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A Study on Reducing Cogging Torque of IPMSM Applying Rotating Tapering

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The Interior Permanent Magnet Synchronous Motor(IPMSM) has a structure in which a permanent magnet is inserted inside the rotor, and cogging torque is generated in its structure. To solve this problem, various methods for reducing the cogging torque are being studied. The first method is to reduce the cogging torque by increasing the air gap length by applying tapering to the rotor or stator core. However, in case of reducing the cogging torque above a certain level, the tapering application method may cause a decrease in output because the position and shape of the permanent magnet are restricted. The second method is to apply skew to the stator or rotor. This is the most reliable way to reduce the cogging torque, but the magnetization rate of the permanent magnet is low, so the manufacturability is low. In this paper, we describe a rotor with rotational tapering that fuses the advantages of tapering and skew and offsets the disadvantages. The motor design used 3D finite element analysis(FEA), and the validity of this paper was verified by making the final model and comparing it with the simulation results.

***Index Terms*—Permanent magnet motors, Brushless motors, AC motors, Torque.**

I. Introduction

Cogging torque is a major cause of motor noise and vibration. Therefore, cogging torque reduction design is an important factor in motor design. Various studies are being conducted to reduce cogging torque. Most of the studies are studies on Surface Permanent Magnet Synchronous Motor(SPMSM) with low cogging torque due to the same d and q-axis inductance [1]-[4], or studies on skew with low manufacturability [5]-[8]. In industries requiring high efficiency and high output, Interior Permanent Magnet Synchronous Motor(IPMSM), which uses both magnetic torque and reluctance torque, is a more suitable motor than SPMSM. However, IPMSM, which has significant polarity with different inductances on the d-axis and q-axis, has a high cogging torque in its structure. Therefore, research is needed to reduce it.

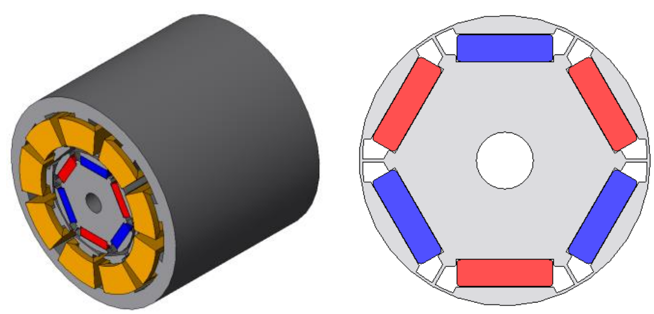
This paper proposed a Rotating Tapering method that reduces cogging torque and improves manufacturability by fusing the method of increasing the air gap length, such as tapering application, and the method of dispersing the d-axis magnetic flux path, such as skew application. This paper compared and analyzed four models, the Basic model, Tapering model, Skew model, and Rotating Tapering model, using 3D finite elements analysis (FEA), and a Rotating Tapering model was manufactured and tested. The validity of Rotating Tapering was verified by comparing it with the simulation results.

II. Basic Model

For the analysis of the proposed shape, the motor was designed as an Electric Power Steering(EPS) motor. IPMSM for EPS has 6 poles and 9 slots, and the winding is double layer, and the concentrated winding is used. Maximum Torque Per Ampere(MTPA) control was used because the characteristics of the EPS motor require a small size and high output. In addition, the stator used a segmented core to increase the slot fill factor. When a segmented core is used, the cogging torque is set as the highest priority because the cogging torque is increased due to the tolerance of the connection part. The specifications and target performance of IPMSM for EPS is shown in Table I. Figure 1 shows the shape of the Basic model, and Figure 2 shows the cogging torque and torque of the Basic model.

TABLE I
Specifications And Target Performance of EPS Motor

Parameter	Value	Unit	Parameter	Value	Unit
Motor Diameter	69	mm	Stack Length	60	mm
Poles / Slots	6/9	-	DC Link	12	V
Rated Current	57.7	Arms	Rated Speed	1000	RPM
Rated Torque	3	N·m	Cogging Torque	50	mN·m



(a) (b)

Fig. 1. Basic Model Shape (a) Whole Model (b) Rotor

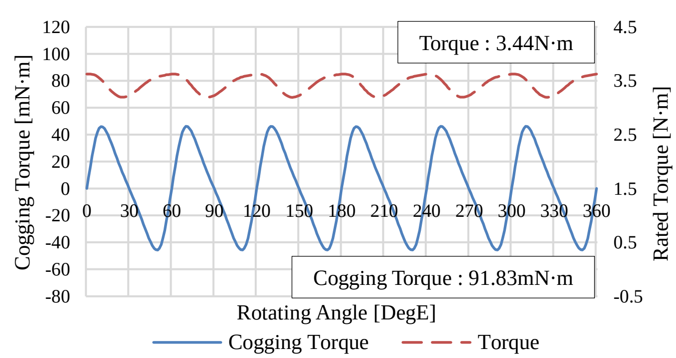


Fig. 2. Basic Model Cogging Torque and Rated Torque Analysis

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The torque of the Basic model is 3.44N·m, which satisfies the target performance, but the cogging torque, which is a structural problem of IPMSM, is 91.83mN·m, which does not satisfy the target.

III. Tapering Model

Tapering is applied to the outer diameter of the rotor to reduce the cogging torque in the Basic model. In consideration of the position and shape of the permanent magnet and the rigidity of the motor, 5mm of tapering was applied. Figure 3 shows the shape of the Tapering model, and Figure 4 shows the cogging torque and torque of the Tapering model.

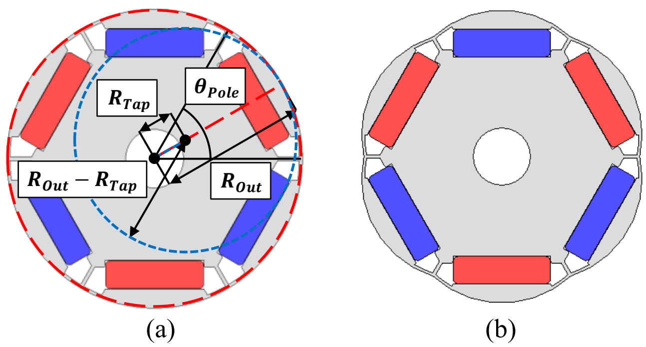

Fig. 3. Tapering Model Rotor (a) Design Variables (b) Application Model

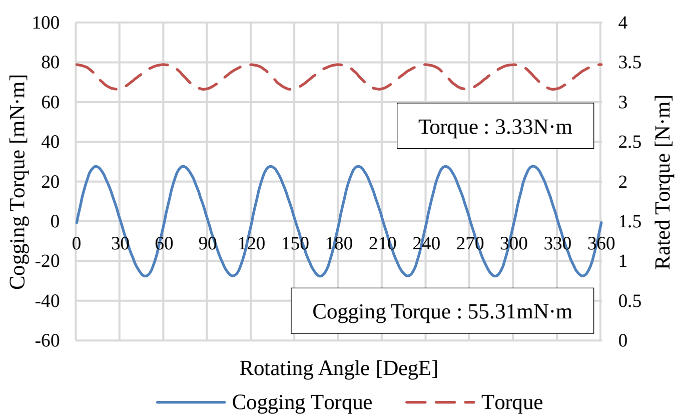

Fig. 4. Tapering Model Cogging Torque and Rated Torque Analysis

TABLE II
Tapering Model Characteristic Comparison

Rotor Type	Cogging Torque	Rated Torque	Torque Ripple
Basic	91.83 mN·m	3.44 N·m	12.56 %
Tapering	55.31 mN·m	3.33 N·m	9.33 %

The torque of the Tapering model is 3.33N·m, which satisfies the target performance. The cogging torque is 55.31mN·m, which is 39.77% lower than that of the Basic model, but it does not reach the target performance. In addition, due to the use of segmented cores, there is a high possibility that the cogging torque is larger than the simulation result. Therefore, a design that further reduces the cogging torque in the Tapering model is required. For this purpose, skew was applied to the Tapering model.

IV. Skew Model

Figure 5 shows the rotor of the Skew model, and an optimal angle of 10˚ was applied for the skew. Figure 6 shows the cogging torque and torque of the Skew model.

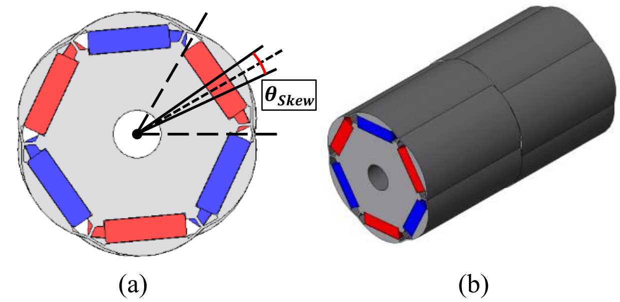

Fig. 5. Skew Model Rotor (a) Design Variables (b) Application Model

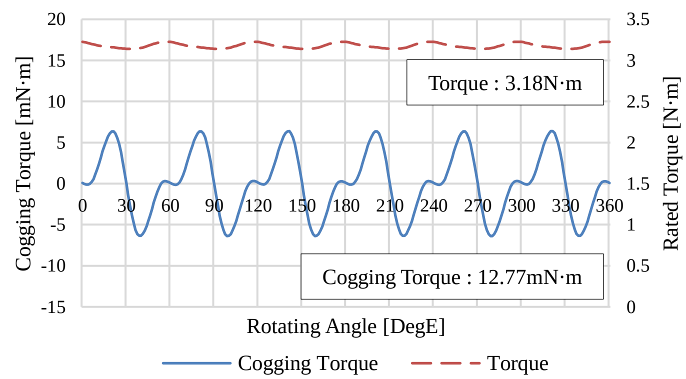

Fig. 6. Skew Model Cogging Torque and Rated Torque Analysis

TABLE III
Skew Model Characteristic Comparison

Rotor Type	Cogging Torque	Rated Torque	Torque Ripple
Tapering	55.31 mN·m	3.33 N·m	9.33 %
Skew	12.77 mN·m	3.18 N·m	2.77 %

The torque of the Skew model is 3.18Nm and the cogging torque is 12.77mN·m, which is 76.91% lower than that of the Tapering model, which satisfies the target performance. However, the skew application method is difficult to magnetize due to the division of the permanent magnet, so the manufacturability is low. Skew is an efficient method in terms of reducing cogging torque, but it is difficult to mass-produce due to low manufacturability.

V. Rotating Tapering Model

Rotating Tapering is proposed as a method to solve the magnetization problem and reduce the cogging torque. The method of lowering the cogging torque by increasing the air gap length like tapering and lowering the sum of the cogging torque of each step by dispersing the path of the d-axis magnetic flux like Skew is the same, but it is a method of using an integrated permanent magnet by fixing the permanent magnet insertion space. Figure 7 shows the rotor cross section and 3D shape of the Rotating Tapering model.

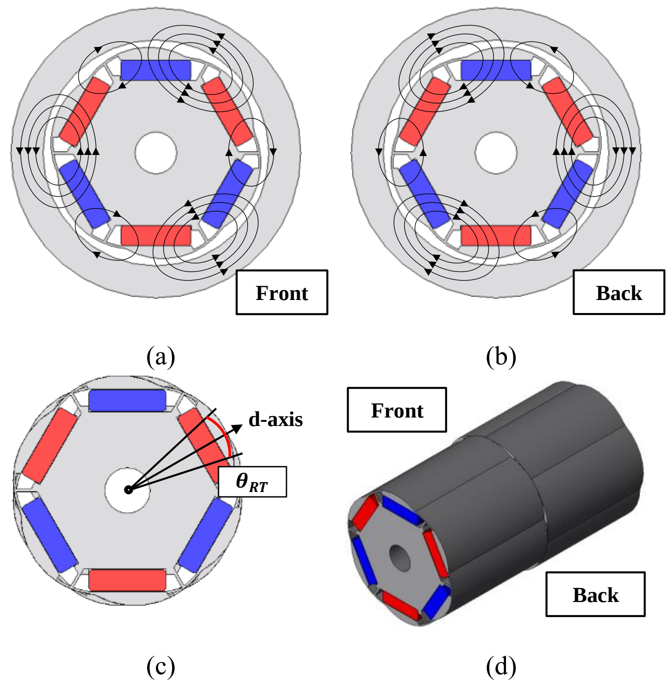

Fig. 7. Rotating Tapering Model Rotor Shape (a) Front Part Flux Line (b) Back Part Flux Line (c) Design Variables (d) 3D Shape

Rotating Tapering distributes the air gap flux using an asymmetric rotor core as shown in Fig 7. Unlike skew, the minimum angle of cogging torque depends on the position and size of the permanent magnet. To analyze the minimum angle of cogging torque, the rotating angle was analyzed at intervals of 5˚ from 0˚ to 60˚. Figure 8 shows the cogging torque waveform and trend.

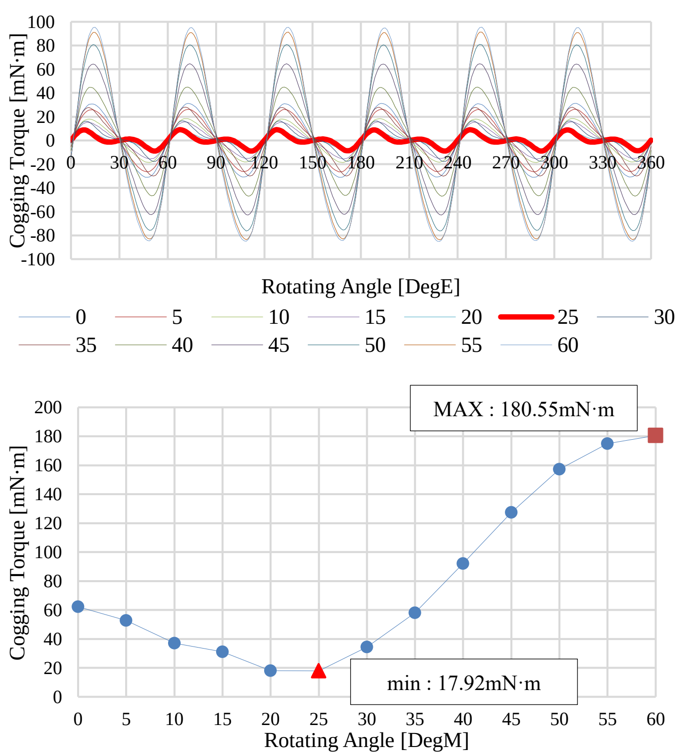

Fig. 8. Cogging Torque Analysis According to Rotating Angle

At Rotating Angle=25˚, the cogging torque is the smallest at 17.92mNm. The minimum cogging torque model was selected as the Rotating Tapering model. Figure 9 is an exploded view of the Rotating Tapering model and Figure 10 shows the load characteristics during MTPA control of the Rotating Tapering model.

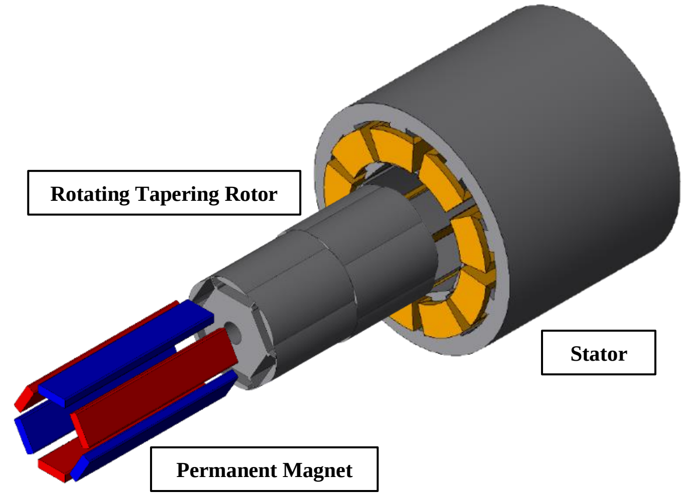

Fig. 9. Rotating Tapering Model Exploded View

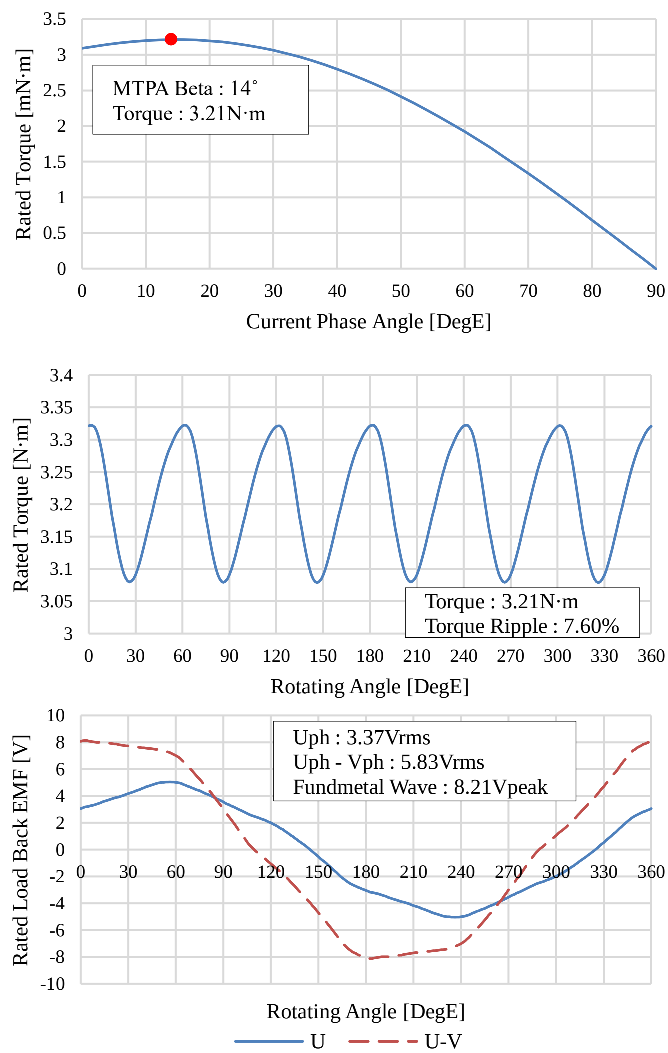

Fig. 10. Characteristics Analysis of Rotating Tapering Model MTPA Control

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When controlling the MTPA of the Rotating Tapering model, the torque is 3.21N·m, which satisfies the target performance of 3N·m. In addition, the peak of the fundamental wave of the back electromotive force is 8.21V, which also satisfies the voltage limit.

VI. Comparison By Rotor Type

Figure 11 shows the cogging torque and torque for each rotor type, and Table IV shows the characteristics of each rotor type.

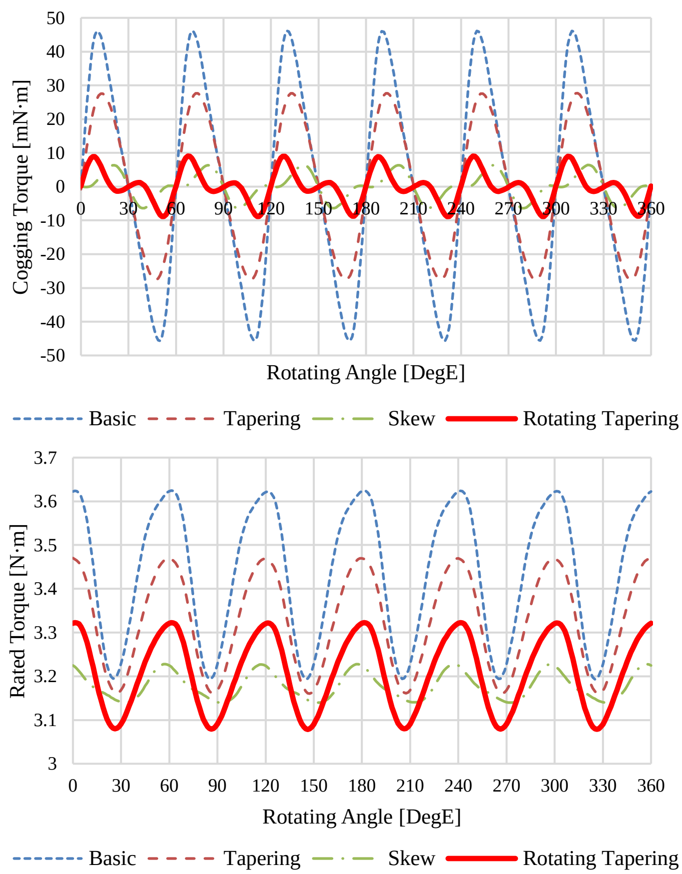

Fig. 11. Cogging Torque and Rated Torque by Rotor Type

TABLE IV
Characteristic Comparison By Rotor Type

Rotor Type	Cogging Torque	Rated Torque	Torque Ripple
Basic	91.83 mN·m	3.44 N·m	12.56 %
Tapering	55.31 mN·m	3.33 N·m	9.33%
Skew	12.77 mN·m	3.18 N·m	2.77 %
Rotating Tapering	17.92 mN·m	3.21 N·m	7.60 %

The disadvantage of rotating tapering is that the increase in air gap results in less torque compared to the basic model. This is unavoidable at the same magnet shape and the same magnet position in the rotor.

The rated torque is 6.69% lower than the Basic model and 3.54% lower than the Tapering model, but the torque ripple is reduced by 39.44% compared to the Basic model and 18.47% compared to the Tapering model. Compared to the Skew model, the torque ripple is about 174% larger, but the torque ripple of the Skew model is too small, so it is within the allowable range and the rated torque is about 1% higher. However, the cogging torque of the Rotating Tapering model is reduced by 80.49% compared to the Basic model and 67.6% compared to the Tapering model. It is about 40% higher than the Skew model, but it is much more advantageous in terms of manufacturability. Compared to the skew that divides the permanent magnet, rotating tapering is much more advantageous in terms of manufacturability because the permanent magnet is used completely. This is an important factor in mass production.

As such, Rotating Tapering reduces torque slightly, but is effective in terms of reducing cogging torque and torque ripple.

A Rotating Tapering model that satisfies the target performance was applied to IPMSM for column type eps and manufactured.

VII. Fabrication and Test

Figure 12 shows the rotor and stator of the manufactured motor. Rotating Tapering is applied to the rotor and the stator is made of segmented core.

Fig. 12. Fabricated IPMSM for EPS

In order to check the performance of the manufactured motor, the no-load back electromotive force was measured prior to the load test. Figure 13 shows the test results and simulation results of the back electromotive force between the U and V phase at 1000 RPM.

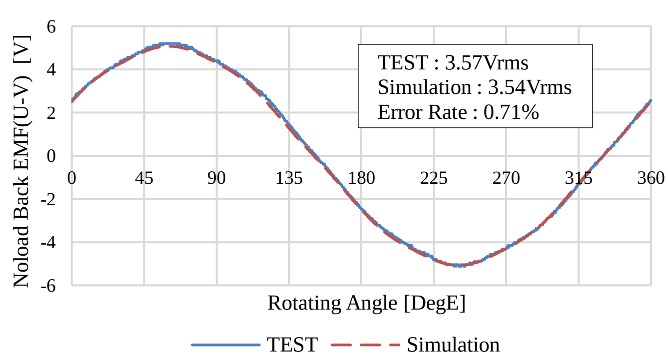

Fig. 13. Noload Back EMF Test Results and Simulation Results

The error rate between the test results and simulation results of no-load back electromotive force was 0.71%, confirming that the design and manufacturing were done properly.

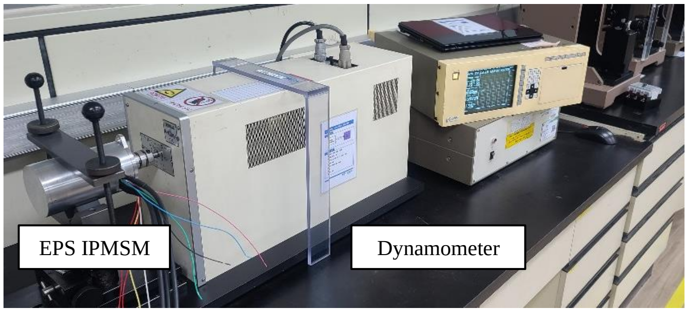

Fig. 14. Cogging Torque Test Dynamometer

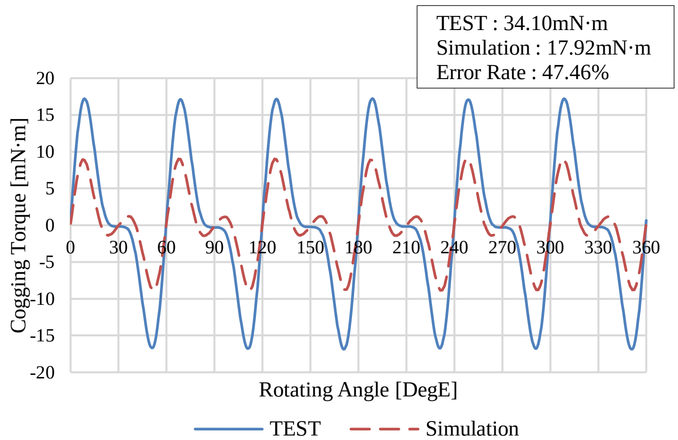

Fig. 15. Cogging Torque Test Results and Simulation Results

The cogging torque test result is 34.10mNm. The error rate with the simulation is 47.46%, and the main cause of the error is thought to be production using a segmented core.

Although errors occurred due to mechanical tolerance due to the characteristics of prototypes, IPMSM applied with rotating tapering satisfied the target performance of cogging torque even considering the error rate. It is expected that the cogging torque can be further reduced if more precise manufacturing is performed when manufacturing mass-produced products.

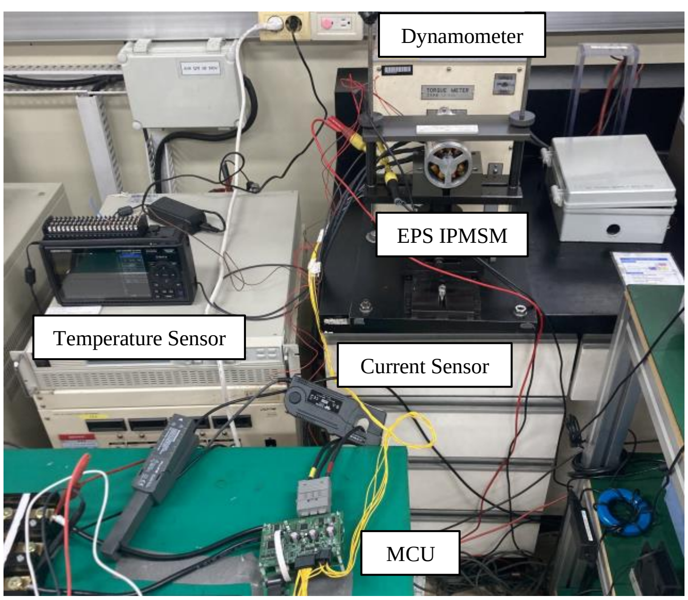

Fig. 16. Motor Testing Equipment

Figure 16 shows the motor test equipment. The load test measured the torque according to the current phase angle and the magnitude of the current. The current phase angle was measured at intervals of 5˚ from 0˚ to 90˚, and the current was measured from 0A to 90Apeak in 15A units considering the winding temperature. Since the current density is high due to the characteristics of the EPS motor, a temperature sensor was used in consideration of the winding temperature, and a dedicated MCU was used to accurately control the Rotating Tapering applied motor. Figure is the results of the load torque test.

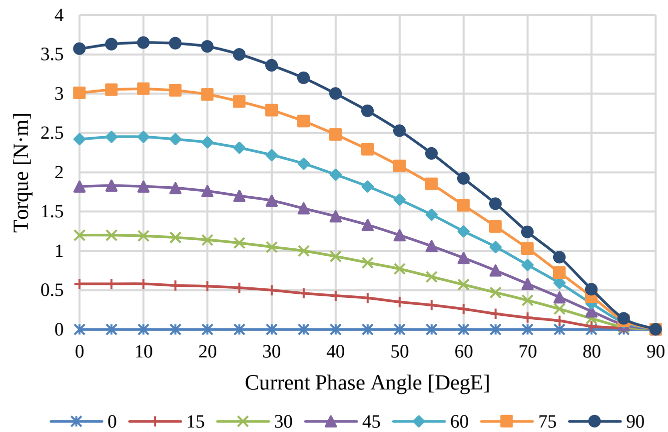

Fig. 17. Load Torque Test Results

The test result satisfies the target torque of 3Nm at 75Apeak (53.3Arms). It satisfies the target torque even at a current less than the rated current of 81.6Apeak (57.7Arms). The target torque is satisfied from 0˚ to 15˚ of current phase angle when 75Apeak (53.3Arms) is applied, and 0˚ to 40˚ of current phase angle when 90Apeak (63.6Arms) is applied.

VIII. CONCLUSION

This paper proposed Rotating Tapering, a new shape design method for reducing cogging torque. It shows a higher reduction rate of cogging torque compared to the tapering method, and although the cogging torque is larger than that of the skew, the output is high, and the problems of magnetization and manufacturability caused by the division of permanent magnets are solved. Rotating Tapering secures the manufacturability of the core because the front and back parts have the same shape. Also, the problem of manufacturing due to magnetization is solved by using an integrated permanent magnet.

The Rotating Tapering method can be applied not only to small motors such as EPS motors but also to all types of IPMSMs and is advantageous for mass production. It is expected that IPMSM with Rotating Tapering will be effective in applications such as home appliances, kitchen appliances, and vehicle traction motors that require high output and reduce cogging torque, the main cause of vibration and noise.

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