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RESEARCH ARTICLE

Comparative Study of Permanent Magnet Shapes in Outer Rotor PMSM for EC Fan in Data Center

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ABSTRACT With the rapid growth of AI data centers, high-efficiency electrical machines have become increasingly important for HVAC applications. Outer-rotor surface permanent magnet synchronous motors (SPMSMs) with ferrite magnets are widely adopted for electrically commutated (EC) fans in AI data centers due to their low cost and high efficiency. Since the electromagnetic performance of SPMSMs is significantly influenced by the permanent magnet shape, extensive studies have been conducted to improve efficiency and reduce torque ripple. In this paper, a comparative study of outer-rotor PMSMs with four permanent magnet shapes—chamfer, linear chamfer, taper, and cycloid—is conducted for EC fan applications. For a fair comparison, all models are optimized under identical constraints using a multi-objective genetic algorithm (MOGA) based on finite element analysis (FEA). Electromagnetic characteristics, including back electromotive force (BEMF), torque, torque ripple, and efficiency, are evaluated. The results show that the chamfer-type magnet achieves the highest efficiency despite slightly higher harmonic components. To validate the FEA results, a prototype is manufactured and experimentally evaluated under both no-load and load conditions. The FEA results are validated through the comparison with the experimental results, demonstrating a BEMF error of 1.4 % and an efficiency deviation of less than 1 %. In addition, the efficiency of the prototype motor satisfies the IE5 efficiency class according to the IEC 60034-30-2.

INDEX TERMS Data center, electrically commutated fan, electrically commutated motor, shape of permanent magnet, surface-mounted permanent magnet synchronous motor (SPMSM).

I. INTRODUCTION

With the increasing usage of artificial intelligence (AI), the heat generated within data centers has significantly increased. It leads to a growing demand for HVAC (heating, ventilation, and air conditioning) systems, as illustrated in Fig. 1 [1], [2], [3], [4], [5]. HVAC systems regulate indoor thermal environments by controlling temperature and airflow. They consist of cooling units and air-moving components, such as

fans and air-handling units, that work together to reduce heat and maintain stable operating conditions.

HVAC systems in a data center manage the high heat loads generated by IT equipment. These systems commonly employ computer room air conditioning (CRAC) units and air handling units equipped with variable frequency drive (VFD) fans to match airflow rates to changing thermal demands [1]. Because continuous cooling and air circulation are required, HVAC systems consume a significant portion of the total energy in data centers. As a result, improving the efficiency of HVAC systems is essential to reducing the

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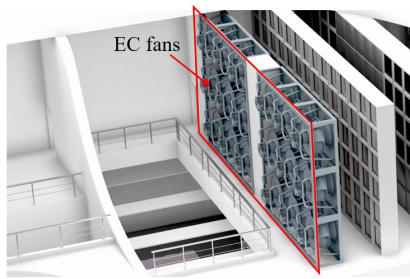


FIGURE 1. HVAC in AI data center, adapted from [5].

overall Power Usage Effectiveness (PUE) [6], [7], [8], [9]. Conventional alternating current (AC) fans have been widely used in HVAC systems due to their simple structure and low initial cost. However, AC fans driven by induction motors without VFD typically operate at a fixed speed determined by the input frequency, which limits their operating range [10]. Although AC fans with variable frequency drives can operate over a wide speed range to improve system efficiency, they increase system complexity and cost due to the requirement of additional external components that are not integrated into AC fans. As a result, the overall system becomes a bulky system, as illustrated in Fig. 2(a). To overcome these limitations, electrically commutated (EC) fans have been studied as an alternative solution for HVAC systems in AI data centers. EC fans integrate the motor and drive into a single compact unit, eliminating the need for external control devices, as illustrated in Fig. 2(b) [5]. This integrated structure enables speed control, improved energy efficiency, and reduced system complexity. In particular, EC fans can adjust airflow according to operating conditions, leading to significant energy savings compared to conventional AC fans. In addition, EC fans offer additional advantages such as lower noise, higher reliability, and reduced maintenance requirements, as shown in Fig. 3 [12].

Among various motor types, permanent magnet synchronous motors (PMSMs) using ferrite magnets are widely adopted in EC fan applications because they have a low cost and lower eddy current losses in the magnets than rare-earth permanent magnets. However, ferrite magnets have relatively low magnetic flux density compared with rare-earth permanent magnets. To compensate for these limitations, outer-rotor PMSM structures have been investigated. Although the outer rotor is structurally more complex than the inner rotor, the increased air-gap flux density improves the output capability of the motor.

In surface-mounted PMSMs (SPMSMs), since the permanent magnets are directly exposed to the air gap, the air-gap flux density is primarily determined by the rotor geometry. The air-gap flux density directly affects motor performance, as its fundamental component is related to back-EMF and torque production, while its harmonic components contribute to torque ripple. Accordingly, the electromagnetic performance of PMSMs has been widely studied with respect

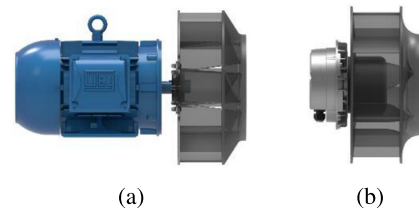


FIGURE 2. Structure of fans (a) AC fan (b) EC fan, reproduced from [11].

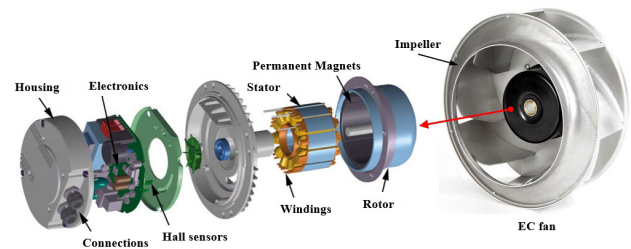


FIGURE 3. Exploded view of EC fan, adapted from [12].

to permanent magnet shape design [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. To improve torque performance and reduce torque ripple, various studies have focused on optimizing the permanent magnet shape. Methods such as harmonic-based magnet shape design and sinusoidal-based optimization were proposed to improve torque performance and reduce air-gap flux density harmonics [13], [14], [15], [16]. In [17] and [18], studies have investigated uneven magnet shapes and eccentric rotor structures to compensate for unbalanced winding distribution and reduce unbalanced magnetic pull. Various magnet shapes, such as cycloid, axial, butterfly, egg, and loaf shapes, have been compared to improve torque density and reduce torque ripple [19], [20], [21]. Despite these studies, a comprehensive and systematic comparison of electromagnetic performance under identical design conditions has not yet been fully explored.

In this paper, a comparative analysis of outer-rotor PMSMs with four permanent magnet shapes—chamfer, linear chamfer, taper, and cycloid—is conducted for EC fan in AI data centers. For a fair comparison, all models are optimized under identical design constraints using a multi-objective genetic algorithm (MOGA) based on finite element analysis (FEA). The electromagnetic characteristics of the optimized models, including back electromotive force (BEMF), torque, torque ripple, and efficiency, are evaluated. Based on the optimization results, the chamfer-type magnet has superior performance compared to the other configurations. The selected model is fabricated, and its performance is experimentally validated through no-load and load tests. Furthermore, efficiency is evaluated at standardized operating points defined in IEC 61800-9-2 for variable drive speed applications. The experimental results confirm the accuracy of the FEA predictions and demonstrate that the proposed

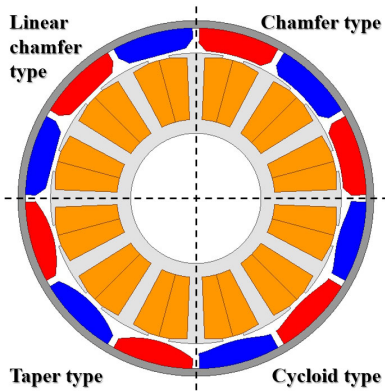


FIGURE 4. Shape of magnet type model.

TABLE 1. Machine specification.

Parameter	Value	Unit
Rated output power	3	kW
Rated speed	3200	rpm
Rated current	6	A _{rms}
Number of pole / slot	10 / 12	-
Diameter of stator outer / rotor inner	142 / 116	mm
Stack length	80	mm
Number of turns per coil	59	-
Stator core material	50PN470	-
Rotor core material	SS400	-
Permanent magnet material	PMF-7BE	-

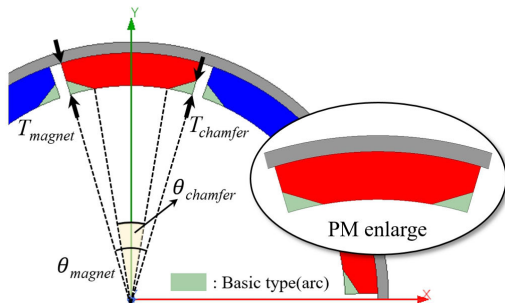


FIGURE 5. Shape and design variables of chamfer type.

motor satisfies the IE5 efficiency class according to IEC 60034-30-2 [23].

This paper is organized as follows. Section II describes the design variables for each magnet shape. Section III presents the MOGA-based optimization method and results. Section IV compares the electromagnetic characteristics of the optimized models. Section V discusses the manufacture and experimental validation. Finally, VI concludes the paper.

II. DESIGN VARIABLES OF PERMANENT MAGNET SHAPE

Four types of permanent magnets are selected: chamfer, linear chamfer, taper, and cycloid, as illustrated in Fig.4.

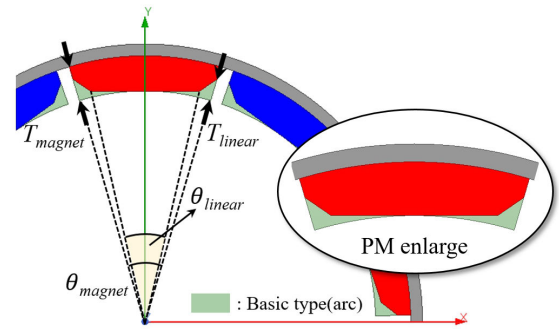


FIGURE 6. Shape and design variables of linear chamfer type.

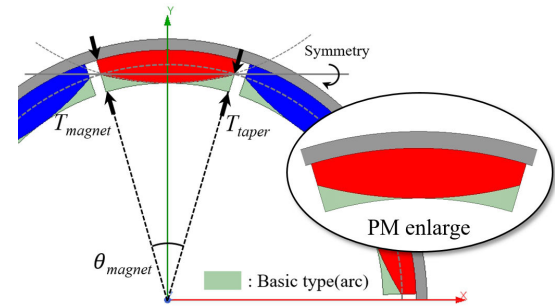


FIGURE 7. Shape and design variables of taper type.

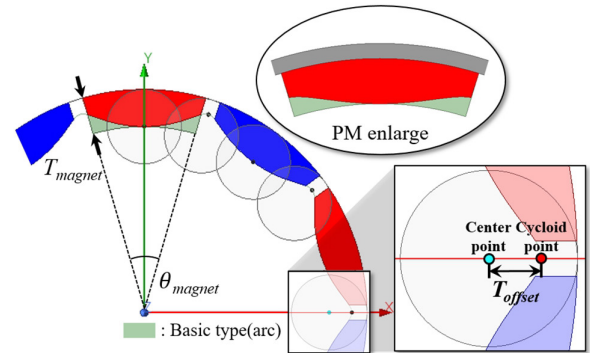


FIGURE 8. Shape and design variables of cycloid type.

The common design variables are defined as T_{magnet} , which represents the permanent magnet thickness, and θ_{magnet} , which represents the permanent magnet angle. The machine specifications listed in Table 1 were selected considering representative operating conditions of industrial EC fan systems for HVAC applications in AI data centers. In particular, the rated output power and speed were determined based on practical ventilation and cooling requirements. In addition, ferrite permanent magnets and an outer-rotor structure were adopted to achieve cost-effective operation for EC fan applications.

The chamfer type is derived from the conventional arc-type permanent magnet, with chamfered corners applied at both ends, as shown in Fig. 5. The design variables for the chamfer PM are defined and compared with those of the conventional

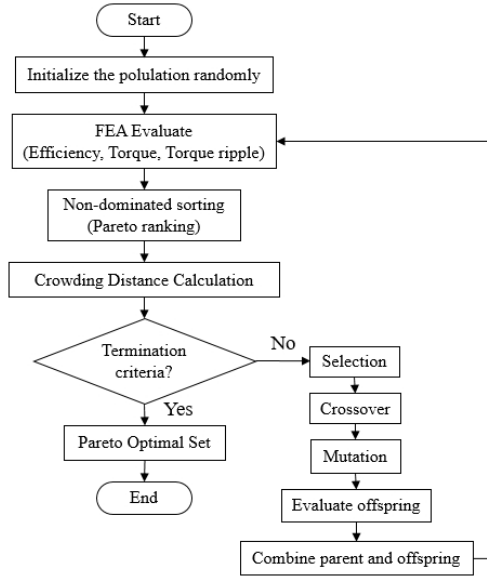


FIGURE 9. Flowchart of MOGA.

arc type in Fig. 5. Specifically, $T_{chamfer}$ means the thickness of the chamfered edges at both ends, while $\theta_{chamfer}$ represents the angular span of the PM excluding the chamfered regions. Based on these definitions, increasing $T_{chamfer}$ and decreasing $\theta_{chamfer}$ result in a more pronounced corner removal from conventional arc type PM.

The linear chamfer type is a shape created based on the chamfer defined above, and the permanent magnet on the gap side is a straight line, as illustrated in Fig. 6. As shown in Fig. 6, the design variables for the linear chamfer type are defined and compared with those for the conventional arc type. The design variables for a linear chamfer can be represented as T_{linear} , which is the thickness of the chamfered edges at both ends, and θ_{linear} , which is the angle between the straight lines. Based on these definitions, an increase in T_{linear} and a decrease in θ_{linear} correspond to a greater extent of material removal from the conventional arc-type geometry.

The taper type is a shape in which the thickness of a PM becomes thinner from the center to both ends. Fig. 7 shows the design variables for the taper type and compares them with those for the conventional arc type. The taper design variable, T_{taper} , indicates the degree of chamfering of the permanent magnet in T_{magnet} . The curvature of a permanent magnet is equal to an arc cut by T_{taper} . The larger T_{taper} , the more the permanent magnet is cut and the greater the curvature.

The cycloid type is a curve that shows how a cycloid point, which is an arbitrary point inside a circle, changes as the circle rotates along the outer diameter of a permanent magnet [19]. Fig. 8 shows the design variables of the cycloid type and compares them with the conventional arc type. T_{offset} , a design variable of the cycloid, is the offset of the cycloid point from the center of the circle rotating along the outer diameter of the permanent magnet. The smaller T_{offset} , the closer it gets to the center of the circle, resulting in a shape

TABLE 2. Design variable range of permanent magnet type.

Type		Design variable	Min	Max	Unit
Common design variables		T_{magnet}	7	9	mm
		θ_{magnet}	0.88	0.98	-
Individual design variables	Chamfer	$T_{chamfer}$	1	4.5	mm
		$\theta_{chamfer}$	0	1	-
	Linear chamfer	T_{linear}	4.5	9	mm
		θ_{linear}	0	1	-
	Taper	T_{taper}	0	4.5	mm
	Cycloid	T_{offset}	0	4.5	mm

similar to a conventional arc type. The Cartesian coordinate values of the cycloid point can be expressed as (1) [19]. θ is the angle of center point of the circle, R_{fc} is outer diameter of permanent magnet, R_{rc} is radius of the circle, n_{wave} is number of pole.

$$x(t) = (R_{fc} - R_{rc}) \cos(\theta) + T_{offset} \cos((n_{wave} - 1)\theta)$$

$$y(t) = (R_{fc} - R_{rc}) \sin(\theta) - T_{offset} \sin((n_{wave} - 1)\theta) \quad (1)$$

III. OPTIMIZATION OF PERMANENT MAGNET SHAPE

A. PROBLEM FORMULATION

To determine the optimal design for each permanent magnet shape, multi-objective optimization was performed on the four permanent magnet shapes presented in the previous section. To investigate the influence of permanent magnet shape, all design parameters except the permanent magnet geometry were kept identical across the four models. The common design variables of the four models were optimized within the same design range to ensure a fair comparison. The optimization objectives were defined to maximize efficiency and average torque while minimizing torque ripple. In particular, the efficiency constraint in (3) was selected based on an empirical standard indicating that an efficiency of 93 % was achievable for the proposed EC fan motor. The objective functions and constraints are expressed as (2)–(5).

$$F(x) = [f_1(x), f_2(x), f_3(x)] \quad (2)$$

$$f_1(x) = \eta(x) = \frac{P_{out}}{P_{in}} \times 100 \geq 93[\%] \quad (3)$$

$$f_2(x) = P_{out}(x) = 3[\text{kW}] \quad (4)$$

$$f_3(x) = T_{ripple}(x) = \frac{T_{max} - T_{min}}{T_{avg}} \times 100 \leq 1[\%] \quad (5)$$

where $\eta(x)$ denotes efficiency, P_{out} is the output power, and P_{in} is the input power. T_{avg} represents the average torque, while T_{max} and T_{min} denote the maximum and minimum torque values, respectively. In addition to the objective functions, minimum performance requirements were imposed as constraints to ensure feasible motor performance.

B. MULTI-OBJECTIVE OPTIMIZATION

To solve the optimization problem defined in Section III-A, a multi-objective genetic algorithm (MOGA) was employed.

TABLE 3. Constraints of optimal design.

Parameter	Value	Unit
Efficiency	≥ 93	%
Output power	$= 3$	kW
Torque ripple	≤ 1	%

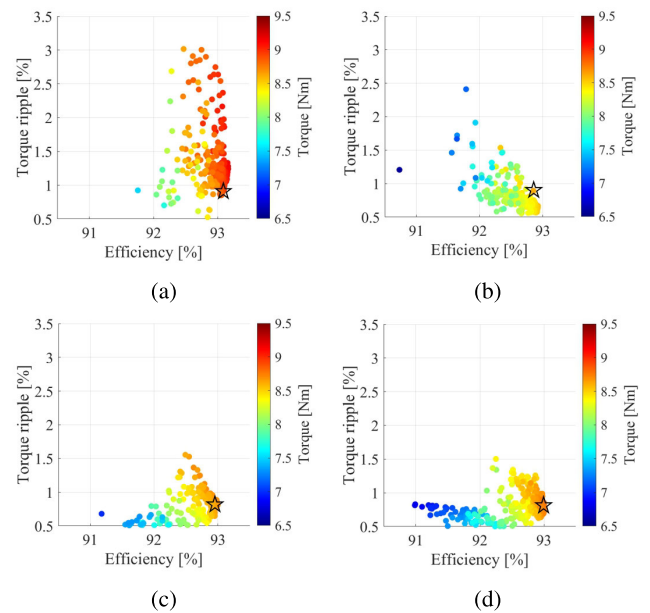
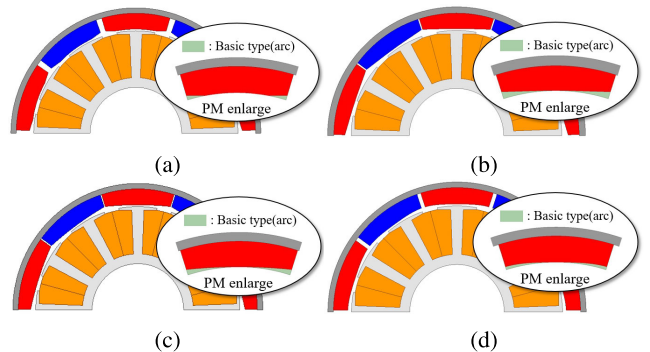
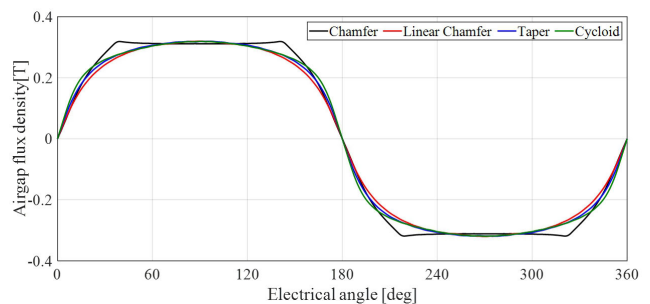
TABLE 4. Performance comparison with optimal models for each permanent magnet shape.

Contents	Chamfer	Linear chamfer	Taper	Cycloid	Unit
Power	3				kW
Torque	8.96				Nm
Current	5.6	5.84	5.74	5.75	A _{rms}
Torque ripple	0.91	0.88	0.84	0.82	%
Efficiency	93.04	92.76	92.92	92.91	%

MOGA is widely used for multi-objective optimization problems because it can obtain a set of Pareto-optimal solutions that account for trade-offs among multiple objective functions [24], [25]. The overall optimization procedure is presented in Fig. 9. First, the initial population is randomly generated within the predefined design variable ranges. Each individual represents a candidate design of the permanent magnet shape. The objective functions, including efficiency, average torque, and torque ripple, are evaluated using FEA. After the evaluation process, non-dominated sorting is performed to classify the individuals according to Pareto dominance. The crowding distance is then calculated to maintain diversity among the solutions. Based on the ranking and crowding distance, selection, crossover, and mutation operators are applied to generate offspring populations. The parent and offspring populations are subsequently combined, and the non-dominated sorting process is repeated to select the next generation. This iterative process continues until the termination criterion is satisfied, resulting in a set of Pareto-optimal solutions for each permanent magnet shape. The optimization was performed for the four permanent magnet shapes under rated conditions.

C. OPTIMIZATION RESULTS

The multi-objective optimization was independently performed for the four permanent magnet shapes. Although the objective functions were identical across all models, the design variables comprised both common and geometry-specific variables, depending on the permanent magnet shape. The common design variables were optimized within the same range to ensure a fair comparison among the four models, while individual design variables were introduced to describe the geometric characteristics of each permanent magnet type. The design variables and their corresponding ranges for each model are summarized in Table 2. The optimization objectives were defined to maximize efficiency

**FIGURE 10.** Pareto-optimal solutions of each permanent magnet shape (a) chamfer type (b) linear chamfer type (c) taper type (d) cycloid type.**FIGURE 11.** Shape comparison of optimal models (a) chamfer type (b) linear chamfer type (c) taper type (d) cycloid type.**FIGURE 12.** Waveforms of airgap flux density for the each model.

and average torque while minimizing torque ripple, as shown in Table 3. These objective functions were applied equally to all four permanent magnet shapes to investigate the influence of magnet geometry on motor performance. The optimization results for each permanent magnet type are illustrated in

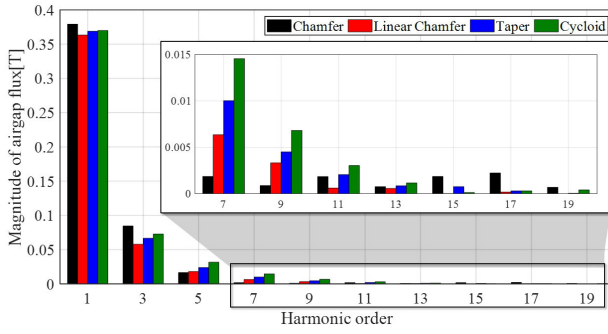


FIGURE 13. FFT results of airgap flux density for each model.

Figs. 10 and 11. As shown in Fig. 10, the x -axis indicates efficiency, while the y -axis represents torque ripple. The color bar represents the average torque, and the scales are the same. Among the Pareto-optimal solutions, the final design for each permanent magnet shape was selected based on the objective function. The selected optimal designs are indicated, as illustrated in Fig. 11. The optimal design result of each permanent magnet shape is illustrated in Fig. 10. The electromagnetic performance of the selected models is further evaluated and compared in the following section.

IV. PERFORMANCE COMPARISON

The performance of the optimal model for each permanent magnet shape is evaluated in this section. Table 4 shows the performance comparison of the optimal models for each permanent magnet. As shown in Table 4, the cycloid model has the lowest torque ripple, while the chamfer has the highest, but the gap is not significant. The chamfer model has the highest efficiency, while the taper and cycloid models are similar, and the linear chamfer model has the lowest.

Since the airgap flux density significantly influences motor performance, the waveforms of airgap flux density are compared, as illustrated in Fig. 12. To isolate the effect of magnet geometry from slot harmonics, the comparison is performed under a slotless configuration. As shown in Fig. 12, although the overall waveforms exhibit similar tendencies, differences in the waveform shape and magnitude are observed depending on the permanent magnet geometry. The airgap flux density is represented in the radial direction from the airgap perspective. In the chamfer model, the center region of the permanent magnet maintains an arc shape, resulting in a relatively constant airgap length and a partially flat waveform region. In contrast, the linear chamfer model is more significantly modified from the conventional arc-type geometry, resulting in the lowest airgap flux density among the models. The taper and cycloid models retain more of the conventional arc-type geometry than the linear chamfer model, leading to relatively higher airgap flux density waveforms. Although the chamfer type shows relatively larger harmonic distortion, it has a slightly higher fundamental gap flux component, which allows higher output power under identical current. Fig. 13 presents the FFT results

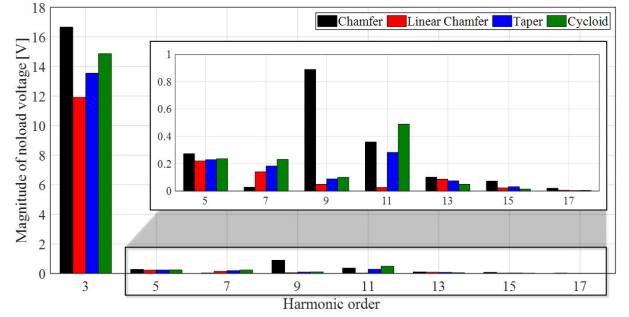


FIGURE 14. Noload voltage harmonic of the models.

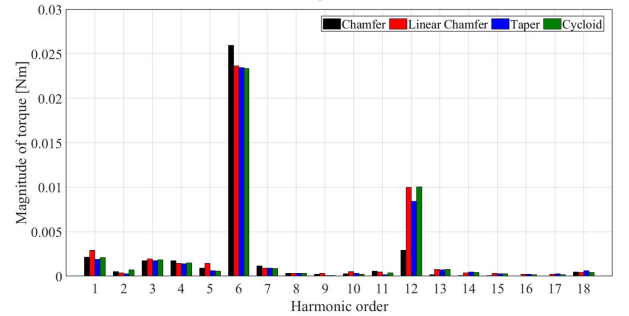


FIGURE 15. Torque harmonic comparison of the models.

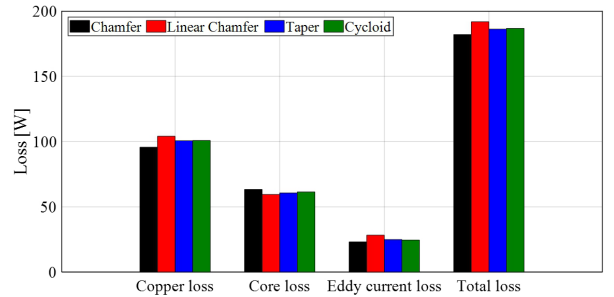


FIGURE 16. Comparison with electromagnetic loss of the optimal models for permanent magnet shape.

of the airgap flux density. The magnitude of the fundamental component varies slightly depending on the shape, demonstrating that the chamfer type is higher than other types. In the 3rd-order harmonic, the magnitude decreases in the order of chamfer, cycloid, taper, and linear chamfer. Fig. 14 shows the magnitude of harmonic component by analyzing the no-load voltage through FFT, indicating that the chamfer type has larger fundamental component while it contains relatively larger harmonic components. Therefore, the chamfer type is superior compared with other types while the torque ripple of the chamfer type is higher than that of other types.

The torque ripple of SPMSM can be expressed as follows [26]:

$$T_{\text{ripple}} = -\frac{pL_{stk}R_g g \pi}{\mu_0} \times \sum_{n=1}^{\infty} (6n \mp 1) B_{r,6n \mp 1} B_{s,6n \mp 1} \sin(6n\omega t \pm \alpha) \quad (6)$$

where p is the number of pole pairs, L_{stk} is the effective stack length, R_g is the average air gap radius, g is the length of the air gap, μ_0 is the permeability of vacuum, $6n$ is the harmonic order of torque, $B_{r,h}$ and $B_{s,h}$ are the h -th harmonic component of air gap magnetic flux density in rotor and stator, respectively, ω is the electrical angular speed, α is the angle at which the current vector leads the d -axis, respectively.

From (6), the torque ripple of SPMSM is directly affected by the harmonic component of airgap flux density, demonstrating that the main torque ripple harmonic order is $6n$. Fig. 15 shows the magnitude of the torque according to the harmonic order by analyzing the FFT. It can be observed that the 6th- and 12th-order components are more significant than the others. The chamfer type exhibits slightly higher harmonic components compared to the other shapes, resulting in increased torque ripple.

Fig. 16 shows the copper loss, iron loss, eddy current loss, and total loss of the selected four models. Although the number of turns is the same, the applied current differs, resulting in a difference in copper loss. The chamfer model that requires the least current has the lowest copper loss. On the other hand, the chamfer model has the largest iron loss and the smallest eddy current loss. In terms of total loss, the chamfer has the lowest and therefore the highest efficiency. The chamfer model, which has low current and high efficiency for the same output, was selected as the final model and manufactured.

V. EXPERIMENT VERIFICATION

A. PROTOTYPE AND TEST SETUP

A prototype was manufactured using the final chamfer model shown in Fig. 11(a) and tested for validation of FEA results. Fig. 17(a) shows the prototype of the rotor and the permanent magnet with the optimized chamfered shape, while Fig. 17(b) and (c) are the stator core and entire stator with three-phase winding of the prototype. The experimental setup is implemented using a dynamometer, power supply, Yaskawa driver, and power analyzer, as illustrated in Fig. 18. The test motor is driven by the Yaskawa inverter, and its operating speed is controlled by the dynamometer. Key electrical and mechanical quantities, including torque, current, and voltage, are measured using appropriate sensors. The no-load BEMF waveforms are acquired using an oscilloscope, and the motor efficiency is evaluated using a power analyzer. The target operating speed was controlled using the dynamometer, and the corresponding current condition was applied through the inverter to match the FEA operating conditions.

B. EXPERIMENT RESULT

In the no-load test, the line-to-line BEMF was measured at a speed of 3200 rpm. Fig. 19 shows the FEA and test waveforms for two cycles of the no-load line-to-line back EMF. When comparing the fundamental components, the

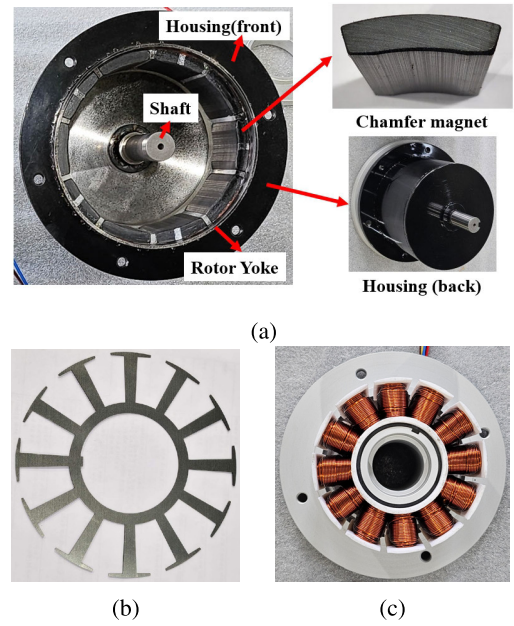


FIGURE 17. Prototype of chamfer type motor (a) rotor (b) stator core (c) entire stator.

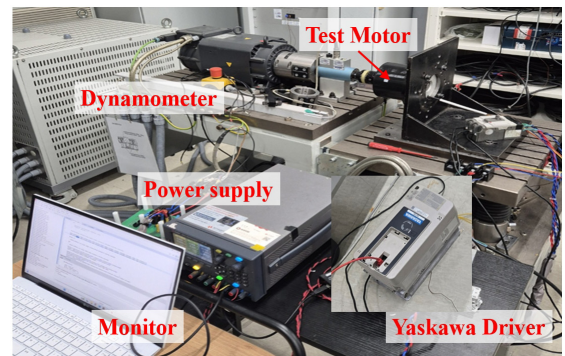


FIGURE 18. Experiment environment.

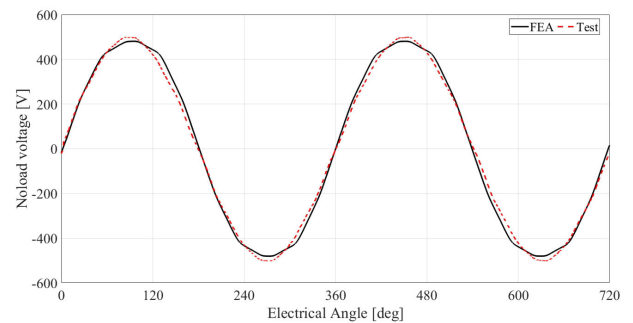


FIGURE 19. Comparison with FEA and experiment result of no-load line BEMF.

error is 1.4 %, indicating good agreement between FEA and experimental results.

In the load test, the motor performance is evaluated under rated and various operating conditions to compare

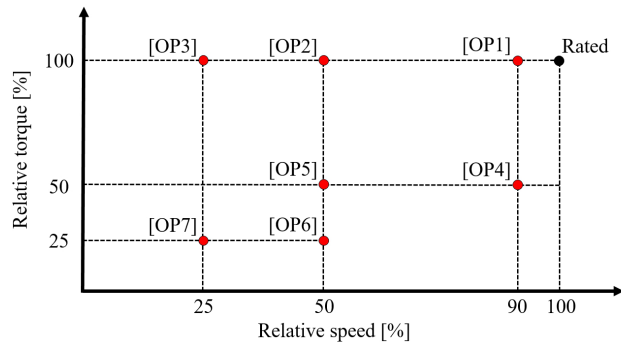


FIGURE 20. Motor test operating points according to IEC 60034-2-3.

TABLE 5. Operating points based on IEC 60034-2-3.

Operating point	Speed [% of rated]	Torque [% of rated]
Rated condition	100	100
OP1	90	100
OP2	50	100
OP3	25	100
OP4	100	50
OP5	50	50
OP6	50	25
OP7	25	25

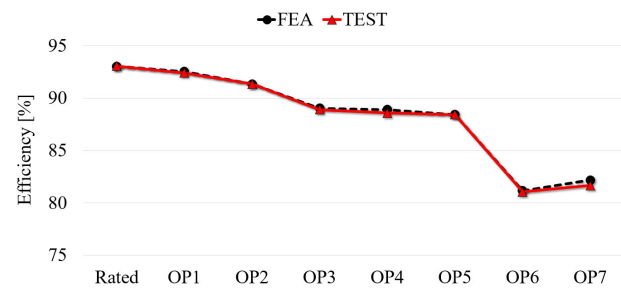


FIGURE 21. Efficiency comparison between FEA and test at operating points.

FEA predictions with experimental results. Since EC fan systems operate under variable-speed and variable-load conditions, motor performance must be evaluated over a wide operating range rather than at a single rated point [8], [9]. Accordingly, a variable-speed load test was conducted at representative operating points in accordance with IEC 60034-2-3, which defines test methods for determining the losses and efficiency of converter-fed AC motors [27]. Fig. 20 illustrates the operating points defined by relative torque and relative speed, and Table 5 summarizes the corresponding conditions.

The measured efficiency using the power analyzer is compared with FEA results, as illustrated in Fig. 21. The experimental results show good agreement with the FEA results over the entire operating range, with a

maximum efficiency difference of less than 0.5%. For efficiency classification, the motor efficiency was evaluated at the representative operating point (OP1: 90% of rated speed and 100% of rated torque) in accordance with IEC 60034-30-2. The measured efficiency exceeds the nominal efficiency threshold for the IE5 class, indicating that the proposed motor satisfies the IE5 efficiency class. These results show that the proposed motor maintains reliable performance across the evaluated operating range, confirming its applicability to EC fan applications.

VI. CONCLUSION

In this paper, an outer-rotor SPMSM with ferrite permanent magnets was designed and analyzed with consideration of permanent magnet shape. Four magnet shapes—chamfer, linear chamfer, taper, and cycloid—were comparatively studied under identical design conditions using MOGA-based FEA. Among the optimized models, the chamfer type showed the best overall performance because this shape has a higher fundamental component of magnetic flux density, which results in improved efficiency. The selected model was manufactured and experimentally validated through no-load and load tests. The measured no-load BEMF closely matches the FEA results, with a fundamental error of 1.4 %. Furthermore, load tests were conducted under variable operating conditions in accordance with IEC 60034-2-3, and the experimental results are consistent with the FEA predictions, with a maximum efficiency deviation of less than 0.5 %. The motor efficiency at the representative operating point (90% of rated speed and 100% of rated torque) is evaluated according to IEC 60034-30-2, and the measured efficiency satisfies the IE5 efficiency class. These results indicate that the proposed motor is applicable to EC fan applications in data center HVAC systems.

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