A Study on the Design of BLDC Motor for Air Conditioning and Characterization of Slot Shape for Torque Ripple Reduction

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This paper seeks to reduce the torque ripple that causes noise vibration in order to solve the noise problem of air-conditioning motors, which have emerged as a trend from an energy perspective to electric vehicles using electric motors for driving. In order to reduce torque ripple, an overhang application for equivalent application of analysis and three-dimensional interpretation of the magnetization direction of a permanent magnet and a shape to be reduced by deforming an electromagnetic shape are selected. The harmonic components were analyzed using finite element method and Fast Fourier Transform, and the influence on magnetic flux was analyzed by applying slot asymmetry and stator Shoe offset in the analysis, and torque ripple reduction design was carried out by improving harmonics.As a result, a motor shape for reducing torque ripple compared with an existing shape is presented.

Keywords: PMSM, Torque Ripple, Overhang, FFT, Slot asymmetry, offset.

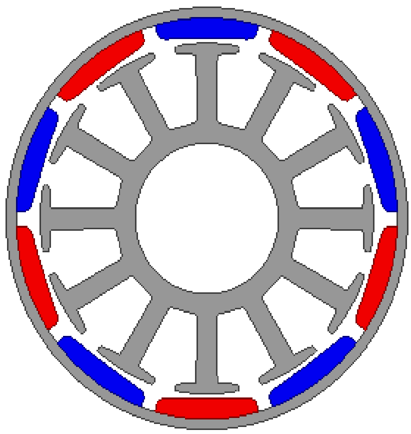
1. Introduction

Due to the social trend of demanding high efficiency from an energy perspective, permanent magnet motors are used as mainstream FAN motors for air conditioning, and the use of BLDC (Brushless DC) motors is increasing. BLDC motors can be used to improve efficiency, precise control and miniaturization. In addition, stability improvement and low noise and low vibration can be realized. In addition, BLDC motors have similar production and processes to AC motors, so mass-production facilities can be shared, and the winding method, which was mainly distributed, has recently become possible to manufacture high-efficiency motors by applying a centralized method that simplifies the manufacturing process and reduces cost [1-18]. In this paper, the design and characterization of a centralized high-efficiency external rotation BLDC motor were performed. In addition, in terms of cogging torque, which adversely affects speed control and position control and causes noise and vibration, the form of Surface Permanent Magnet (SPM) instead of Interior Permanent Magnet (IPM) was applied. Pole arc ratio and slot opening were considered to reduce torque ripple. Furthermore, slot asymmetric application is advanced to reduce torque ripple indicating the effects of noise and vibration. In the case of electromagnetic field analysis, FEM analysis was performed.

2. Research process

2.1. Shape and Structure of BLDC

The SPM-shaped BLDC motor has the advantage of being advantageous for high torque and high power factor, and it is easy to cool permanent magnets.



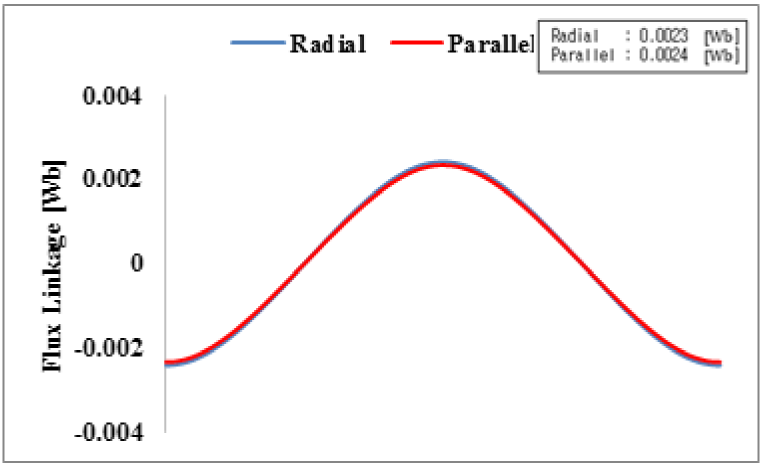
[Fig. 1. SPM BLDC Motor Shape Base]

[Table 1. SPM BLDC Motor Specifications]

Part	Parameter	Value	Unit
Spec.	8step Speed	3,480	[RPM]
	Rated Current	26	[A]
	8step Torque	0.716	[Nm]
	Output power	260.9	[W]
Stator	Outer Dia.	69.7	[mm]
	Inner Dia.	30	[mm]
	Stack Length	15	[mm]
Rotor	Outer Dia.	83.9	[mm]
	Inner Dia.	79.7	[mm]
	Stack Length	21	[mm]
Airgap		1	[mm]

2.2. Magnetic Magnetization

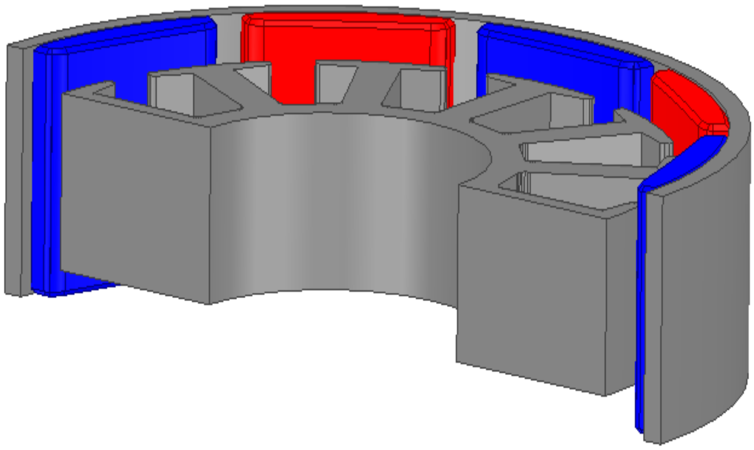
Permanent magnets include Radial magnetization and Parallel magnetization. In the case of two magnetizations, they are used differently depending on the target. Fig.2 is a comparison of magnetic flux due to magnetization of permanent magnets. Radial magnetization generates a larger magnetic flux value than Parallel magnetization. From an efficiency perspective, it can be seen that if the magnetic flux is larger among the two comparison models, the amount of applied current is relatively small to meet the required torque, which reduces loss and improves efficiency. On the other hand, a smaller magnetic flux of the two comparison models means that a relatively larger amount of applied current is applied, which means an increase in the copper loss increases loss and reduces efficiency. Among the two comparative models, Parallel magnetization is difficult to select in terms of efficiency, but different in terms of noise. In the case of harmonics connected to noise, it decreases as the applied current increases. Therefore, the magnetic flux of Parallel magnetization is small, and more current is applied than Radial to meet the required torque, and the harmonic wave is reduced to show strength in terms of noise. In the comparative analysis of the magnetization, the Radial magnet's cogging torque is 3.27 mNm and the Parallel magnet is 2.74 mNm. Therefore, in this paper, permanent magnet Parallel magnetization was selected and proceeded [2, 3].



[Fig. 2. Flux Linkage of Magnetization]

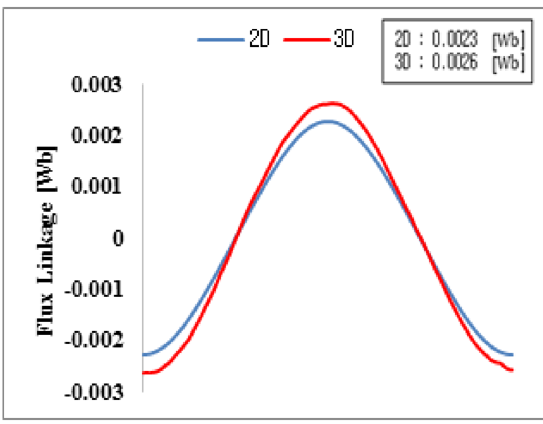
2.3. Derivation of Overhang Coefficients

Fig. 3 is the 3D shape of the BLDC motor that was analyzed. In the case of overhang structures with different stacking lengths of the stator and rotor, 3D FEM analysis should be performed for accurate analysis. However, the disadvantage is that it requires a lot of time for analysis.

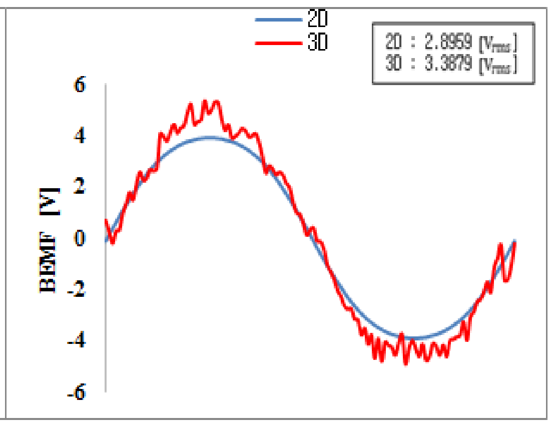


[Fig. 3. SPM BLDC Motor 3D]

To shorten this analysis time, 2D FEM analysis should be conducted. In order to apply the overhang structure for 2D FEM analysis equivalently, the overhang coefficient must be derived (4-8). In 2D FEM analysis, the torque characteristics differ greatly depending on the stator stacking length, and since the spcc material applied to the rotor does not have any significant difference in electromagnetic field characteristics depending on the axial length, the shorter stacking length, the stator stacking length, is applied as the stacking length of the 2D analysis. Therefore, the overhang coefficient must be applied to apply the 3D permanent magnet 21mm in 2D equivalent. To derive the overhang coefficient, the magnetic flux of the permanent magnet derived by conducting the no-load 2D FEM analysis and the no-load 3D FEM analysis of the BLDC motor was derived through Fig. 4 and the no-load counter electromotive force Fig. 5.

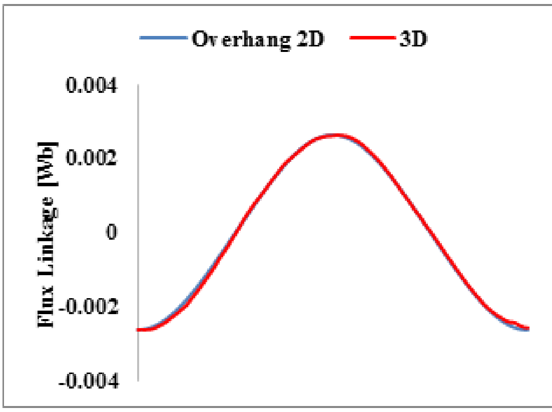


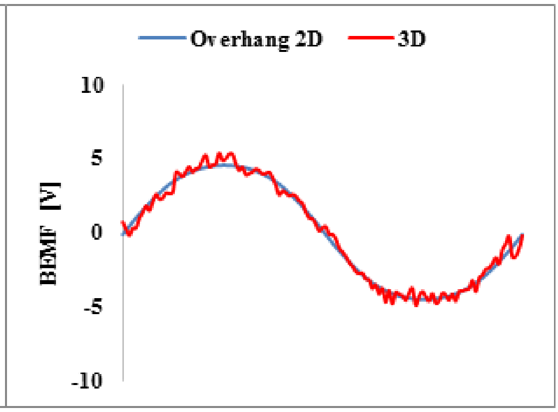
[Fig. 4. Noload Flux Linkage]



[Fig. 5. Noload Back EMF]

The derived overhang coefficient is 3D Flux Linkage / 2D Flux Linkage = 3D BEMF / 2D BEMF = 1.17. To apply the magnet length of 21 mm to 15 mm, the analysis was performed by applying the overhang coefficient to the residual magnetic flux density Br. When the overhang coefficient is applied, the same magnetic flux is generated as shown in Figure 6, and the error of the counter electromotive force is 1.1%, as shown in Figure 7.

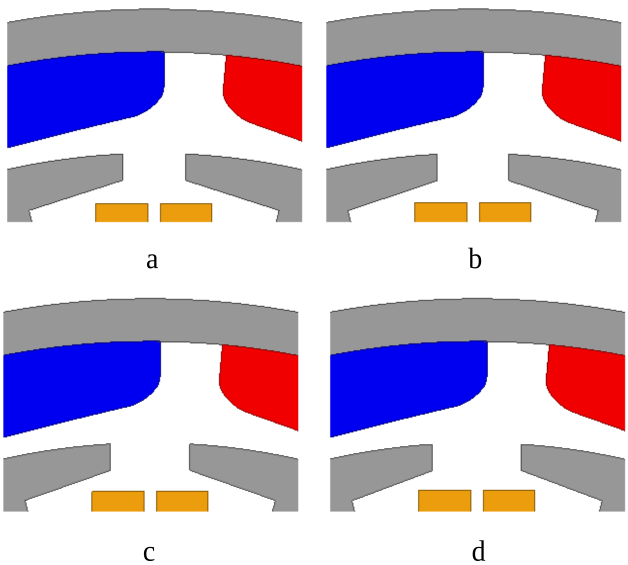




[Fig. 6. Overhang applied Magnetic Flux comparison] [Fig. 7. Overhang applied Back EMF]

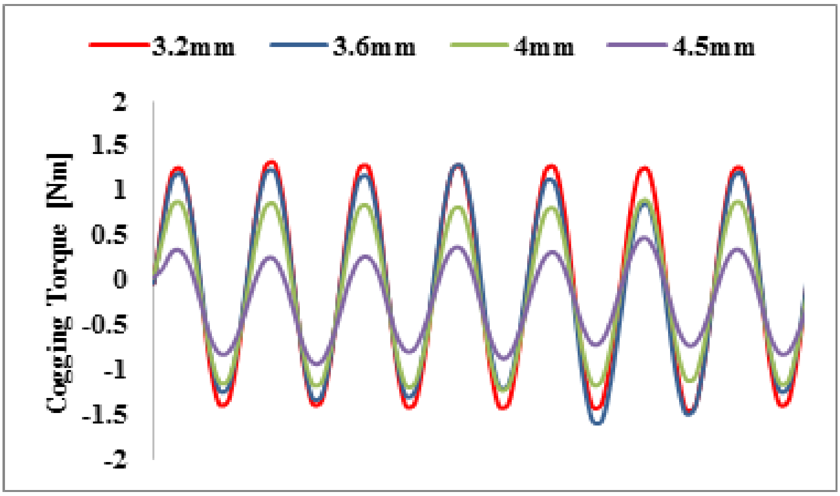
2.4. Analysis of Stator Shape for Reducing Torque Ripple

The BLDC motor is a brushless motor that uses a permanent magnet for a field in a DC motor. The BLDC motor for air conditioning should have excellent torque characteristics and should be designed to have low torque ripples in consideration of noise and vibration [9]. To reduce the torque ripples of the motor used in this paper, the characteristics were analyzed by changing the slot opening length among the stator shapes to 3.2 to 4.5 mm in consideration of winding fabrication as shown in Fig. 8 [11].



(a) Slot Opening 3.2mm (b) Slot Opening 3.6mm (c) Slot Opening 4.0mm (d) Slot Opening 4.5mm

[Fig. 8. Slot Opening Change to Reduce Torque Ripple]



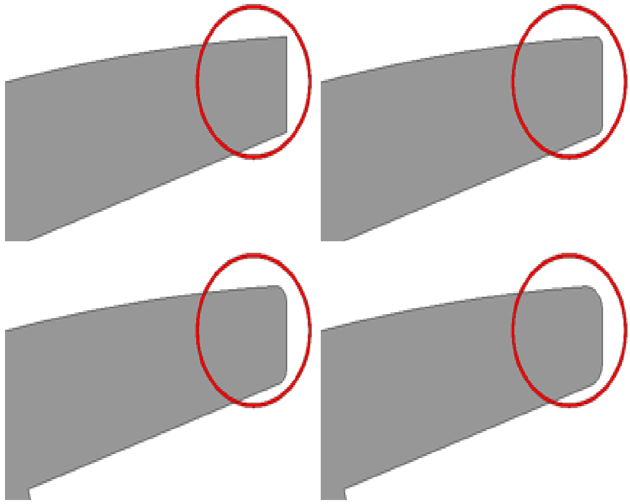
[Fig. 9. Cogging Torque each Slot Opening]

Fig.9 compared waveforms as a result of cogging torque analysis by slot open length. (a) Cogging torque pk to pk 2.7484 Nm of the model, (b) Cogging torque pk to pk 2.8518 Nm of the model, (c) Cogging torque pk to pk 2.0910 Nm of the model, and (d) Cogging torque pk to pk 1.3919 Nm of the model.

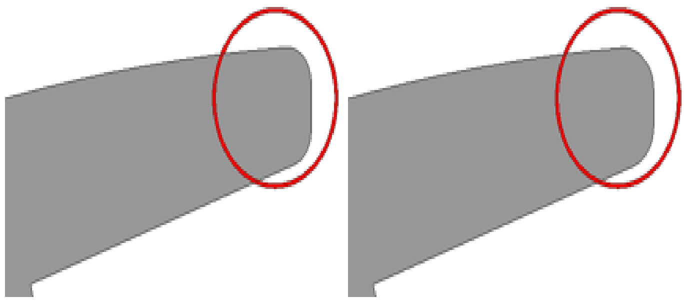
Slot opening of the (d) model from which the smallest cogging torque value is derived was selected as a design factor for designing motors that meet BLDC motor characterization and target specifications presented in this paper[12].

2.5. Analysis of Slot Open Shape for Torque Ripple Improvement

In consideration of the workability of the stator, curvature is applied to a slot open with an angular angle to improve torque ripple by making the flow of magnetic flux more continuous. Like Fig.10, the interpretation was carried out by applying a curvature of 0.1 to 0.5 mm to both ends of the slot opening.



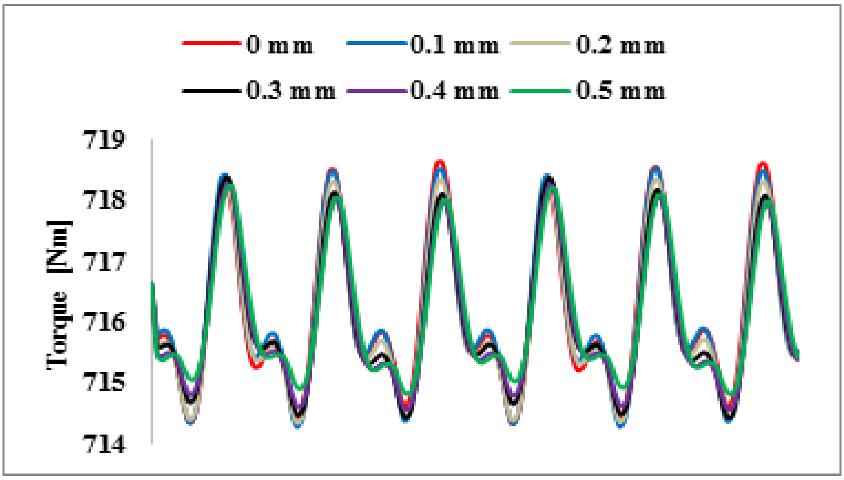
(a) Corner Fillet 0 mm (b) Corner Fillet 0.1 mm (c) Corner Fillet 0.2 mm (d) Corner Fillet 0.3 mm



(e) Corner Fillet 0.4 mm (f) Corner Fillet 0.5 mm

[Fig. 10. Slot Opening Corner Fillet by Length]

Fig.10 compared waveforms as a result of cogging torque analysis by slot open length. (a) Cogging torque pktopk1.7964Nm of the model, (b) Cogging torque pktopk1.8062Nm of the model, (c) Cogging torque pktopk1.5147Nm of the model, (d) Cogging torque pktopk1.2753Nm of the model, and (e) Cogging torque pg0.5959Nm.

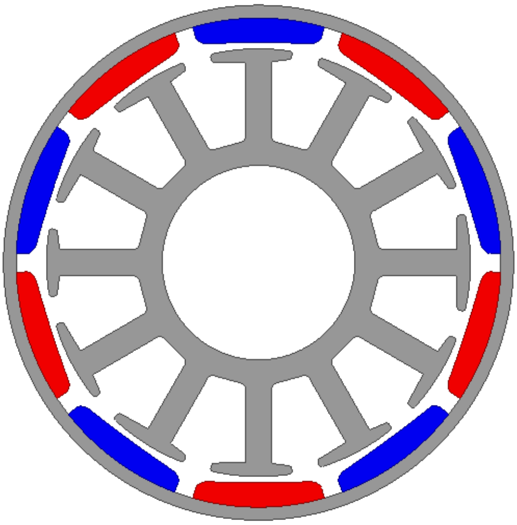


[Fig. 11. Torque Ripple each Corner Fillet]

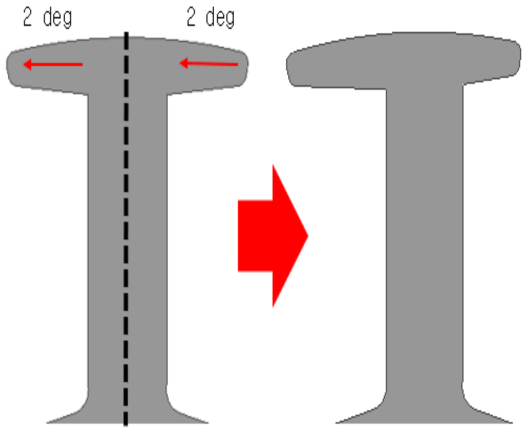
Fig.11 is a waveform that represents torque ripple when applied with curvature. The basic torque ripple in (a) is 0.60%, the torque ripple in (b) is 0.59%, the torque ripple in (c) is 0.56%, the torque ripple in (d) is 0.55%, the torque ripple in (e) is 0.52% and the torque ripple in (f) is 0.48%. When applying curvature, it was found that torque ripple decreases when applying curvature of 0.5mm, which is the optimum ratio to polar j-hope and stator shape, and (f) was selected as the design factor[13].

2.6. Slot asymmetry for improving torque ripple

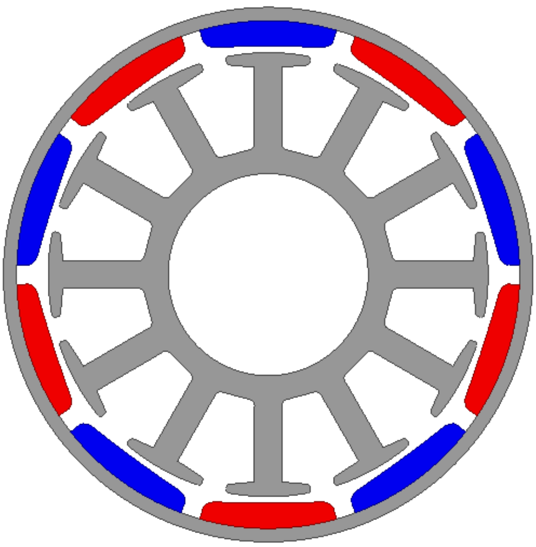
Harmonics and torque ripple are factors of correlation. When analyzing harmonics derived from FFT analysis, integer multiples of slots or polar pairs of harmonics appear large. To reduce torque ripple, proceed with a design to reduce harmonics that typically appear larger. In this paper, however, slot asymmetry was applied to apply a method of increasing and reducing the overall harmonic difference by increasing the magnitude of the remaining harmonic order except for the highest harmonic order [2, 14]. Comparing Fig.16 with Fig.17, Fig.18, it can be seen that S2 with deteriorated torque ripple characteristics has increased the 10th and 12th order of Radial Force and Tangential Force FFT compared to Base. For S1 with improved torque ripple characteristics, the 10th and 12th order of Radial Force and Tangential Force FFT decreases, while the remaining harmonics except for 10th and 12th order harmonics increase in magnitude, reducing overall harmonic differences and decreasing torque ripple.



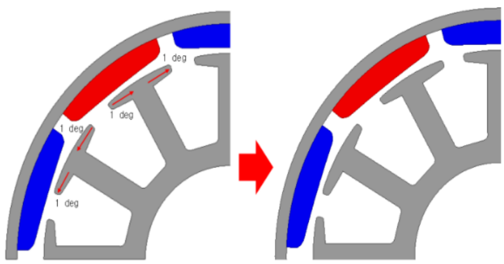
[Fig. 12. Slot asymmetry applied 1 S1]



[Fig. 13. Slot asymmetry applied 1 detail]



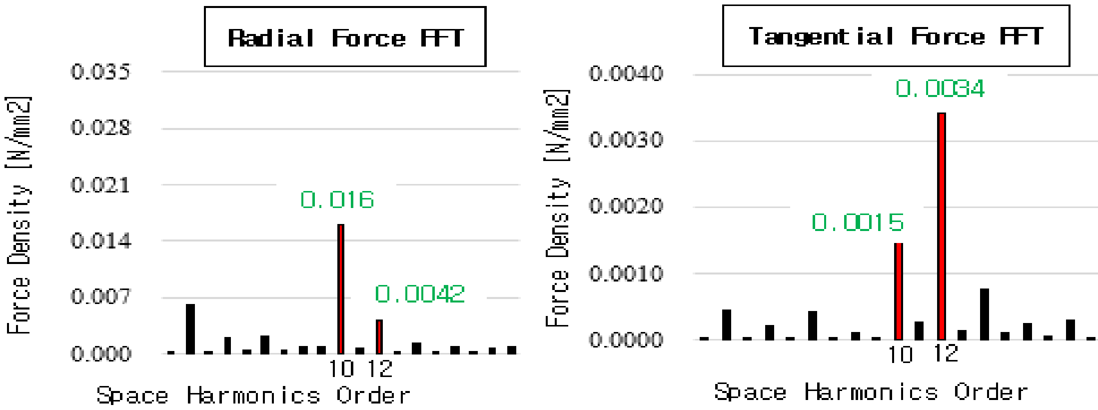
[Fig. 14. Slot asymmetry applied 2 S2]



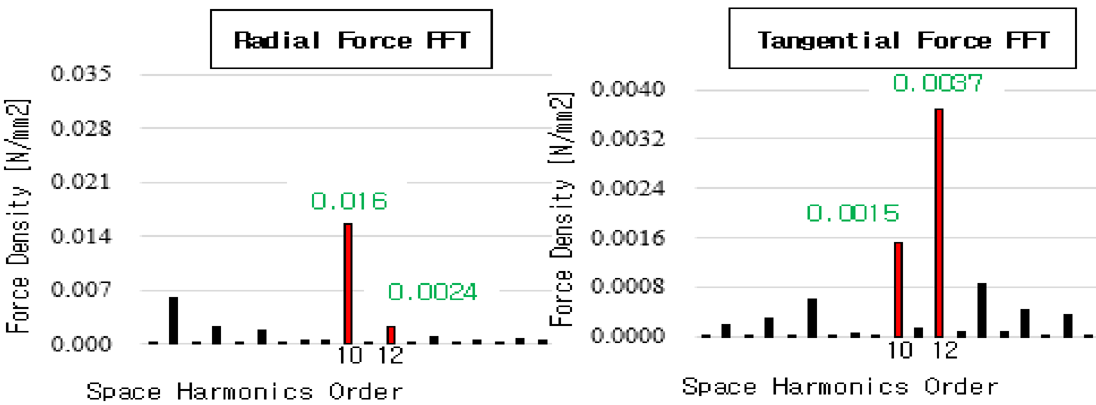
[Fig. 15. Slot asymmetry applied 1 detail]

Table 2. Torque Ripple comparison

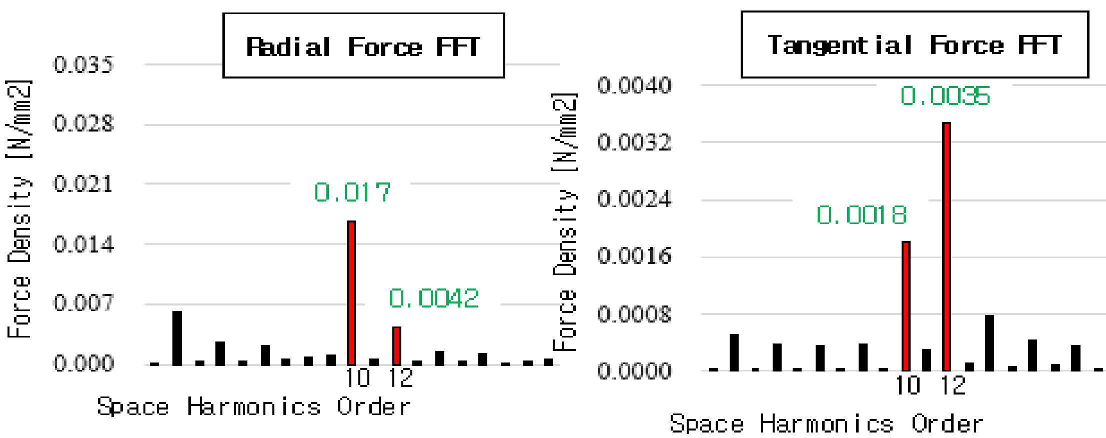
Parameter	Unit	Base	S1	S2
Torque	[Nm]	0.716		
Torque Ripple	[%]	0.36	0.3	6.20
Motor Speed	[RPM]	3,480		



[Fig. 16. Base FFT]



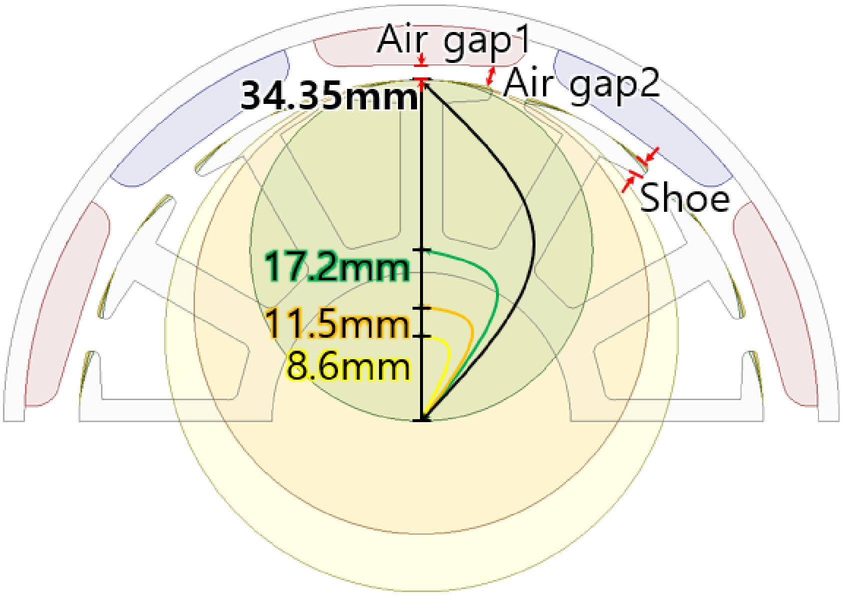
[Fig. 17. S1 FFT]



[Fig. 18. S2 FFT]

2.7. Fixing characteristics throughput application

In order to improve torque ripple characteristics, a stator Offset is applied to improve saturation of magnetic flux generated in the stator Shoe. A stator Offset draws a circle 1/2, 1/4 and 1/6 times the outer diameter of a basic stator reference stator at the Offset point, and removes the part where the circle does not overlap with the stator. A stator shape is embodied by applying it as shown in Fig. 19.

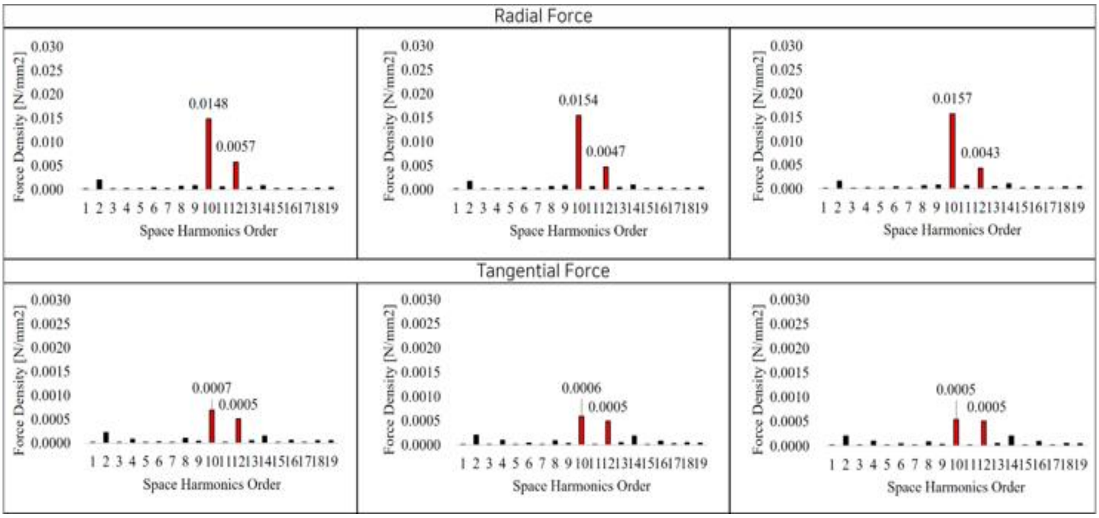


[Fig. 19. Offset example]

Table 3. Offset data

Model	Unit	Offset 1	Offset 2	Offset 3
Offset	[mm]	17.2	11.5	8.6
Air gap 1	[mm]	1.5	1.5	1.5
Air gap 2	[mm]	2.2	1.88	1.75

As a result of the electromagnetic field characterization applied to Offset, (a) torque ripple of 0.18% for Offset 1, (b) torque ripple of 0.32% for Offset 2, and (c) torque ripple of 0.43% for Offset 3, as shown in Table 3. At the time of applying Offset, it can be confirmed that a path of void magnetic flux optimum to the shape is formed and torque ripple is reduced.



[Fig. 20. Offset]

As a result of the electromagnetic field characterization applied to Offset, (a) torque ripple of 0.18% for Offset 1, (b) torque ripple of 0.32% for Offset 2, and (c) torque ripple of 0.43% for Offset 3, as shown in Table 3. At the time of applying Offset, it can be confirmed that a path of void magnetic flux optimum to the shape is formed and torque ripple is reduced[15].

4. CONCLUSION

Noise is being highlighted as the noise of air-conditioning motors buried in engine noise has changed from internal combustion engine cars to electric motor vehicles. Accordingly, noise reduction is required and torque ripple of the motor must be reduced to reduce noise, and the magnetic flux path is changed through magnetization of permanent magnets, electromagnetic shape change, especially stator shape change to reduce torque ripple.

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