The Use of NdFeB Magnets to Increase the Efficiency of Electric Motors for Cordless Appliances

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Cordless appliances typically employ permanent magnet DC motors as primary movers. Such motors are likely to be the main factor limiting the battery life of such appliances. Higher efficiency motors reduce the electrical loading on the battery, thereby extending battery life. Higher efficiency motors also provide increased output power with the same package size or reduced package size with the same output power, thereby improving the functionality and value of the appliance.. The replacement of ferrite magnets with higher-energy Neodymium-iron-boron magnets in DC motors allows for improved designs that are shown to provide a significant increase in motor efficiency.

Background

An ever-increasing number of cordless appliances are being introduced each year, as consumers desire the convenience of not being constrained by an ac outlet and a power cord. Most cordless appliances employ a dc motor as the primary mover and consumer of battery power. Corded appliances have a virtually unlimited amount of input power from the ac line at their disposal. On the other hand, the input energy – and therefore the output power – of their cordless counterparts is limited by the Volt X Amp X hours (VAh) rating of the rechargeable battery power supply. Thus, maximizing the efficiency of the dc motor is the key to squeezing out the most battery life and output power from the unit.

As battery energy ratings increase, the realm of cordless appliances is reaching to higher power, continuous-duty applications such as lawnmowers and blower/vacuums. The functionality of these devices can be severely limited by battery life and motor efficiency.

DC motors with brush-type commutation and ferrite permanent magnets are most commonly employed in cordless appliances. An example of such a motor is shown schematically in Figure 1. The DC brush motor is relatively inexpensive and is capable of 65-70% efficiency in the conversion of electrical to mechanical energy.

Higher energy permanent magnet materials enable the production of higher efficiency motors. Recent improvements in the magnetic, mechanical, and thermal properties of neodymium-iron-boron ("Neo") magnetic materials, together with the evolution of low cost, high volume manufacturing processes for magnets have made the replacement of traditional ferrite permanent magnets attractive in many applications.

While the development of Neo magnets has had a significant technical and economic impact on the aerospace and industrial sectors of the electric motor industry, these advancements have been slow to gain acceptance from the higher-volume appliance and automotive sectors. The reason for this has been the higher cost of Neo compared to ferrite, without regard to the added value that Neo can provide to most applications. Continual price reductions in both Neo magnets and the powders from which they are made are finally enabling the replacement of ceramic ferrite magnets in many low cost, high volume applications. The cost difference between a Neo and ferrite magnet solution is narrowing, the value of which will be evident in improvements to motor production and performance.

DC motor investigated

A cordless leafblower-vacuum was chosen as a demanding application worthy of a motor optimization exercise for several reasons. Such a device operates at 100% duty cycle for prolonged period, and the goal for this unit was 15 minutes between charges with a 12V X 3.8 Amp-hr rechargeable NiCad battery (currently under development). Increased motor output power improves functionality with more powerful blowing and vacuum action, and reduced motor weight is ergonomically desirable.

A readily-available 12V DC blower motor from an automobile HVAC system was chosen as an appropriately-sized motor which could be employed in a cordless leafblower-vacuum. This motor is shown in Figure2. It is a 4-pole, 16-slot DC brush machine using sintered ferrite arc segments. The 1.3 kg motor has a 100 mm outer diameter and a 60 mm axial length.

It is important for the selection of magnet grade to know that this motor will operate within an ambient temperature range from -40^oC to +40^oC, and that the maximum magnet temperature could reach 105^oC.

Bonded Neo properties

The performance of a permanent magnet is described by its ***2nd quadrant demagnetization curve***. Several such curves, representing the materials considered in this study, are shown in Figure 3. The standard ceramic ferrite grade magnet presently used in the demonstration blower motor clearly has the lowest magnetic properties compared to two different types of bonded Neo magnet whose characteristics are also shown. The higher the ***remanence*** (B_r) of a magnet, the better it can be utilized to maximize the efficiency of a DC motor. The product of a magnet's operating ***flux density*** (B) and its ***magnetizing force*** (H) is a direct measure of its energy density, the maximum of which $(BH)_{max}$ is a characteristic ***energy product*** which is commonly used as a figure of merit for a permanent magnet material.

Bonded Neo magnets are fabricated by mixing Neo powder with an epoxy or plastic binder and then compression or injection molding the magnet to shape. Approximately 80% magnet-to-epoxy loading can be achieved in compression-molded bonded Neo, while 60% loading is typical for injection-molded Neo. Thus, compression molding yields higher magnetic properties, but injection molding allows for a wider variety of shapes and more efficient manufacturing techniques. Ceramic ferrites are fabricated via pressing and sintering, yielding brittle magnets that must be ground with diamond wheels to achieve the tight tolerances required for motors. In most applications, bonded Neo magnets can be employed "as-pressed" with minimal secondary operations required.

To maximize motor performance benefits, a bonded Neo magnet should use the highest remanence Neo powder applicable at the maximum magnet temperature. The moderate maximum operating temperature for this application allows the use of a Nylon binder for injection-molded Neo. A compression-molded magnet achieves a still higher remanence because of the improved loading when blended with epoxy resin.

Motor design issues

Provided the gain in flux density is not too great, as is the case with injection-molded Neo magnets, a direct substitution for the existing ferrite arc segments can be made. This allowed use of the existing motor housing and armature assemblies. When the demonstration blower motor was modified in this way, the increased magnetic flux now available was used to lower the current draw of the motor and thus to increase its efficiency.

When comparing similarly-sized motors, a ***motor constant*** K_m is often used as a figure of merit, and a higher K_m generally translates to higher motor efficiency. K_m is equal to K_t/sqrt(R), where K_t is the motor's ***torque constant*** (Newton-meters/amp) and R is its armature winding ***resistance*** (ohms).

The increased air gap magnetic flux density provided by bonded Neo yields a higher K_m, which in turn can be utilized either to increase K_t while retaining an identical winding, or to retain K_t while reducing R, or to both increase K_t and reduce R by lesser amounts. The latter approach was chosen in order to reproduce as closely as possible the original ferrite motor's torque versus speed characteristic. This was accomplished by rewinding the armature with fewer turns of thicker wire. Figure 4 is a photograph of the disassembled demonstration motor, with four new injection-molded Neo arcs installed, and the armature winding removed in preparation for rewinding.

The demonstration blower motor with injection-molded Neo was built and tested, and it was also analyzed using finite element analysis (FEA). Figure 5a (left side) shows a typical flux density distribution calculated by FEA at a motor current of 10 amps. The color contours indicate that the flux density levels both in the outer housing and in the armature teeth are nearing saturation, since we have directly substituted its ferrite arcs with the higher energy bonded Neo material.

If you directly replace a ferrite magnet with Neo, you run the risk that greater flux from the Neo material can drive the housing and the armature laminations into saturation, increasing iron losses and limiting the potential gain in efficiency. Several steps should be taken to alleviate magnetic saturation in this design. First, the relative radial thicknesses of the magnet arcs and the steel outer housing should be adjusted to maximize the air gap magnetic flux density. Next, the lamination spoke width should be increased. Converting the inner lamination spokes to a solid rotor hub also provides a nominal increase in motor performance. The maximum efficiency could easily be raised a further 5–10% over the "direct replacement" design through optimization of the magnet, housing, and armature lamination dimensions.

Another design iteration employing magnet arcs made from compression-molded Neo was evaluated using FEA. Because this magnet grade is far superior to ferrite, it was not practical for a “direct replacement” in the blower motor. The higher energy of compression-molded Neo would drive the housing and armature laminations well into saturation, but this is alleviated in the design whose flux plot is shown in Figure 5b (right side), again at a motor current of 10 amps. Comparison of the injection-molded vs. the compression-molded fluxplots of Figure 5 clearly shows the adjustments to magnet and housing thicknesses, lamination spoke width, and the rotor hub.

Motor performance improvements

The goal of this study was to use the higher energy available from bonded Neo magnets to improve the efficiency of the blower motor, while maintaining its original torque versus speed characteristic. This was achieved by simultaneously modifying the armature winding. The armature current is reduced for any given output torque as shown in the characteristics of Figure 6. The corresponding gains in motor efficiency are also shown in Figure 6.

Table 1 summarizes the results of this study. The higher magnet properties the two selected bonded Neo materials enabled an increase in ***motor constant*** K_m. At the motor’s normal continuous operating torque of 0.6 Nm, there is a 2.0 amp (10%) reduction in current draw by replacing ferrite with injection-molded Neo, and a 4.0 amps (21%) drop in current by using compression-molded Neo.

Appliance benefits

The figures above represent the increase in motor efficiency and the reduction in current drain resulting from an increase in the motor constant (K_m). This increase in K_m is achieved via the replacement of the motor’s ferrite magnets with bonded Neo. The battery life of the cordless leafblower-vacuum is inversely proportional to the current drawn from the motor at its operating torque. Therefore, the leafblower incorporating compression-molded Neo magnets will last over 20% longer between battery charges than a device with a ferrite-magnet motor. Further optimization of both injection- and compression-molded Neo magnet motor designs will yield still further increases in battery life.

The higher energy of the bonded Neo magnets can be effectively utilized to provide other benefits in addition to increased motor efficiency and reduced current draw. For the same output power as the ferrite motor, a bonded Neo motor can be made smaller in diameter and/or shorter in axial length. Considering that the blower motor comprises a significant percentage of the weight of the leafblower-vacuum, a smaller bonded Neo motor will increase the perceived value of such a device. Conversely, a bonded Neo motor of the same size as the ferrite motor can generate a higher output power, and, therefore, blow more air. In this case, a bonded Neo motor will improve the functionality of the leafblower.

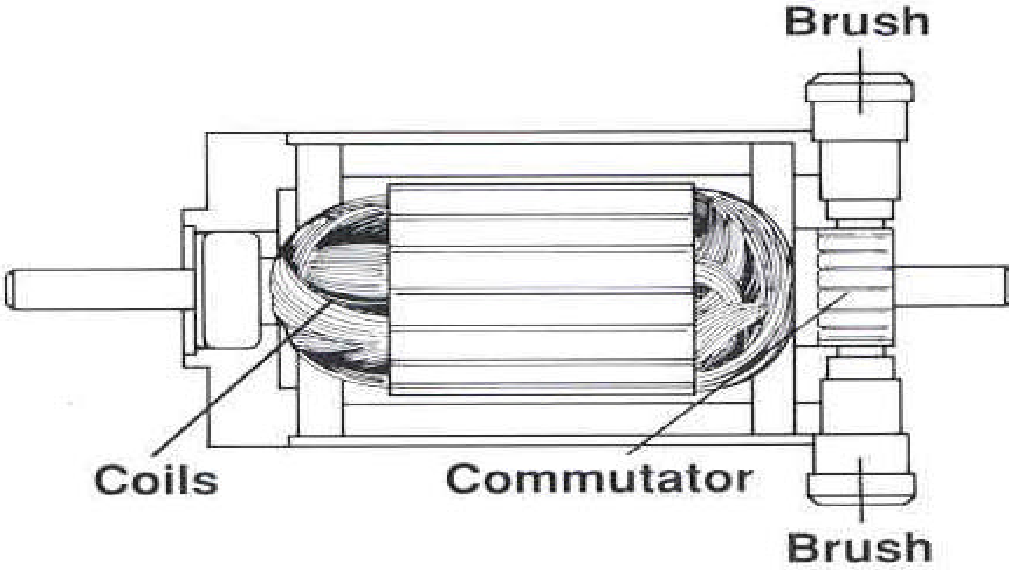

Figure 1. DC brush motor.

Figure 2. 12V DC blower motor.

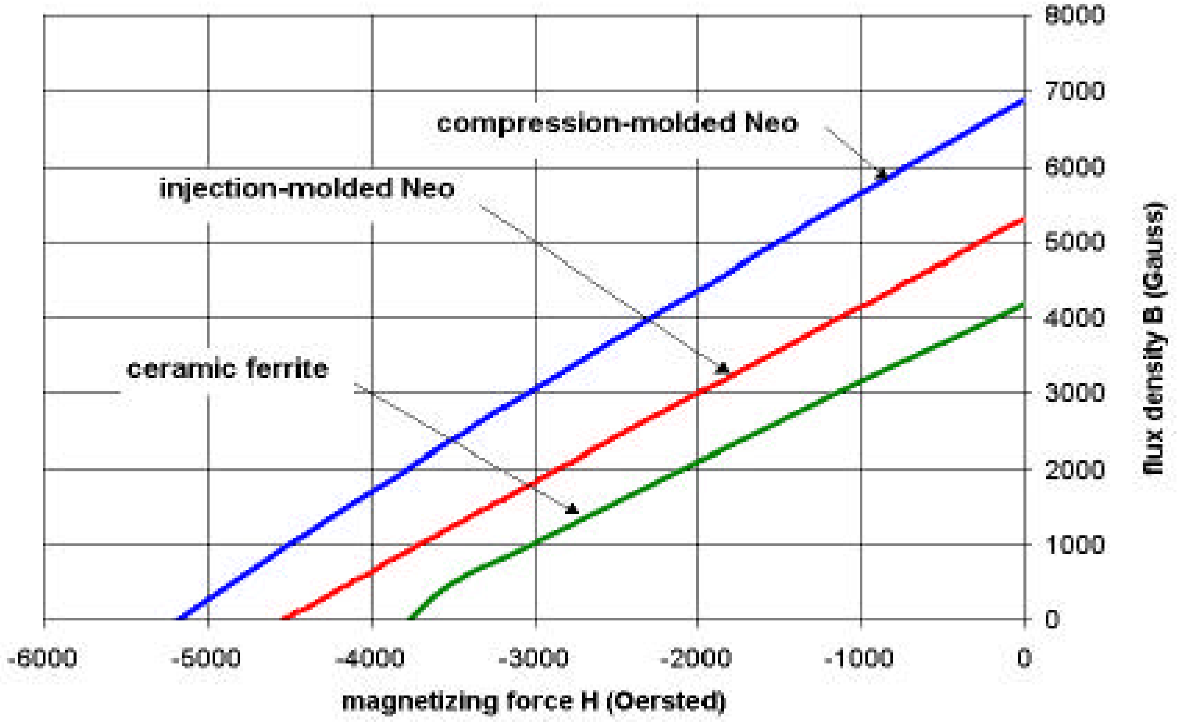

Figure 3. Comparison of magnetic properties.

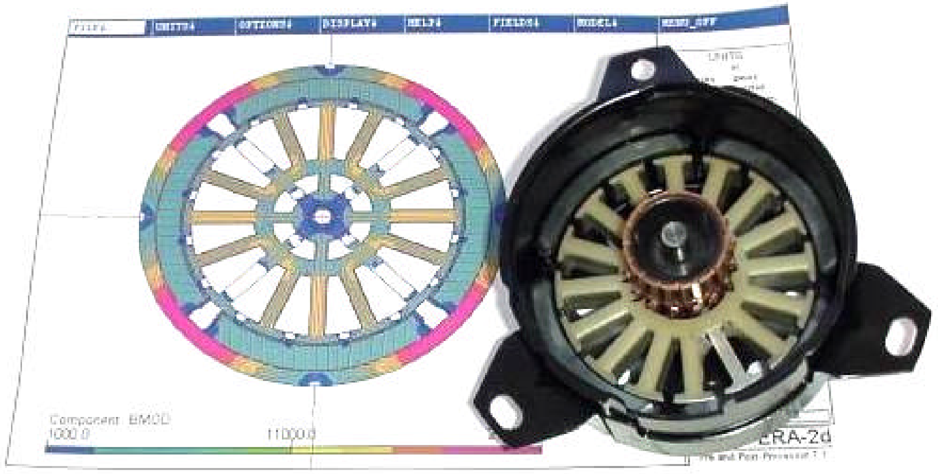

Figure 4. Disassembled blower motor with injection-molded Neo arcs.

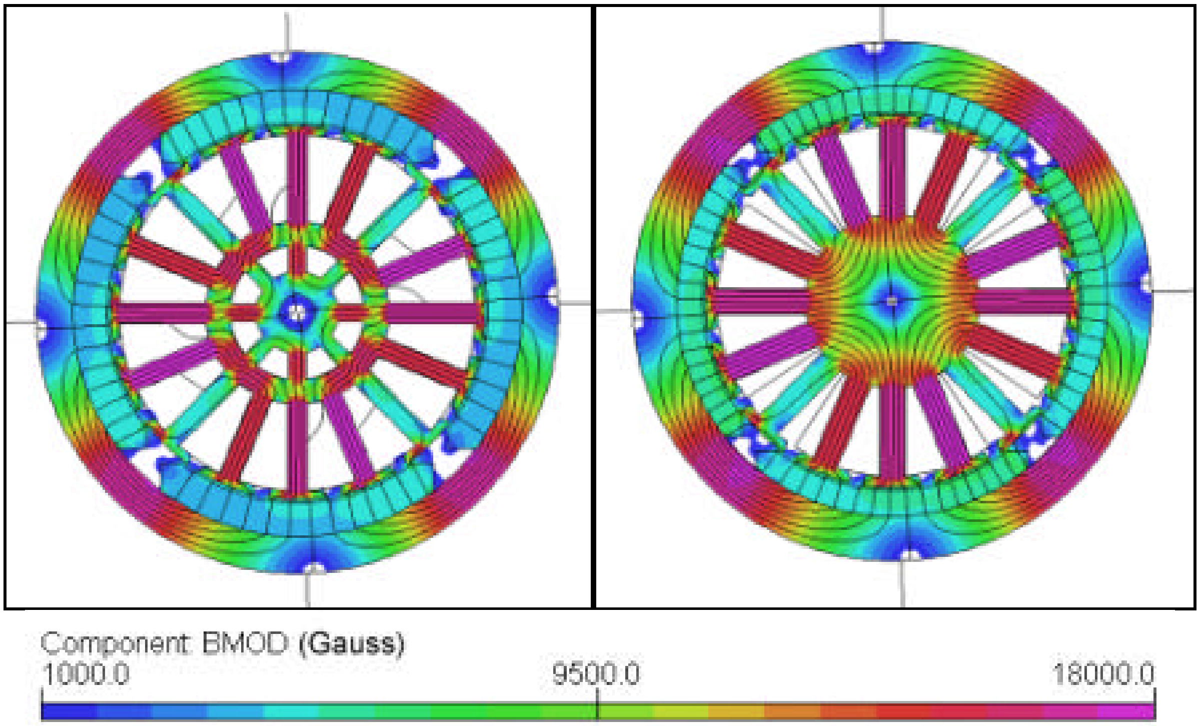

Figure 5. Magnetic fluxplot comparison of blower motor with: a. injection-molded Neo magnets (left); b. compression-molded Neo magnets (right).

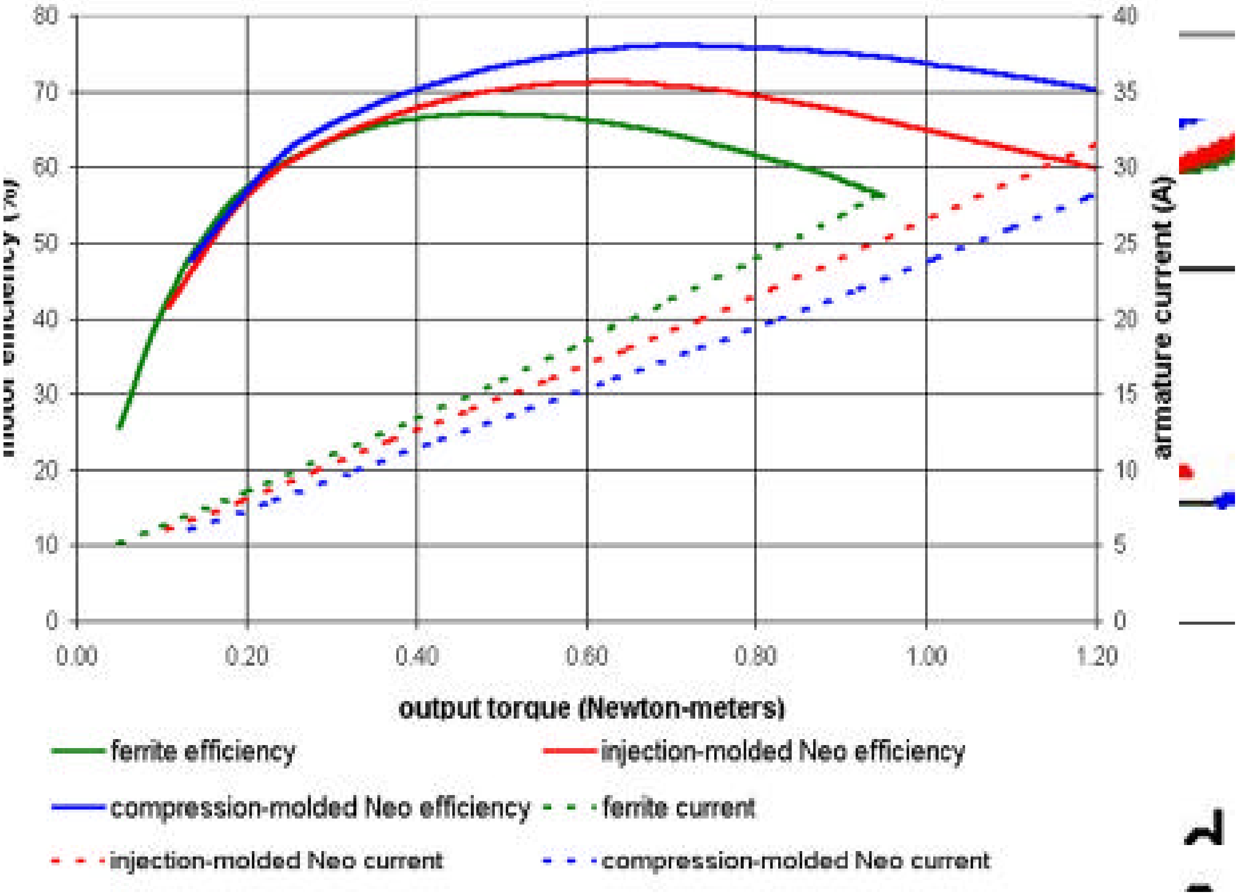

Figure 6. Comparison of torque vs. efficiency and torque vs. current curves for the blower motor designs investigated.

Parameter	Unit	Ferrite	Injection-Molded Neo	Compression-Molded Neo
Remanence - Br	Gauss	4200	5200	6950
Intrinsic Coercivity - Hci	Oersted	4000	9500	9500
Energy Product - (BH)max	MGOe	4.0	5.4	10.4
Torque Constant (Kt)	N-m/A	0.0357	0.0397	0.0444
Winding Resistance (R)	Ohms	0.177	0.143	0.113
Motor Constant (Km)	N-m/W^.5	0.085	0.105	0.132
Maximum Motor Efficiency	%	66.7	71.3	76.2
Current draw @ 0.6 N-m	Amperes	19.0	17.0	15.0
Battery life (3.8 Amp-hours)	minutes	12.0	13.4	15.2

Table 1. Summary of ferrite vs. bonded Neo blower motor designs.