The Influence of Magnetization Pattern on the Performance of Permanent Magnet Eddy Current Couplings and Brakes

Hyun-Rok Cha*, Han-Wook Cho and Sung-Ho Lee†**

Abstract – This paper examines permanent magnet eddy current couplings and brakes. Specifically, the effect of permanent magnet magnetization patterns on the magnetic field and force production is investigated. The eddy current couplings and brakes employ high energy-product neodymium-iron-boron (NdFeB) permanent magnets that act on iron-backed copper drums to provide torque transfer from motor to load without mechanical contact. A 2-dimensional finite element modeling is performed to predict the electromagnetic behavior and the torque-speed characteristics of permanent magnet type eddy current couplings and brakes under constant speed operation.

Keywords: Eddy current brake, Eddy current coupling, Halbach magnetization

1. Introduction

In recent years, power-electronic adjustable-speed or variable-frequency drives (VFD) have been very successfully introduced to provide a high-efficiency alternative means of control by matching the motor output speed and torque to the requirements of the load. However, the resulting energy savings are obtained at the cost of significant capital expenditure (for the VFD) and, in certain cases, operational problems for the motor [1, 2]. VFD generated electronic harmonics cause system problems and may overheat motor windings.

The eddy current couplings and brakes compare very well with VFD in terms of overall energy efficiency. Drag forces due to eddy currents induced by the relative motion of a conductor and a magnetic field occur in many practical devices: motors, brakes, couplings, magnetic bearings, and magnetically levitated vehicles [1, 3].

In eddy current machines, the magnetic field source can be produced by winding systems or by permanent magnets. This last solution allows for the elimination of an electrical supply system and simplification of the coupling and brake structures [2]. In particular, the development of the modern high-energy magnet materials has allowed the replacement of field coils with permanent magnets in eddy current couplings and brakes.

In eddy current couplings and brakes with solid rotors, electromagnets can be replaced by a magnet, but a device such as a mechanical clutch must be added to move the exciting magnetic field toward or away from the rotating drum. Therefore, the eddy current machine with permanent magnet is mechanically more complex, but it is independent of any electric power source and control. This may be attractive in some applications.

The principle behind the operation of such a system relates to basic electromagnetic induction theory. The interaction between the magnetizing field and eddy currents results in forces that oppose (or follow) the movement, producing the braking (or coupling) action [3].

Using 2-dimensional finite element analysis, this paper deals with the influence of the magnetization patterns and one of the design parameters on the performance of the permanent magnet eddy current devices, specifically the

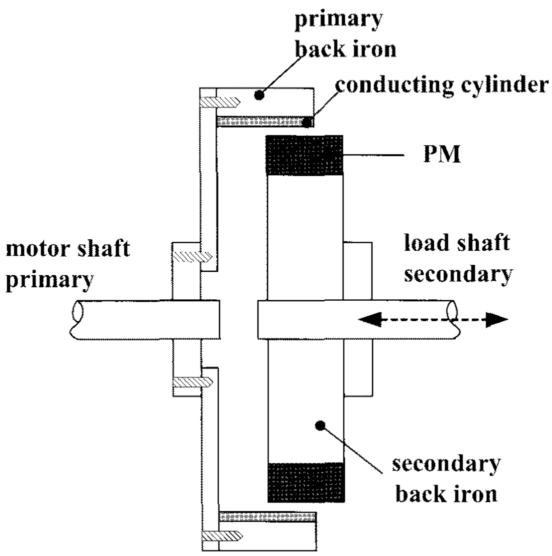

Fig. 1. Mechanical schematic of permanent magnet eddy current coupling and brake.

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Received: 29 August, 2007 ; Accepted: 5 February, 2008

extent to which device performance, in terms of the magnetic field and the braking torque-speed characteristics.

Fig. 1 shows the mechanical schematic of adjustable speed permanent magnet eddy current coupling and brake.

2. Permanent Magnet Eddy Current Machine Configuration

The basic structure of the eddy current device comprises the moving (or stationary) set of magnets that are separated from the stationary (or moving) conducting cylinder by an air-gap. Fig. 2 shows the cross-sectional schematic of the permanent magnet eddy current coupling and brake.

If held stationary, the conducting cylinder acts as an eddy current brake; if free to rotate, the conducting cylinder will follow the magnet cylinder with a relative speed which is a function of the transmitted torque. In order to provide the facility of control to a permanent magnet eddy current machine, it is necessary to be able to adjust the rate of change of magnetic flux linkage of the conducting cylinder. One way this can be done is moving the magnets [1]. Fig. 3 presents the varying airgap spacing between the magnet rotors and the conductor rotors that result in controlled output speed. The output speed is adjustable, controllable, and repeatable. The permanent magnet rotor can be magnetized as highlighted in Fig. 4 where the magnetizing topologies of permanent magnet eddy current machines are shown. Figs. 4(a) and (b) show external magnet topologies with conventional radial and parallel magnetized magnets, respectively. Fig. 4(c) gives the topology with the exterior polar Halbach magnetization, while Fig. 4(d) provides the topology with horizontally magnetized magnets separated by iron pole pieces. In Halbach magnetized topology, the moving (or stationary) part including magnets can be either air-cored or iron-cored in the primary steel region. Table 1 shows the specifications of the permanent magnet eddy current machine.

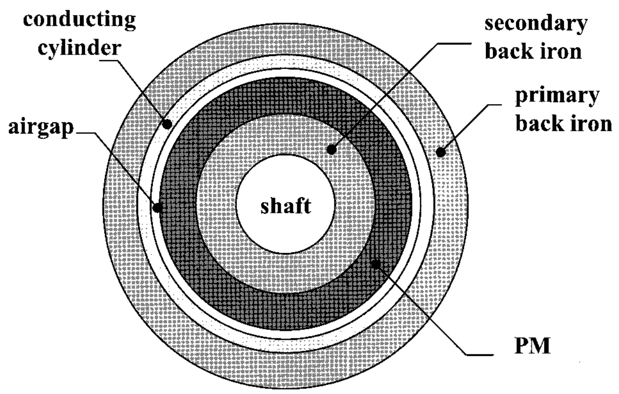

Fig. 2. Cross-sectional schematic of analysis model.

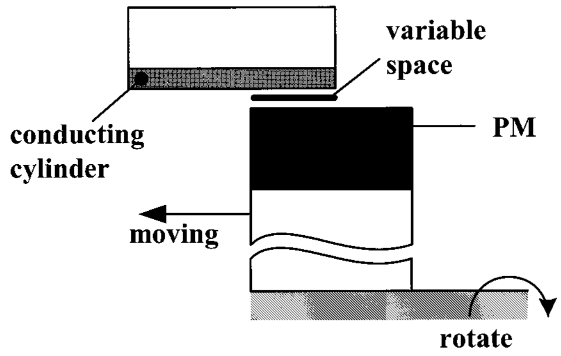

Fig. 3. Variation of airgap spacing between the magnet rotor and the conductor rotor.

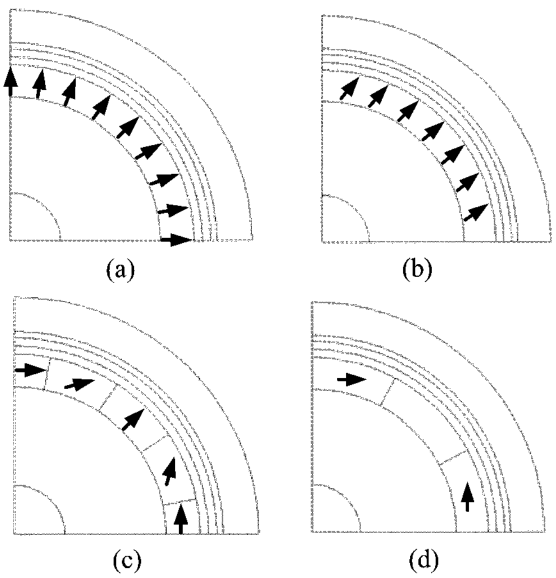

Fig. 4. Permanent magnet eddy current machine topologies according to magnetization patterns: (a) radial magnetization, (b) parallel magnetization (c) Halbach magnetization, and (d) horizontal magnetization.

3. Finite Element Analysis Model

The 2-dimensional dc steady state eddy current analysis of permanent magnet eddy current machines is carried out using a moving coordinate system [5].

The eddy currents are located in the moving conducting cylinder only, with a distribution that is fixed with respect to the magnetic frame of reference.

Since the eddy currents reflect the pole structure of the exciting field (the permanent magnets), only one pole pitch is required to solve the field problem completely [4]. Maxwell's equation is therefore reduced to the following.

$$\text{curl}\ \vec{H} = \vec{J} \qquad (1)$$

$$\text{div}\ \vec{B} = 0 \qquad (2)$$

When the moving part including the magnets rotates, eddy currents are induced in the conducting cylinder. In the moving conductor region, the governing equations using the A-ϕ method are given by

$$\text{curl}\,\nu\,\text{curl}\vec{A} = \sigma\left(\vec{u} \times \text{curl}\vec{A} - \text{grad}\,\phi\right) \quad (3)$$

$$\text{div}\left\{\sigma\left(\vec{u} \times \text{curl}\vec{A} - \text{grad}\,\phi\right)\right\} = 0 \quad (4)$$

Where :

$\vec{A}$ magnetic vector potential;

$\vec{u}$ velocity;

ϕ electric scalar potential;

ν, σ reluctivity and conductivity of the material, respectively;

In the permanent magnet region, the governing equation is expressed as

$$\text{curl}\,\nu\,\text{curl}\vec{A} = \nu\,\text{curl}\vec{M}, \quad (5)$$

Where : $\vec{M}$ is the magnetization vector.

The braking torque, T, developed by the brake (or coupler) is related to the total eddy current loss, W_e, and the angular velocity, ω, as follows:

$$T = \frac{W_e}{\omega} \quad (6)$$

Under the condition of a given speed, the analysis is carried out every 1.5 degrees of the moving part rotation at the initial position.

4. Parametric Analysis

In this section, the influence of magnetization pattern and physical design parameters of the permanent magnet eddy current couplings and brakes are investigated. The study is performed using the 2-dimensional finite element analysis.

4.1 Influence of Magnetization Pattern

As is well known, permanent magnet machine performance is influenced by the magnetization pattern of the rotor permanent magnet.

Fig. 5 shows the magnetic field distributions at the air-gap according to the magnetization patterns of each rotor topology, respectively, when the magnet cylinder is at a standstill.

For a fixed value of the magnet height, Fig. 6 compares the air-gap flux density distributions versus the angular position of each. It can be seen that Halbach magnetized topology with back-iron has superior flux density in the air-gap region.

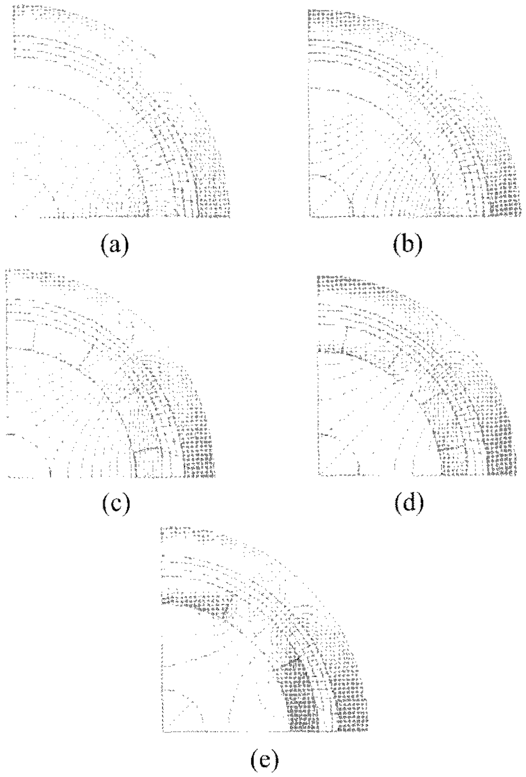

Fig. 5. Magneto-static field distributions according to magnetization patterns:
(a) radial magnetization with back-iron
(b) parallel magnetization with back-iron
(c) Halbach magnetization with back-iron
(d) Halbach magnetization without back-iron
(e) horizontal magnetization without back-iron

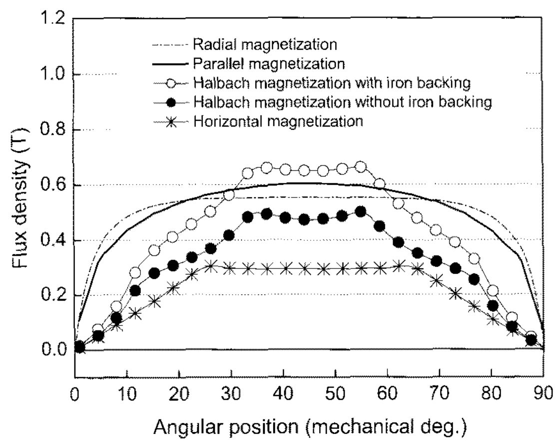

Fig. 6. Airgap flux density distributions of each topology versus angular position. : 0 rpm (standstill)

When the magnet cylinder rotates at 1000 rpm, Fig. 7 shows the magnetic field distributions according to the magnetization patterns of each rotor topology, respectively. Fig. 8 compares the air-gap flux density distributions versus the angular position of each topology. It can be seen that, for the rotation of the magnet cylinder, the air-gap flux density decreases and has a non-uniform distribution due to the effect of eddy current. Fig. 9 shows the proportion of the distortion of air-gap flux density distribution of each topology.

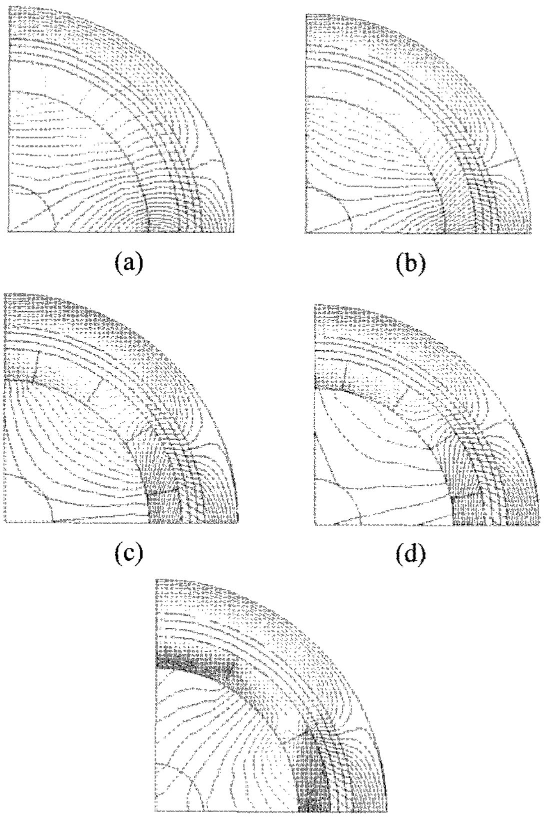

Fig. 7. Magneto-static field distributions according to magnetization patterns at 1000 rpm:
(a) radial magnetization with back-iron
(b) parallel magnetization with back-iron.
(c) Halbach magnetization with back-iron
(d) Halbach magnetization without back-iron,
(e) horizontal magnetization without back-iron.

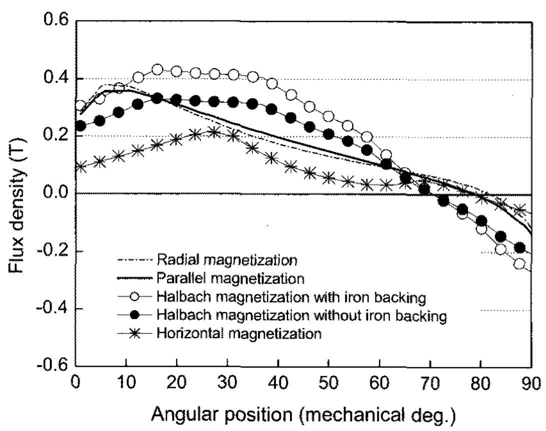

Fig. 8. Airgap flux density distributions of each topology versus angular position: 1000 rpm.

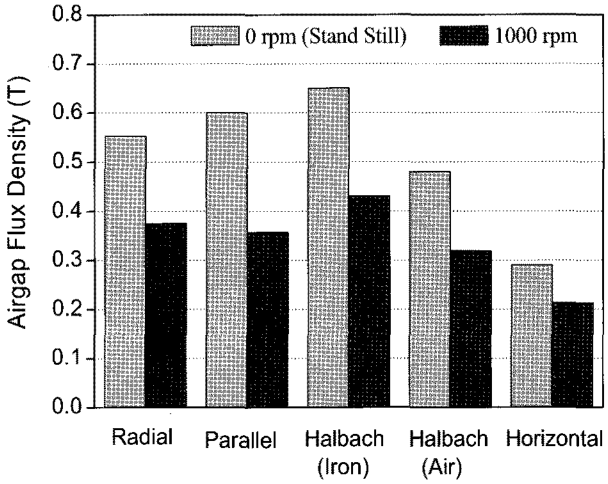

Fig. 9. Proportion of the distortion of airgap flux density distribution for five different magnetization patterns.

4.2 Influence of Magnet Dimensions

One of the most important design parameters is the permanent magnet thickness. In this section, the effect of magnet dimension, thickness, is analyzed. The study has been performed considering a constant magnet volume [2].

Fig. 10 compares the maximum air-gap flux density of each topology for variable permanent magnet thickness. It can be seen that, by increasing magnet thickness, the air-gap flux density increases. Halbach magnetized topology with back-on has superior flux linkage.

For a fixed rotating speed, at 1000 rpm the braking torque increases with magnet thickness. Fig. 11 shows the

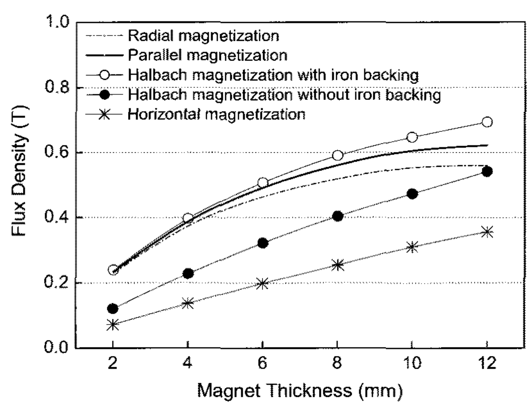

Fig. 10. Variation of peak air-gap flux density vs. magnet thickness for the topologies with five different magnetization patterns; 1000 rpm.

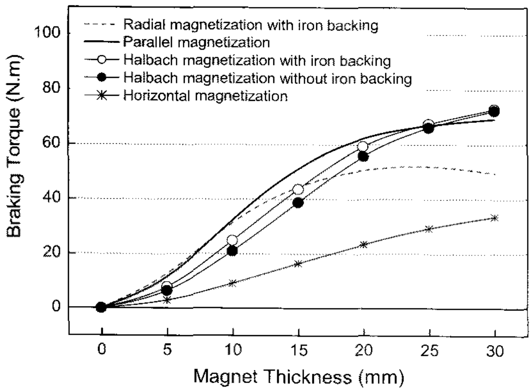

Fig. 11. Variation of peak braking force vs. magnet thickness for the topologies with five different magnetization patterns: 1000 rpm.

variation of the braking torque with the variation of magnet thickness.

5. Speed-Torque Characteristics

The braking torque variation with the rotation speed for various topologies is calculated and plotted in Fig. 12 for given values of the magnet thickness, axial length, and air-gap.

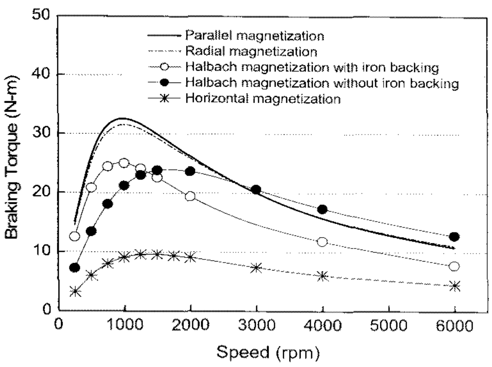

Fig. 12. Braking torque vs. speed for various topologies.

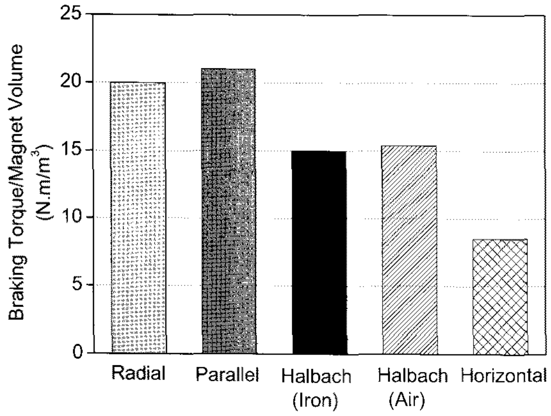

Fig. 13. Comparison of braking torque per magnet volume for five different topologies.

The results are shown with an iron / aluminum rotor and the torque-speed curve has its peak value of 33 N·m between 900-1000 rpm in the parallel magnetized eddy current coupling and brake model.

Fig. 13 compares the maximum braking torque per magnet volume for each topology. From these analysis results, it can be seen that the parallel-magnetized topology has the superior braking torque performance.

6. Conclusion

The magnetic field and torque-speed characteristics of permanent magnet eddy current couplings and brakes with five different magnetization patterns have been analyzed and discussed using the 2-dimensional finite element method for the eddy current analysis. And the influences of several geometrical and physical design parameters have investigated. A comparative study has shown that the parallel-magnetized eddy current topology has the superior braking torque capability. A further study on the analytical approach in eddy current machines with parallel magnetized rotor and experimental verification is required.

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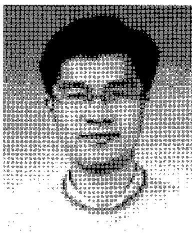

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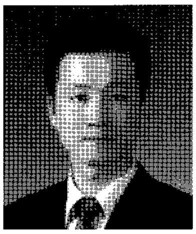

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