

Study on AC Copper Loss in Slotless Permanent Magnet Synchronous Motor

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Slotless permanent magnet synchronous motor (PMSM) are widely used in precision and high-speed applications but face significant AC copper loss due to direct flux linkage with the windings. This study uses finite element analysis (FEA) to investigate the mechanisms of AC copper loss in slotless PMSM. Results show that wire diameter and flux linkage are the primary factors: increasing wire diameter from 0.2 mm to 0.6 mm raises AC copper loss by 577%, while shifting the wire position to reduce flux linkage lowers it by 8.27%. These findings highlight the importance of conductor size and placement in reducing losses. Future research will examine the effects of number of turn, number of pole, and wire shape, and validate the analysis results through prototype testing.

Index Terms—AC copper loss, finite element analysis(FEA), permanent magnet synchronous motor (PMSM), slotless type.

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) are widely used in applications such as electric vehicle, vacuum cleaner, high-precision servo system and UAM(Urban Air Mobility) because of their high torque density. PMSM stator can be categorized into slotted and slotless types. Slotted PMSM, which typically have higher torque density than slotless PMSM, are used in many industries [1]. However, slotted PMSM can have drawbacks such as cogging torque, increased torque ripple due to spatial harmonics and eddy current losses in the permanent magnets. As a result, slotless PMSM are considered for specific applications that demand precision control and ultra-high-speed operation [2].

Recently, AC copper loss in PMSM has received increased attention, leading to several studies [3]-[5]. In [3], researchers examined how wire shape affects AC copper loss in a high-speed stator PM flux-switching permanent magnet motor. In [4], they investigated loss reduction methods in an axial flux permanent magnet motor by arranging flat wires either vertically or horizontally. In [5], they analyzed the influence of rotor eccentricity on AC copper loss in a high-speed slotless PMSM. Although AC copper loss is a major contributor to overall losses in PMSM, most existing studies focus on slotted PMSM, with little research on slotless PMSM.

In this paper, AC copper loss in slotless PMSM is analyzed using a finite element analysis (FEA). AC copper loss is determined by the magnetic flux density and size of wire. Since the magnetic flux density in slotless PMSM is varied by the distance from rotor, AC copper loss is analyzed for the position of the coil. Furthermore, the number and size of wire is considered to analyze AC copper loss under the same condition of the torque. As a result, the design method in slotless PMSM to reduce AC copper loss is investigated, and the experimental verification will be conducted in the full paper.

II. CHARACTERISTICS OF AC LOSS IN SLOTLESS PMSM

A. Structure of Slotless PMSM

Fig. 1 shows the structure of a slotless PMSM with a rotor based on a surface PMSM (SPMSM). TABLE 1 lists its detailed specifications where the poles and slots are set to 4 and 12 and the slot pitch is three pitches. As shown in Fig. 1 the slotless PMSM has no stator teeth and its mechanical air gap differs from its magnetic air gap.

B. Mechanism of AC copper loss

In general PMSM experience two main types of AC copper loss the skin effect and the proximity effect. The skin effect occurs when alternating current concentrates on a conductor surface reducing the effective cross-sectional area increasing resistance and thus increasing copper loss. The proximity effect refers to distortions in current density caused by magnetic interactions between adjacent conductors which produce additional losses [4], [5].

The eddy current loss per volume for round wire can be calculated based on the following equation [5].

$$P_{eddy} = \frac{B_p^2 \omega^2 d^2}{32\rho} \quad (2)$$

Where, B_p is the peak flux density, B_p contains both radial and tangential magnetic densities, ω is the electrical angular frequency, d is the wire diameter, ρ is the restivity

To evaluate the influence of the skin effect, it is necessary to calculate the depth to which current can penetrate the conductor, known as the skin depth. The skin depth can be calculated based on the following equation [5].

$$\delta = \sqrt{\frac{2}{\omega\gamma\mu}} \quad (3)$$

Where, γ is the conductivity of the conductor, and μ is the permeability.

TABLE I
SPECIFICATION OF SLOTLESS PMSM

Content	Value	Unit
Outer diameter of Stator	21	mm
Air gap	0.5	mm
Speed	12,900	r/min
Power	28	W

III. INVESTIGATION OF AC LOSS IN SLOTLESS PMSM

A. Size of Conductor

In (2), the volumetric eddy current loss increases in proportion to the square of the wire size. Thus, to compare AC copper loss at different wire sizes, wires ranging from 0.2 mm to 0.6 mm were analyzed. As shown in Fig. 2, when the wire size is 0.6 mm, AC copper loss is about 577% higher than at 0.2 mm. Because AC copper loss rises sharply with increasing wire size, it must be considered during the design phase of slotless PMSM.

B. Position of Conductor

Magnetic flux density was measured for both the original model and the wire-shift model, as shown in Fig. 3. Because the wire-shift model effectively increases the magnetic air gap, the flux linking with the wire decreases. According to (2), eddy current loss per volume increases in proportion to the square of the flux density, so shifting the wire can lower AC copper loss. As shown in Fig. 5, shifting the wire by 0.2 mm reduces AC copper loss by up to 8.27%.

IV. CONCLUSION

This paper analyzes AC copper loss in a slotless PMSM, where the loss occurs not from skin or proximity effects due to the low electrical frequency but from the direct magnetic flux linkage between the permanent magnets and the conductors. It is shown that increasing the wire diameter raises the AC copper loss, whereas shifting the wire position to reduce flux linkage can lower it. Future work will investigate how the number of turns and wire shape influence the loss, with experimental validation using the model in Fig. 6.

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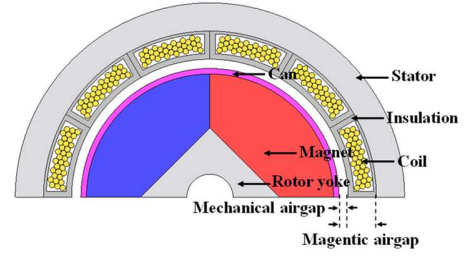


Fig. 1. Structure of slotless PMSM.

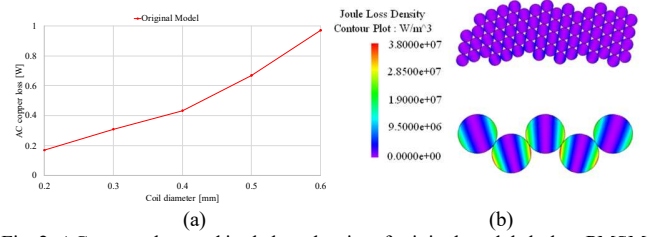


Fig. 2. AC copper loss and joule loss density of original model slotless PMSM (a) AC copper loss (b) Joule loss density, coil diameter : 0.2, 0.6mm.

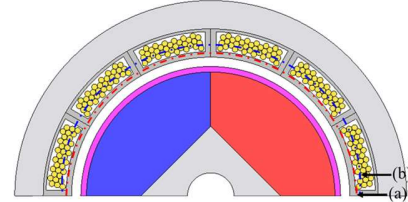


Fig. 3. Magnetic flux density measurement point of slotless PMSM (a) Original model (b) Wire shift model.

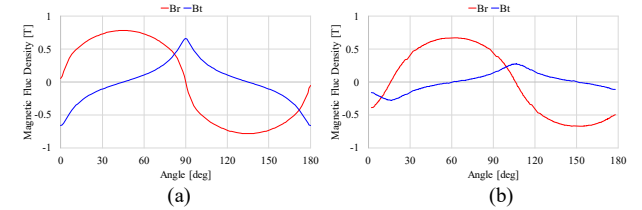


Fig. 4. Magnetic flux density of slotless PMSM (a) Original model (b) Wire shift model.

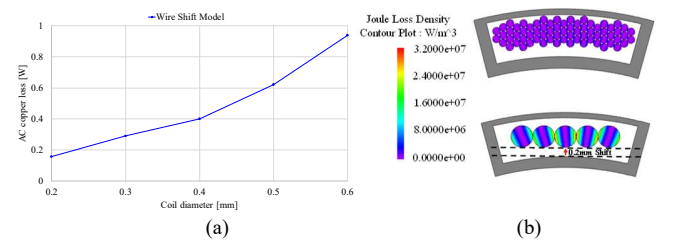


Fig. 5. AC copper loss and joule loss density of wire shift model slotless PMSM (a) AC copper loss (b) Joule loss density, coil diameter : 0.2, 0.6mm.

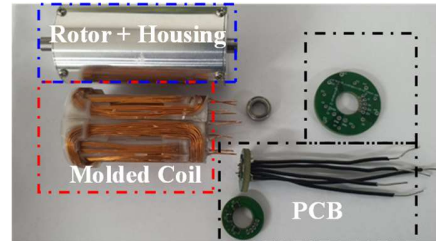


Fig. 6. Components of Slotless PMSM.