

Design for Size Reduction of an Electronical Regenerative Brake Motor Using MSO Coils

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In electrical regenerative braking systems, permanent magnet synchronous motors with fractional slot combinations are commonly used. Concentrated windings with lap winding configurations are typically employed. However, for compact 500 W-class motors, achieving a slot fill factor exceeding 50–60 % with conventional lap-wound concentrated windings poses significant challenges, limiting motor miniaturization. This paper explores the design of a size-reduced motor using maximum slot occupation (MSO) coils, which enable a slot fill factor exceeding 80 %. To verify the effect of the MSO coil only, the rotor geometry was designed to match the prototype. The performance of the designed model was evaluated using finite element analysis and d - and q -axis equivalent circuit analysis. The results confirm that the proposed design maintains comparable performance to the prototype while achieving approximately 28 % reduction in the stator core volume.

Index Terms— Benchmarking testing, Electromagnetic analysis, Finite element analysis, Permanent magnet motors, Torque.

I. INTRODUCTION

The importance of energy recovery through electronic regenerative braking (ERB) systems has become increasingly emphasized due to the growing demand for electric and hybrid electric vehicles. In particular, ERB systems have established themselves as a key technology for reducing fuel consumption and enhancing driving performance by efficiently recovering energy and storing it in batteries. ERB systems generate braking force by forming hydraulic pressure in the main cylinder through piston actuation powered by a motor, playing a crucial role in maximizing regenerative energy through coordinated control with the traction motor's regenerative braking [1].

In ERB systems, motors that generate power primarily utilize permanent magnet synchronous motors (PMSMs) with fractional pole/slot combinations, which offer advantages in terms of motor size reduction. However, conventional motors with lap-wound concentrated windings face limitations in miniaturization, as achieving a slot fill factor exceeding 50 % is challenging. To address these limitations, this paper presents a size reduction design for motors utilizing maximum slot occupation (MSO) coils, which enable a slot fill factor of over 80 % [2]. To isolate the effect of MSO coils, the rotor geometry was designed identically to that of the conventional lap-wound model. The performance of the designed model was evaluated using finite element analysis (FEA) and d - and q -axis equivalent circuit analysis (ECA) [3]. The results confirm that the proposed design maintains comparable.

II. DESIGN PROCESS FROM PROTOTYPE TO MSO COIL MODEL

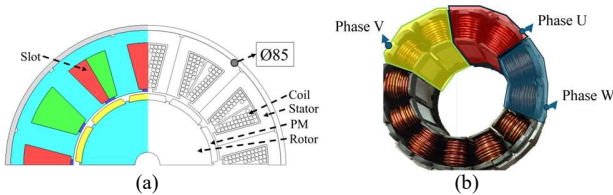


Fig. 1. Configuration of prototype. (a) FEA model. (b) Stator ASS'Y.

TABLE I
PROTOTYPE DETAILS

Item	Prototype
Stator Outer Diameter (mm)	85.0
Rotor Outer Diameter (mm)	40.8
Maximum Torque (Nm)	2.9
Fill Factor (%)	58.0
Phase Resistance (mΩ)	21
Connection Type	Delta

This study analyzes the size reduction achieved through the replacement of conventional winding with MSO coils in the drive motor of an ERB system. The specifications of the prototype used in the ERB system are shown in Fig. 1 and Table I. To isolate the effects of MSO coil application, the rotor geometry was kept identical to that of the prototype rotor. The stator design was modified from the delta winding configuration used in the prototype to a star winding configuration for the MSO coil model. This change aimed to reduce the manufacturing complexity of MSO coils by decreasing the number of turns per coil. To ensure a similar no-load back-EMF as the prototype, the MSO coil model with star winding was designed with 8 turns per coil (8-layer per single MSO coil). Furthermore, to maintain the same current density under maximum current conditions as the prototype, each strand of the MSO coil was designed with a cross-sectional area of 3.293 mm². Fig. 2 compares the models before and after applying the MSO coil, showing a reduction in the stator outer diameter from 85 mm to 72 mm. This reduction resulted in a volumetric decrease of 28.25 %. The fill factor of the MSO Coil model is 83.4 %, and the phase resistance is 11.28 mΩ.

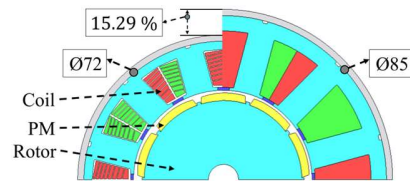


Fig. 2. Comparison between the MSO coil model and prototype.

III. PROTOTYPE VS MSO COIL MODEL

A. No-load characteristics analysis

The no-load back-EMF of the MSO coil model was calculated as 2.877 Vrms, which is approximately 4.97 % lower than the prototype's back-EMF of 3.02 Vrms. Due to the limited design flexibility in the number of turns per coil in low-voltage motors, the back-EMF was intentionally designed slightly lower. Increasing the number of turns per coil from 8 to 9 to compensate for the reduced back-EMF would result in a significant increase in back-EMF error (to over 7 %), making such a design change inappropriate. In addition, the cogging torque of the MSO coil model was measured at 10.03 mNm, representing a 58.5 % reduction compared to the prototype's cogging torque of 24.17 mNm. The results are shown in Fig. 3.

B. Performance analysis based on key parameters

Compared to the prototype, the MSO coil-applied model exhibited a reduced stator core area and lower magnetic field intensity, resulting in decreased iron losses. Furthermore, the transition from circular copper wire to rectangular copper wire increased the cross-sectional area, necessitating an analysis of the resulting changes in current distribution and AC resistance. The current density and AC resistance were analyzed, as shown in Fig. 4. Subsequently, the d - and q -axis inductances and flux linkage were analyzed using ECA. The d - and q -axis inductances of the prototype were approximately three times higher than those of the MSO coil model. Additionally, the flux linkage was approximately $\sqrt{3}$ times higher due to changes in the effective flux path caused by the altered phase current-voltage relationship. These results are presented in Fig. 5. Finally, model specifications analysis was evaluated under a DC voltage of 12.0 V, with the results summarized in Fig. 6. At a reference speed of 1,650 rpm and a current of 63.63 Arms, the torque values of the prototype and the MSO coil model were 2.94 Nm and 2.91 Nm, respectively, showing a difference of approximately 1.02 %. The increased coil cross-sectional area of the MSO coil model changed the current distribution and increased the AC resistance, which resulted in an efficiency that was approximately 8 % lower than that of the prototype.

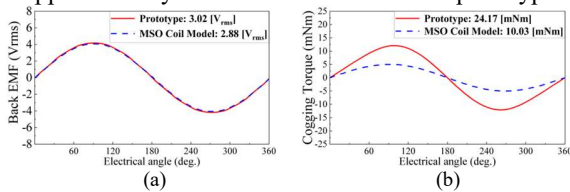


Fig. 3. Comparison between the no-load analysis in the prototype and the MSO coil model. (a) no-load phase back-EMF. (b) cogging torque.

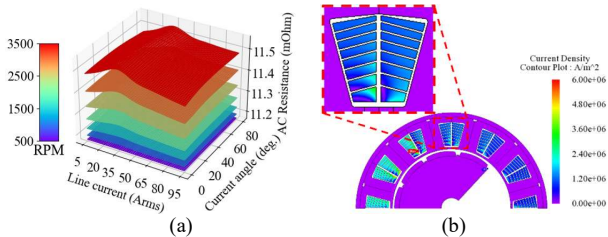


Fig. 4. Analysis of AC resistance and current density in the MSO coil model. (a) AC resistance. (b) Current density.

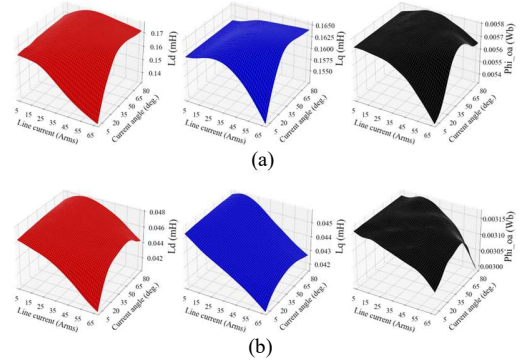


Fig. 5. Comparison of d - and q -axis inductances and flux linkage. (a) Prototype. (b) MSO coil model.

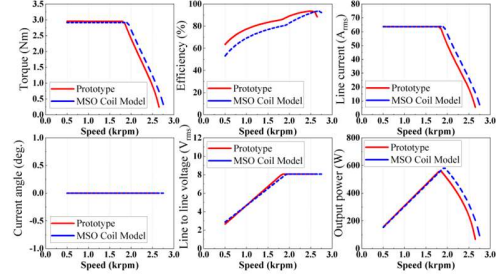


Fig. 6. Comparison of Specification analysis between prototype and MSO coil model.

IV. CONCLUSION

This study transitions from the ERB prototype to the MSO coil model to achieve size reduction and compare the performance of the two models. As a result, the stator outer diameter was reduced by 15.29 % compared to the prototype while maintaining comparable performance. Although the efficiency was slightly lower than that of the prototype, the impact is expected to be negligible as the model operation is primarily limited to braking scenarios. In the future, thermal equivalent circuit analysis will be conducted to evaluate thermal issues arising from the increased cross-sectional area of the MSO coil.

ACKNOWLEDGEMENT

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