A Novel Self-Shielding Permanent Magnet Rotor Assembly

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Abstract

The use of permanent magnets in brushless motors and generators is highly desirable in that they have great potential for reducing weight and increasing efficiency. A self-shielding cylindrical permanent-magnet assembly has been designed and was found to produce high fields at the outer magnet surface and very little flux leakage into the interior rotor space. Construction of this assembly is simplified because it is composed of magnets of simple triangular cross sections, which have only four distinct orientations. The self-shielding nature of the design obviates any need for ferromagnetic material for flux shaping or shielding, thus simplifying greatly the mathematical analysis of the design and reducing its weight and bulk. Finite element methods are used to analyze a hypothetical permanent-magnet rotor assembly with regard to various design parameters.

Introduction

The drive towards greater efficiency and reliability in electric motors and generators has led to a good deal of study of the use of the hard permanent magnets for brushless devices.[1,2,3,4] All previous designs have relied on the use of ferromagnetic materials in the rotor, along with the permanent magnets, for field shaping and control. The iron, besides being a source of excess weight, serves to complicate motor design and evaluation because the direct- and quadrature axis reactances, X_d and X_q, are nonlinear and very load dependent. This proposed design lends itself to high-field multipole configurations without any ferromagnetic rotor materials and attendant difficulties.

The fundamental principle of this design is based upon the technique of gradual magnetic field variation between regions with different field orientations.[5,6] This yields a high flux, low leakage design suitable for motor and generator rotors or, with some modification, high-gradient magnetic separators.[7]

Discussion

As this paper is not meant to be an exhaustive analysis, we propose to make several simplifying assumptions. First, we take all permanent magnets to have $B_r = 10$ kG and a linear second quadrant demagnetization curve. Second, we assume that a variable frequency inverter drives the stator coils, thereby eliminating any need for a squirrel cage or rotor slots for starting, as we are always in synchronism. We also assume little or no saturation of the stator iron, an assumption borne out by finite element analysis.

The basic configuration is an eight-pole, three-phase, 60-cycle permanent-magnet brushless motor with a double layer winding. For the sake of discussion, we specify that all the various pole configurations have an outer rotor radius of 10 cm, and air gap of 2 mm, an outer stator radius of 19 cm, and a synchronous speed of 900 rpm, The inner radius, however, is determined by the total number of poles and the constraint that the boundary between any two magnets should exactly bisect the angle between their magnetic field orientations. Letting n be the number of poles, R_o = the outer- rotor radius, R_i = the inner rotor radius, and <9 = 360°/I, we see from Figure 1 that

$$R_0 - R_i = \frac{R_0 \sin\left(\frac{\Theta}{2}\right)}{\tan\left[45° + \left(\frac{\Theta}{4}\right)\right]} + X \quad (1)$$

where

$$X = 2R_0 \pm \frac{\sqrt{4R_0^2 - 4R_0^2 \sin^2(\Theta/2)}}{2} \quad (2)$$

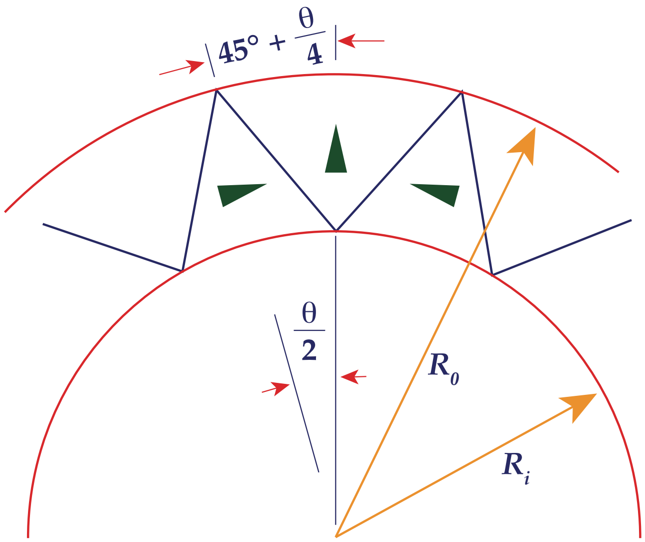

Figure 1 — Illustration of the constraint fixing R_i to the number of poles and R_o

Using the above constraint, we get a R_i = 7.673 cm for the twelve-pole rotor and R_i = 6.682 cm for the eight-pole rotor. As can be seen, the advantage of this design diminishes as the number of poles decreases and the magnet thickness increases.

The no-load 2D finite element flux plots for the eight and twelve-pole rotor designs are shown in Figures 2 and 3, respectively. Because of *x*-axis symmetry, only half structures need to shown.

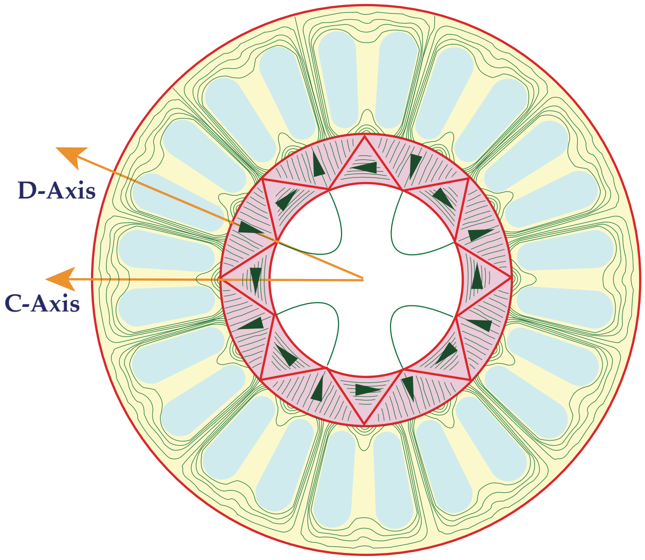

Figure 2 — Two-dimensional finite element flux plot of the eight-pole rotor design under no-load. The outer radius R_0 is 10 cm, the inner radius R_i is 6.682 cm, and the air gap is 2 mm. The direct and quadrature axes are also shown.

Both the eight-pole and twelve-pole designs have fields exceeding 9500 Gauss in the air gap, which is comparable to a conventional design of the same dimensions with only radially oriented magnets mounted on a ferromag- magnetic cylinder.

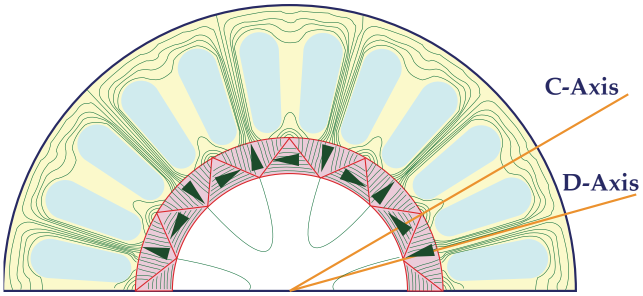

Figure 3 — Two-dimensional finite element flux plot of the twelve-pole rotor design under no load. The outer radius R_o is 10 cm, the inner radius R_i is 7.673 cm, and the air gap is 2 mm. The direct and quadrature axes are also shown.

The self-shielding of these designs excludes significant flux from the interior rotor spaces without the use of ferromagnetic materials. In the eight-pole rotor design, interior fields are below 300 Gauss over 2/3 of the inner area whereas in the twelve-pole design, fields are below 200 Gauss over 3/4 of the inner area.

A complete two-dimensional finite element flux plot of the eight-pole design at 12.5° rotation, under no-load conditions, is shown in Figure 4. Because of the design of the stator, this configuration has a cogging torque periodicity of 15°.

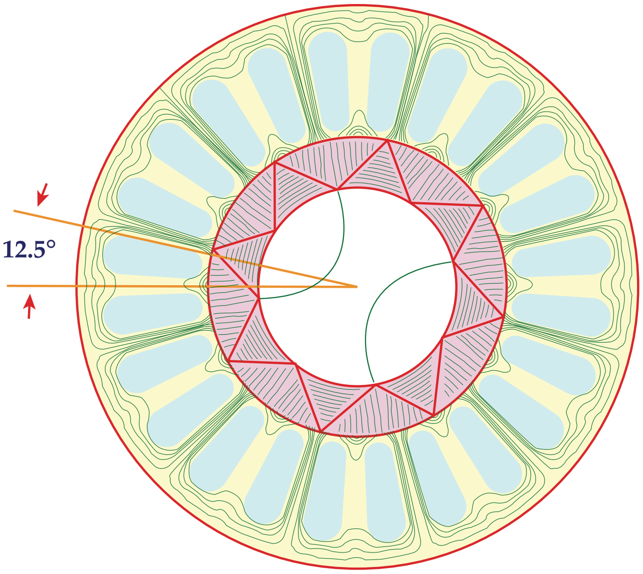

Figure 4 — Full finite element flux plot of the design shown in Figure 2 with the rotor offset 12.5° from the top dead center position.

Conclusion

The advantage of this design manifests itself most noticeably when a large number of poles is desired (high-torque, low-speed motors). As the number of poles increases, both magnet thickness and internal leakage decrease.

Even though we have used a magnetization rotation of slightly greater than 90° between magnets, a better method would have been to change the magnetization gradually between poles. Unfortunately, the fabrication cost of such designs rises rapidly as the number of discrete segments between the direct and quadrature axes increases.

A good deal of analysis remains to be done. Specifically, detailed torque curves (under both load and no-load conditions) must be calculated for comparison with conventional designs, and the design/evaluation of a prototype must be undertaken in order to fully evaluate and compare the proposed designs to the more conventional ones.

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