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Study on the Torque Ripple Reduction Method of SynRM for Electric Vehicles

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Abstract.
Background/Objectives: Synchronous Reluctance Motor for electric vehicle have torque ripple affecting vibration noise which is related user convenience.
Methods/Statistical analysis: Synchronous reluctance motors without permanent magnets do not have permanent magnets inside the rotor. Moreover, the rotor has a complex structure with many segments and barriers. Therefore, parameters that affect the inner shape of the rotor were selected. This paper represents that how the magnitude of torque ripple changes as the set design parameters are changed, and carry out electromagnetic field analysis through 2D Finite Elements Method.
Findings: Synchronous reluctance motors without permanent magnets do not have permanent magnets inside the rotor and have a structurally complex structure. Therefore, design parameters that affect the motor characteristics were selected according to the shape of the inside of the rotor. Analyze how the magnitude of torque ripple changes as the set design parameters are changed, and conduct electromagnetic field analysis through FEM analysis. The design parameters such as barrier, segment thickness, segment angle are varying to analyze the motor characteristic, especially torque ripple. Additionally, by changing the design of rotor structure, motor characteristic can be represented like field flux density, flux path. Small barrier thickness and segment thickness are saturated the part of rotor interrupting the flux flow and it will make the inductance saturation. Also, the influence of inductance which changes as changing the parameter must be analyzed. In this paper, the optimal design parameter, to make minimum torque ripple, is represented.
Improvements/Applications: By structurally changing the shape, the user's convenience is improved through the optimal rotor structure with minimum torque ripple.

Keywords: Synchronous Reluctance Motor, Torque ripple, FEA, Reluctance torque, saliency ratio.

1. INTRODUCTION

Synchronous Reluctance Motor (SynRM) complicated the rotor structure to maximize the reluctance torque and caused difficulty in manufacturing. Previously, it was not widely commercialized due to its weak mechanical stiffness. However, recently SynRM is used as a motor for electric vehicles that is thermally advantageous such as the BMW i3 model and can exhibit high efficiency even in high-speed areas. In general, when using SynRM, it is basic to design to have a high saliency ratio and to design with multi-layer barriers to achieve high torque[1,2]. However, in practice, the multi-layered barrier type is vulnerable to mechanical rigidity, so it must be designed in consideration of the mechanical strongness[3,4]. SynRM has the advantage of being able to represent a variety of rotor shapes, which allows designers to optimize for cost and ease of manufacture[5,6,7]. In particular, SynRM is generally low efficient and power factor than IPMSM. Because there is no permanent magnet in the rotor and it has a complex structure rotor shape affecting inductance[8,9,10]. SynRM has received a lot of attention as a device suitable for high-speed operation because of its simple and robust structure. In order for the motor to produce an target torque, an appropriate level of reluctance torque must be used, and for this purpose, a design to improve the saliency ratio through the rotor shape design is required.

2. SPECIFICATION AND ANALYZING FLOW CHART

2.1. BASE MODEL

2.1.1. Specification

SynRM is an electric motor that operates by maximizing the use of reluctance torque using a saliency ratio with d-and q- axis inductance. The difference and ratio of the d-, q-axis inductance affect the reluctance torque and power factor (1), (2). Therefore, in order to design the saliency ratio according to the d-, q-axis inductance, the analysis is carried out by changing the size of the barrier and segment. It is difficult to manufacture because the rotor structure becomes complicated, but the structure is advantageous in terms of manufacturing because it has a simple shape and there is no permanent magnet inside the rotor.

$$T = \frac{3}{2}\frac{P}{2}(L_d - L_q)i_{ds}i_{qs} \tag{1}$$

$$cos\phi = \frac{\left(\frac{L_d}{L_q}-1\right)}{\sqrt{\left(\frac{L_d}{L_q}\right)^2\frac{1}{sin^2\theta}+\frac{1}{cos^2\theta}}} \tag{2}$$

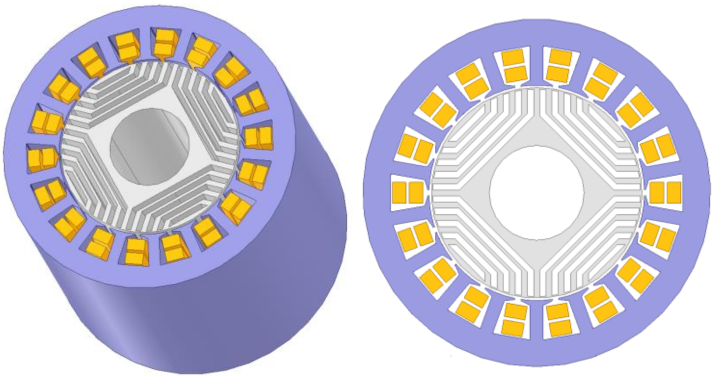

Figure 1. Base Model

The specification about SynRM can be seen in Table 1. For 1.5kW motor, the rated torque is 9.55Nm and the base speed is 1,500rpm, also it is 4 poles, 18 slots.. The rotor and stator diameter ratio is 0.61.The number of parallel circuits is one, the phase resistance is 2.62, and it is in the form of Y connection. The coil uses 0.724ϕ winding based on bare copper wire. The air gap is 0.9mm and it has a five-layers barrier to produce reluctance torque effectively. The thickness of the segment and the barrier is 1.16mm and 2.32mm, respectively. The rib thickness was designed 0.5mm. To maximize utilization efficiency of reluctance torque, the design parameter of segments and barriers is varied.

Table 1. Specification

Parameter	Value	Unit
Rated Power	15	kW
Rated Torque	9.55	Nm
Base Speed	1,500	rpm
Stator Inner/Outer Dia.	81.8/132	Φ
Rotor Inner/Outer Dia.	36/80	Φ
Stack length	123.3	mm
Air gap	0.9	mm
Series turns/phase	47	mm
Coil Dia. (bare)	0.724	mm
Reels	2	-
Phase Resistance	2.62	Ω

2.2. COMPARISON MODEL

2.2.1. Design parameters in the rotor structure

SynRM with saliency ratio and no permanent magnet in the rotor, this study attempts to analyze the electromagnetic field effect and torque ripple change depending on the shape of rotor with d-,q- axis inductance. Therefore, comparison model with different barrier thickness and rib thickness is represented and the differences is shown in Figure 2. It shows nine-models with different shape of rotor structure. Comparative analysis was carried out through 2D FEM analysis.

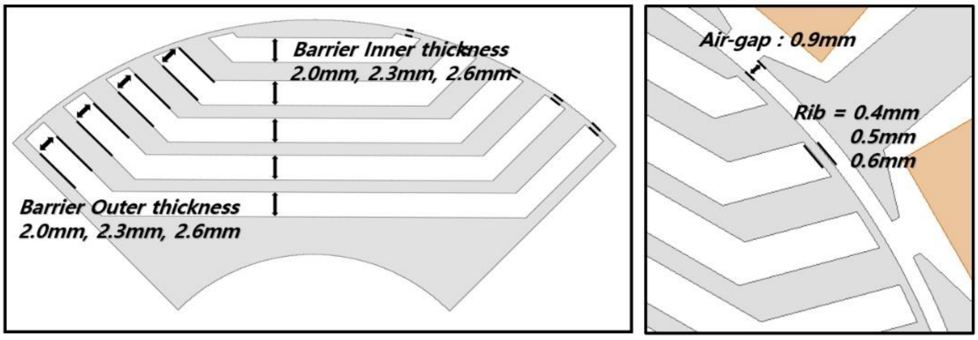

Figure 2. Design parameter in the rotor structure

The inductance and voltage equations in SynRM where the saliency ratio is important are as follows (3),(4),(5). Change the magnetic flux path depending on the barrier layer and perform torque and torque ripple analysis in the next section. SynRM model is described by the following equations.

$$L_d = \frac{3}{2}L_{aa,max} = \frac{3}{2}\frac{\lambda_{aa,max}}{I},\ L_q = \frac{3}{2}L_{aa,min} = \frac{3}{2}\frac{\lambda_{aa,min}}{I} \tag{3}$$

$$V_d = R_s I_d + \frac{d\lambda_d}{dt} - \omega_r\lambda_q,\ V_q = R_s I_q + \frac{d\lambda_q}{dt} + \omega_r\lambda_q \tag{4}$$

$$\lambda_d = L_d I_d\ ,\ \lambda_q = L_q I_q \tag{5}$$

2.2.2. Torque and Torque Ripple Comparison

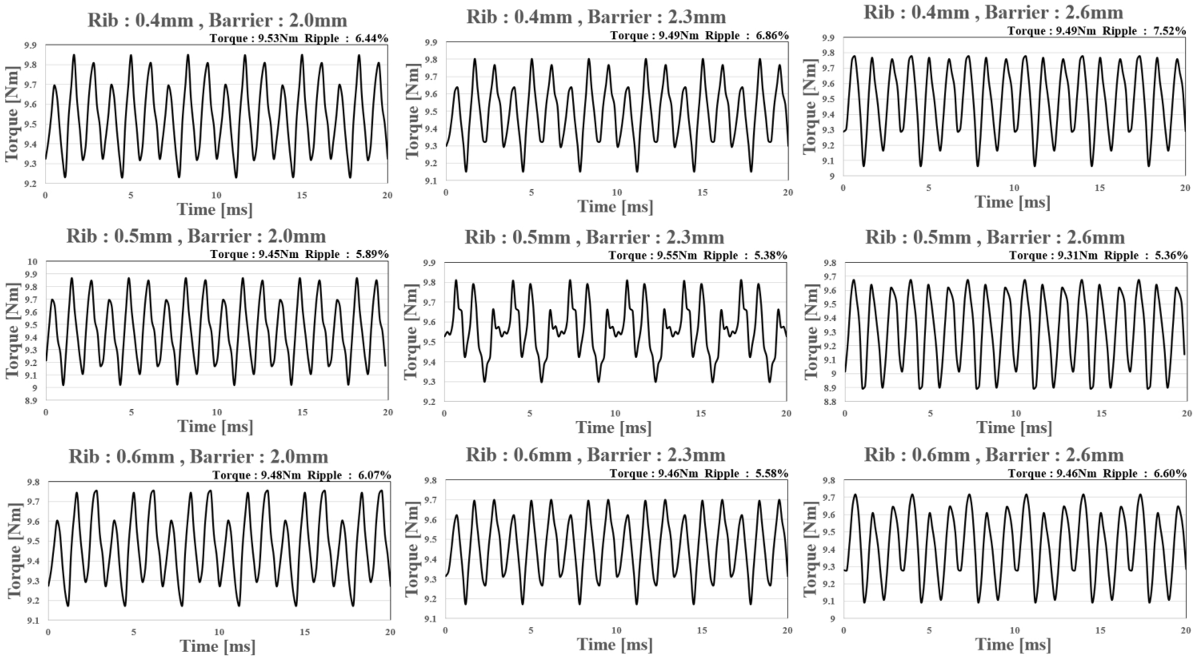

Figure 3. Comparison Torque and Torque ripple according to design parameters , @1,500rpm

The operating points of all nine models were analyzed from the base speed operating points. The torque ripple was the lowest at 0.5mm for rib thickness and 5.36% for barrier thickness at 2.6mm. The highest rib thickness was 0.4mm and the barrier thickness was 7.52% at 2.6mm. As the lip thickness decreases, the magnetic path narrows.

2.2.3. Inductance Comparison

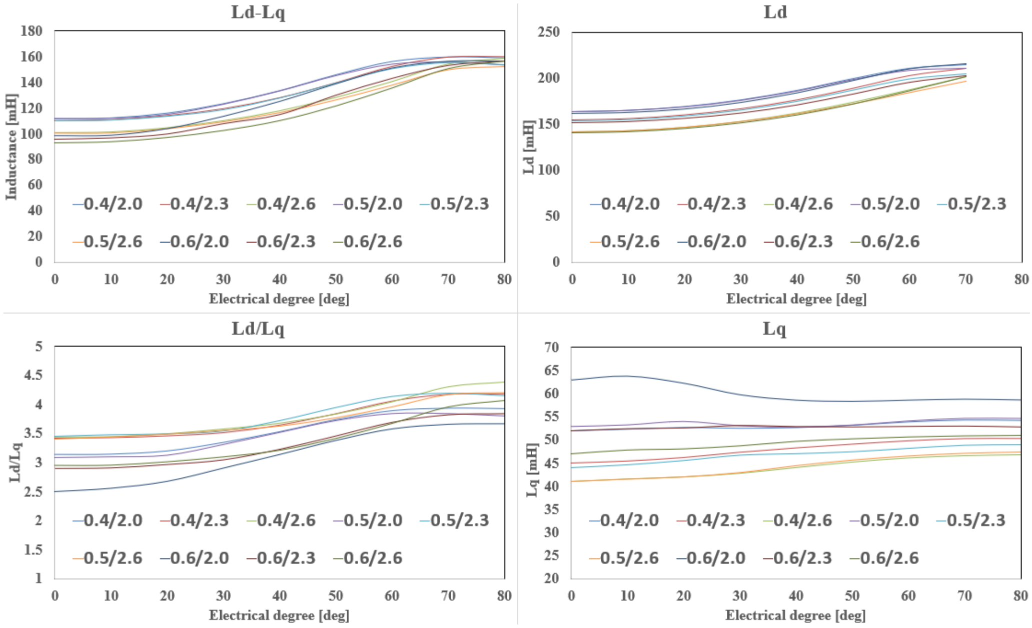

Figure 4. Comparison of inductance

Figure 4 shows the saliency ratio and inductance values according to rib thickness and barrier thickness. As the barrier thickness increases, the saliency ratio tends to increase at high speed, and the d-axis inductance increases as the barrier thickness decreases. In addition, a design in consideration of voltage saturation is required, and also the influence of harmonics cannot be ignored. When the rib thickness is 0.5mm, the saliency is the largest, and as a result of comparing the previous models, when the barrier thickness is 2.6mm, the smallest torque ripple is shown.

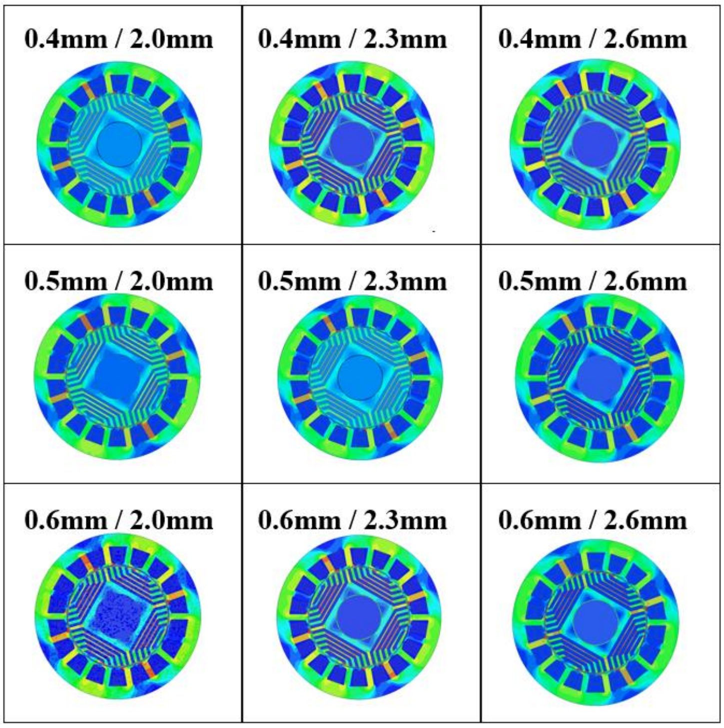

Figure 5. Field analysis according to design parameter

Figure 5 shows the result of the magnetic flux density distribution for each model through 2D FEM analysis. It can be seen that the magnetic flux path between the barriers is saturated. Moreover, as the magnetic flux path is narrow, the inductance and saturation increased, also the magnitude of the voltage increased.

Table 2. Advanced Model Specification

Parameter	Value	Unit
Phase Current	5	Arms
Current Angle	51	deg
Torque	9.5	Nm
Torque Ripple	5.36	%
Vab	334.78	Vrms
P3	1721.5	W
Core Loss	73.36	W
Copper Loss	148.2	W
Power Factor	86.89	%

The specification of the improved design model is shown in Table 2. As a result, the value of the torque ripple decreased, but due to the increased barrier thickness, the current value for producing the same torque increased slightly. It can be confirmed from the previously analyzed results that the increased amount of current affects the saliency pole ratio.

3. CONCLUSION

In this paper, torque ripple and flux field analysis was conducted according to the barrier thickness and rib thickness. As a result, the torque ripple improved by about 0.5% from 5.38% to 4.86%. Although the effect is small, it is represented that the torque ripple can be improved by comparing the inductance according to the barrier and rib thickness. Therefore, it is judged that the improvement design can be proceeded by using a design that reduces torque ripple by applying a skew and a method of applying a notch.

4. ACKNOWLEDGMENT

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