



# Design of Axial Flux Type Permanent Magnet Coupling with Halbach Magnet Array for Optimal Performance Considering Eddy Current Loss Reduction Using 3-D Finite Element Method

Gang-Hyeon Jang<sup>1</sup>, Sung-Won Seo<sup>1</sup>, Chang-Woo Kim<sup>1</sup>, Kyung-Hun Shin<sup>1</sup>, Junghyo Nah<sup>1</sup>, Jang-Young Choi<sup>1\*</sup>

<sup>1</sup>Department of Electrical Engineering, Chungnam National University, 99 Daehak-ro Yuseong-Gu, Daejeon, KS015, Korea

\*Corresponding author E-mail: [choi\\_jy@cnu.ac.kr](mailto:choi_jy@cnu.ac.kr)

## Abstract

**Background/Objectives:** This study proposes and verifies a design method that considers the permanent magnet (PM) loss reduction of axial flux permanent magnet coupling (PMC), to replace mechanical coupling.

**Methods/Statistical analysis:** In this study, the design of an axial magnetic flux PMC is performed using a three-dimensional (3D) commercial finite element (FEM) analysis program, and an optimum design is performed through parametric analysis. In addition, we designed a PMC that minimizes loss by analyzing the PM eddy current loss when using divided magnets.

**Findings:** We found that some parameters (thickness of the PM, number of poles, ratio of inner radius to outer radius) act on the magnetic torque of the axial flux coupling. Using these results, we could obtain the design point. Further, to reduce the PM eddy current loss in the designed coupling, we used the PMs divided radially and circumferentially to obtain the magnet shape to minimize the loss. In addition, the fabricated coupling proved that the design results of the 3D FEM matched with the experimental results.

**Improvements/Applications:** We propose an optimal design method of an axial flux PMC using 3D FEM, and a method to reduce eddy current loss using divided magnets

**Keywords:** magnetic coupling, Halbach magnet array, parametric analysis, magnet eddy current loss, 3D finite element method.

## 1. Introduction

In general, mechanical coupling is used in devices that transmit torque from engines or electric machines. Mechanical coupling may cause torque breakage above the allowable torque of the coupling. This causes damage to the parts because of the variation in torque, and results in dust leakage. Accordingly, regular lubrication and part replacement costs are incurred.

Permanent magnet couplings (PMCs) transmit torque without any mechanical contact. Thus, the mechanical loss is reduced, and if excessive torque is delivered, the damage will be prevented by slip. This has advantages in reducing maintenance costs. In addition, the vibration transmitted to the equipment can be reduced, thereby extending the life of and protecting the equipment when an overload occurs. It can also be used in environments where walls are placed in between, or in a vacuum[1,2,3]. In particular, axial flux permanent magnet coupling (AFPMC) has the advantage of compact and flat construction. Furthermore, it can achieve a high torque-to-weight ratio[4]. Owing to the structural characteristics of the AFPMC, as shown in Fig. 1, its analysis requires the three-dimensional finite element method (3D FEM)[5]. Analyzing the magnetic torque of AFPMCs with a Halbach array is very important because the operation area of the PMCs is restricted to the maximum allowable torque. By accurately predicting the maximum torque value, the product can be minimized, and unnecessary production costs can be reduced. Therefore, in this study, we predict the

magnetic torque characteristics according to the design parameters such as the inner PM radius to the outer PM radius ratio, PM thickness, and pole numbers. To acquire the magnetic torque analysis results of the AFPMCs, we used the 3D FEM. To verify the analysis result from the 3D FEM, the maximum torque value of each airgap was measured and compared using an actual manufactured AFPMC. A PMC has the advantage of transmitting torque without mechanical contact. In the case where the torque is applied to an engine with a large fluctuation, or slip occurs beyond the limit torque, an eddy current caused by a change in the magnetic flux can be generated inside the PM. This can cause heat loss and partial demagnetization of the PM. Demagnetization is a major cause of PMC performance deterioration. Therefore, it is important to design a feature that can reduce the eddy current loss.

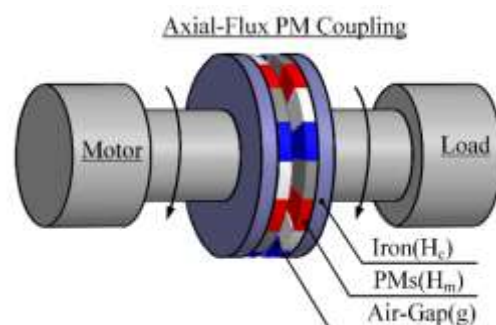


Figure1: Conceptual diagram of permanent magnet coupling system.

## 2. Parametric Analysis for Optimal Design

The maximum torque is determined by several variables: the iron core thickness, PM thickness, inner and outer radii of the magnets, and number of PM poles [6,7].

Parametric analysis was performed to obtain the design points where the PMC can have the maximum torque value at the fixed limit of the PM outer radius and core thickness. The design variables to be obtained were the inner radius, thickness, and the number of pole-pairs of the PM.

First, the number of pole-pairs in which the maximum torque was generated and the inner radius was checked while varying the number of pole-pairs and the inner radius of the PM. Next, the thickness and inner radius, at which the maximum torque was generated, were checked for changes in the PM thickness and inner radius. Finally, the point at which the maximum torque was generated for each airgap with respect to the inner radius of the PMC was identified.

## 3. Results Obtained with 3D Finite Element Analysis

The magnetic torque of the AFPMCs with a Halbach array is critical because the operation area of the PMCs is restricted by the maximum allowable torque [8-10]. By accurately predicting the maximum torque value, the product can be minimized, and unnecessary production costs can be reduced [11].

### 3.1. Number of PM Poles

The PM thickness was 6.5 mm, the outer radius of the PM was 71.5 mm, and the airgap length was fixed at 6 mm. We analyzed the point where the maximum torque was generated while varying the number of pole-pairs and the inner radius of the PM. Fig. 2 shows the results of the analysis. As shown, when the number of pole-pairs of the PM was four, the inner radius was 30–34 mm, which is the same as the result of the analysis above.

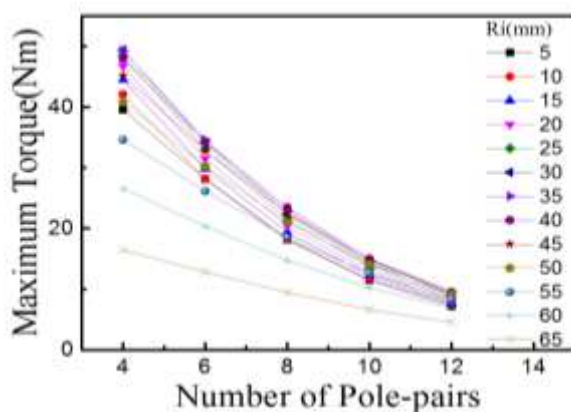


Fig.2: Parametric analysis results according to number of pole-pairs and inner radius of PM.

### 3.2. PM Thickness

Parametric analysis was performed to obtain the point at which the maximum torque was generated by varying the thickness and inner radius of the PM while the number of pole-pairs was four, the airgap length was 6 mm, and the PM was fixed at an outer radius of 71.5 mm. Fig. 3 shows the results of the analysis. We confirmed that the largest torque was generated when the PM thickness was 6–7 mm and the inner radius was 30–34 mm.

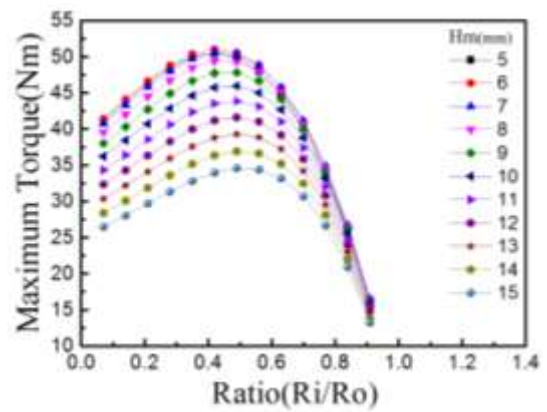


Fig.3: Parametric analysis results according to inner radius of PM and PM thickness.

### 3.3. Airgap Length and Inner Radius of Magnets

The number of pole-pairs of the PM was fixed at four, and the thickness of the PM was 8 mm. If the outer radius was 71.5 mm, the maximum torque was generated while changing the inner radius of the PM from the respective airgap. Parametric analysis was performed to examine the inner radius. Fig. 4 shows the results of the analysis, confirming that the maximum torque was generated at an inner radius of 30–34 mm.

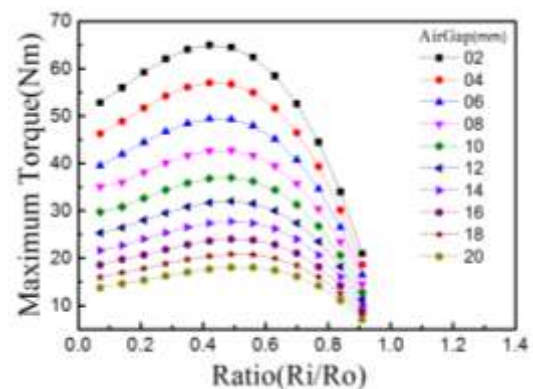


Fig.4: Parametric analysis results according to inner radius of PM and airgap length.

## 4. Experimental Results and Comparison

The optimal design of the AFPMC was performed based on several parametric results. The manufactured AFPMC with the Halbach array is shown in Fig. 5. The PMs were fabricated to consist of four poles, and a two-segment Halbach array. The core material was 35PN230, and the PM material is NdFeB, with a residual magnetic flux density of 1.3 T. The design specifications of the manufactured AFPMC are shown in Table I. To verify the parametric analysis results, the results were compared based on the experimental results of a manufactured AFPMC with the same specifications. Fig. 6 shows the comparison of the maximum torque values obtained from the 3D FEM and the experiment. The results obtained when the airgap changed from 18 mm to 28 mm was compared, and the error between the 3D FEM and the experimental results are shown by the blue line in Fig. 6. We confirmed that the error of the FEM results was 8% or less at the maximum, and that the maximum torque value of the AFPMC was relatively close to the experiment result. Additionally, N42SH PMs have residual magnetic flux densities of up to 1.3 T, but the residual magnetic flux density of the PM used in manufacturing may be lower than 1.3 T. This is thought to be the reason for the error.

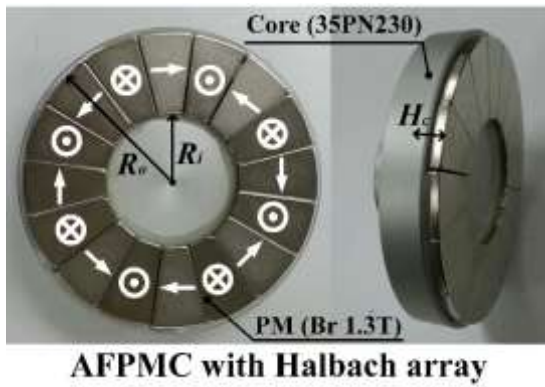


Fig.5: Actual manufactured axialflux permanent magnet coupling with Halbach array using parametric analysis results.

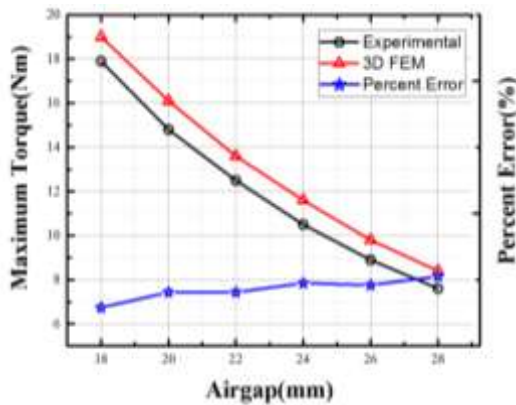


Fig.6: Comparison of measured results of the maximum torque with 3D FEM and experiment according to airgap length.

Table1: PARAMETERS OF THE MANUFACTURED PROTOTYPE AFPMC

Symbol	Quantity	Value
$R_o$	Permanent magnet outer radius	71.5 mm
$R_i$	Permanent magnet inner radius	32 mm
$g$	Air gap	Variable
$H_m$	Permanent magnet thickness	6.5 mm
$P$	Number of pole pairs	4
$H_c$	Iron core thickness	8.8mm
$w_r$	Rated Speed	2000 rpm

## 5. Eddy Current Loss Analysis and Reduction Design

Eddy current may be generated inside the PM when the torque transmitted to the PMC fluctuates or slip occurs beyond the maximum permissible torque of the PMC. The torque fluctuation generally implies the synchronous variation in the torque. In other words, it refers to the fluctuation of the crankshaft due to the gas pressure acting on the piston in the engine and the inertial force due to the motion of the piston and connecting rod. Therefore, we report a design method for an AFPMC that reduces eddy current loss. In our study, a method of reducing the eddy current loss by dividing the PM is used.

### 5.1. Eddy Current Loss Analysis of Manufactured Model

Fig. 7 shows the results of the eddy current analysis when slip occurs in the fabricated model. In this analysis, the case when the airgap length was 3 mm was analyzed. The part that appears red is the portion where the eddy current density is relatively high. As

the temperature of the red part increases, a partial demagnetization phenomenon may occur, and the magnetic flux density of the PM may be reduced. Hence, it is partly responsible for the degradation of the PM performance.

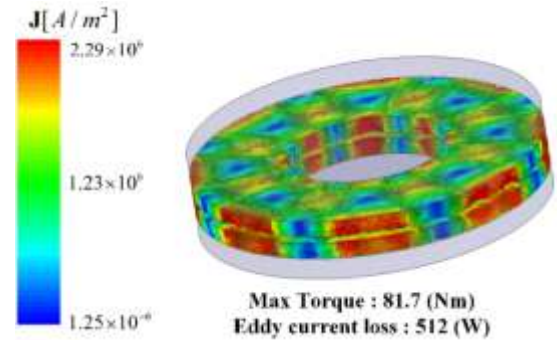


Fig.7: Eddy current distribution of manufactured model.

### 5.2. Proposed Model 1 Using Radially Divided Magnets

Fig. 8 shows a method of radially dividing the PM of the coupling. One PM is divided into two magnets. Therefore, 32 PMs are used on the upper and lower sides, respectively. Compared with Fig. 7, it shows that a relatively small amount of eddy current is generated.

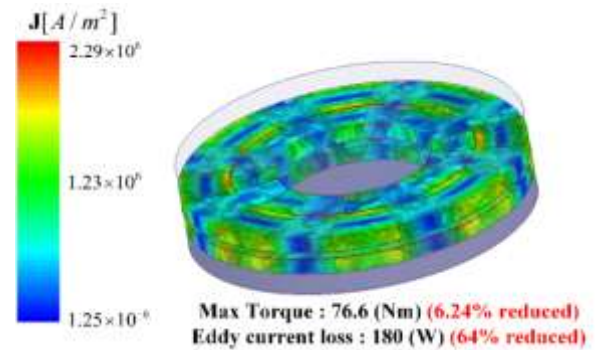


Fig. 8: First proposal for reducing eddy current loss.

### 5.3. Proposed Model 2 Using Circumferentially Divided Magnets

Additionally, we propose a method of dividing the PMs in the circumferential direction. The structure of the four poles is as follows: Two segments will have 16 poles at the top and bottom, respectively, as shown in Fig. 7. The magnetic pole angle of the basic model is 22.5°. In our study, the magnetic pole angle is 22°, to be divided in the circumferential direction. Subsequently, the upper and lower sides will have 16 magnets each. Fig. 9 shows the results of the eddy current density analysis using circumferentially divided magnets.

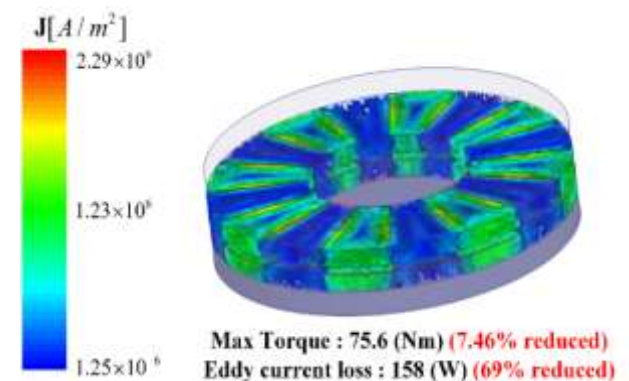


Fig.9: Second proposal for reducing eddy current loss.

#### 5.4. Proposed Model 3 Using Radially and Circumferentially Divided Magnets

Next, we propose a method of dividing the magnets in the radial and circumferential directions. As such, the upper and lower sides will have 32 magnets each. Fig. 10 shows the results of the eddy current density analysis using circumferentially and radially divided magnets.

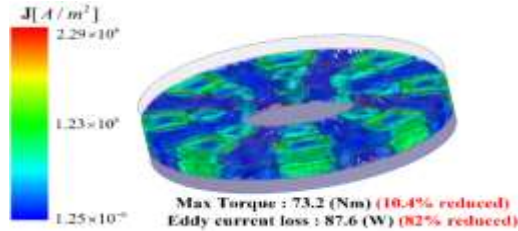


Fig.10: Third proposal for reducing eddy current loss.

## 6. Results and Discussion

In this section, the analysis results of the manufactured model and the three proposed models are analyzed and summarized. The PM angle, the radius of the magnet divided in the radial direction, the PM volume, the eddy current loss, and the maximum torque value generated are shown in Table II. The analysis results of the proposed model show that the eddy current loss is significantly reduced. In particular, the results of model 3 show that the maximum torque value is reduced by 10.4%, and the eddy current loss is reduced by 82%.

Therefore, PM demagnetization can be prevented by reducing the eddy current density while having a torque that is not significantly different from that of the previously manufactured model.

Table2: Comparison of Analysis Result According to Design Method

Parameter	Actual Model	Model 1	Model 2	Model 3
Number of Poles	8	8	8	8
Pole angle(°)	22.5	22.5	22	22
PM radius(mm)	32~71.5	32~50, 50.5~71.5	32~71.5	32~50, 50.5~71.5
PM Volume(mm <sup>3</sup> )	166,944	164,864	163,255	161,216
Eddy current loss(W)	512	180 (64%)	158 (69%)	87.6 (82%)
Maximum Torque (Nm)	81.7	76.6 (6.24%)	75.6 (7.46%)	73.2 (10.4%)

## 7. Conclusion

Herein, the optimal design of an AFPMC that can replace mechanical coupling has been described. Parametric analysis was performed using the 3D FEM under limited conditions, and an AFPMC was manufactured based on the analysis results. The experimental results and the analysis results of the manufactured AFPMC were compared, in which we confirmed that the analysis results were in good agreement with the experimental results. Next, the eddy current loss analysis was performed, and three methods for eddy current loss reduction were proposed. Using the proposed reduction methods, we confirmed that the maximum torque of the AFPMC can be reduced slightly, and the amount of eddy current loss can be reduced considerably. The optimal design point for reducing the eddy current loss can be found in model 3 through a detailed analysis. The methods presented herein are expected to be useful for the optimum design of an AFPMC considering the reduction of eddy current loss.

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