely in place. The rotor magnets were Neomax-30 H with B_r = 1.138T, H_c= 860 kA/m and (BH_{max}) = 247 kJ/m^3, μ_r = 1.05. They have the following typical physical properties:[12]

- Density = 7.4 Mg/m^3
- Electrical resistivity = 1.44 μΩ-m
- Flexural strength = 25 kg/mm^2
- Compressive strength = 75 kg/mm^2
- Tensile strength = 8 kg/mm^2
- Vickers Hardness = 600 HV

It has a temperature limit of 140°C, with temperature co-efficient of -1.26 x 10^{-3}/K. Thermal expansion coefficient = 3.4 x 10^{-6}/K (parallel to c-axis), -4.8 x 10^{-6}/K (perpendicular of a-axis). The magnets were fitted into slots cut in the rotor iron and they extended over the whole 140 mm iron length of the stator.

The starting and synchronization of both designs has been quick and smooth. A record efficiency at full load of 97% has been achieved. The full load power factor was nearly unity. In prolonged load tests there has been no evidence of thermal degradation of the NdBFe magnets.

Inverter-Supplied Synchronous Motors

An extensive area of application for permanent magnet synchronous motors is in combination with inverters to provide variable speed drives.[13] Such applications have normally been filled by dc motor drive systems and more recently by induction motor-inverter drives.

A synchronous motor fitted with a shaft position sensor can provide inverter frequency control such that the motor is in synchronism at all values of speed.[14] Asynchronous starting and synchronizing capability is not required and therefore the squirrel cage can be dispensed with. This permits a design such as that shown in Figure 6 where radially-directed magnets are fixed to the surface of the iron rotor. This design eliminates the loss of magnet flux which occurs with imbedded magnets but it increases the difficulty of maintaining mechanical integrity of the rotor at high speed.

In this design, the gap flux density B_g is approximately equal to the magnet flux density B_m over most of the arc covered by the magnet. In the zero stator current, these flux densities are given to a first approximation by the expression:

$$B_g = B_m = \frac{\ell}{\ell + g} B_r \quad (2)$$

Since the effective air gap length (g) can be constrained to 1-2 mm, a gap density in excess of 0.8T can be achieved with a magnet thickness of the order of 5 mm.

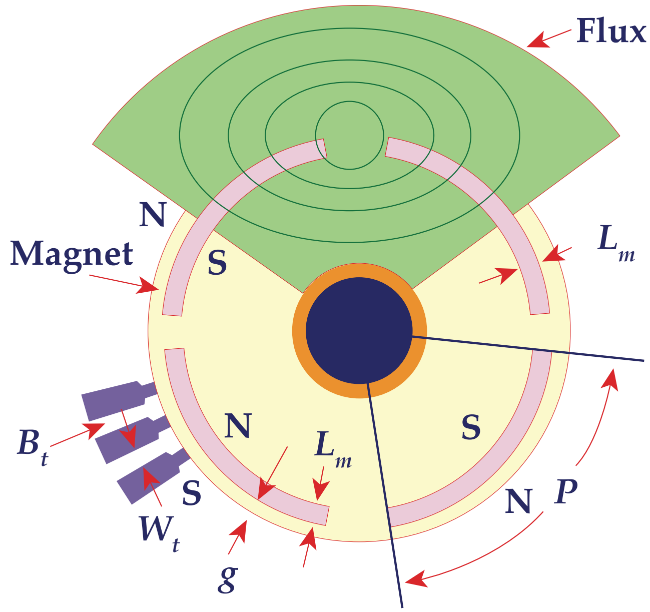

Figure 6 — Permanent Magnet Motor with Radially-directed Peripheral Magnets

The design of Figure 6 has negligible saliency torque since the effective reluctance of the magnet material is essentially the same as that of an equivalent volume of air. The direct and quadrature axis reactances are essentially equal and have the value associated with a large air gap ($g + \ell$).

Because of the large effective value of the air gap flux density, permanent magnet motors of this design are capable of producing high torque per unit of stator current. This leads to rapid dynamic response, a property required of many variable speed drives.

Conclusions

The Neodymium Boron Iron magnet materials are nearly the ideal for use in rotating machines. The available flux density is compatible with the maximum value which can be permitted in the air gap. The demagnetization characteristic is coincident with the recoil line down to negative values of net field for most of these materials, thus making then highly resistant to loss of magnetism due to short circuits and other transients.

These materials are readily machinable and are therefore easy to manufacture into the desired configurations. The relatively low cost per unit weight combined with the high energy product leads to a lowering of the proportion of total machine cost needed for the magnets. The saving in other materials due to the higher torque density capability should lead to overall cost savings.

NdBFe machines should find increasing application in industrial drives (i.e. textile, glass, synthetic fiber, etc.), in the automotive industry and in disk drives. While early applications are in the low power area, integral hp motors now look promising.

Publishing History

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