Conductor Design Method Considering AC Resistance for High Efficiency of PMSM Using High Fill Factor Winding

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This article proposes the design method of conductor considering ac resistance for high efficiency of permanent magnet synchronous motor (PMSM) using high fill factor winding. To achieve high power density of the motor, high fill factor winding, such as hairpin winding, is used. maximum slot occupation (MSO) coils were also developed for the same purpose. However, ac resistance is generated in the high fill factor winding used in the motor, which adversely affects the efficiency of the motor. For high efficiency of the motor using high fill factor windings, the ac resistance must be reduced. Therefore, in order to reduce the ac resistance, a design method in which the size of the respective conductor layers is different is proposed. In this article, the method of reducing ac resistance is verified through analytical methods and FEA. Next, the validity of the proposed method is verified through performance evaluation of the prototype motor designed through the proposed method.

***Index Terms*— AC resistance, high efficiency, high fill factor winding, maximum slot occupation (MSO) coils, permanent magnet synchronous motor (PMSM).**

I. Introduction

Due to the fourth Industrial Revolution, the trend toward electrification is accelerating throughout the industry. Consequently, improvements in the efficiency and power density of motors have become necessary. To enhance the power density, high fill factor windings, such as hairpin windings, are utilized, and the Korea Institute of Industrial Technology (KITECH) has also developed maximum slot occupation (MSO) coils for this purpose [1].

However, ac resistance is an issue in the high fill factor windings used in motors. The ac resistance of the conductors in the slots of the motor is due to eddy currents generated by the magnetic leakage flux of the slots [1], [2]. Eddy currents create an imbalance in the distribution of the current density in the conductors, which causes ac resistance. In particular, this phenomenon appears more remarkably in a conductor close to an air gap, where a large amount of leakage flux exists in the slot. Therefore, it is necessary to properly size the conductors to reduce the ac resistance.

Chin et al. [2] investigated the effect of current density on ac resistance in the initial design of the motor. Cha et al. [1] reduced the tooth width to increase the reluctance of the slot to reduce the slot leakage flux, which is the cause of ac resistance. However, this also led to an increase in the reluctance of the motor, resulting in relatively inefficient operation. These studies targeted motors using MSO coils but did not utilize the characteristics of MSO coils.

Since MSO coils are manufactured using machine tools, they have the advantage of being able to be designed and manufactured with different sizes for each layer of conductor. Therefore, by appropriately designing the size of each conductor in the slot, eddy currents in the conductor can be reduced, and consequently, ac resistance can be reduced.

In this article, a design method of the conductor considering ac resistance for high efficiency of PMSM using a high fill factor winding is proposed. First, the ac resistance of conductors with different heights for each conductor layer was investigated through analytical methods and verified through finite element analysis (FEA). Next, the proposed conductor design method is applied to the permanent magnet synchronous motor (PMSM) using the MSO coil for reducing ac resistance. Finally, the validity of the proposed method is verified through a test on the prototype.

II. Investigation of Effect of Conductor Size on AC Resistance

This section presents an analytical method for ac resistance, verified through comparisons with 2D-FEA results. Additionally, a conductor design method for reducing ac resistance is proposed based on this analytical approach.

A. Analysis Method for Calculating AC Resistance of Different Size Conductors

As mentioned earlier, the cause of ac resistance in the conductor used in the motor is the flux leakage in the slot. Due to the flux leakage in the slot, eddy current flows in the conductor, which causes the ac resistance of the conductor. Moreover, since the flux leakage in the slot tends to flow more as it is closer to the air gap, the effect of ac resistance tends to be greater for the conductor closer to the air gap.

Fig. 1 shows a reference model for investigating the effect of conductor size on ac resistance. The reference models are E- and I-shaped cores, which are similar to motors.

Many researchers have studied a mathematical approach to ac resistance using the reference model in Fig. 1. Pyrhönen

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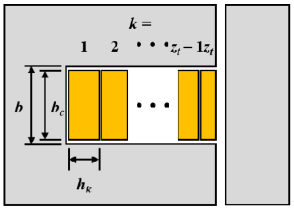

Symbol	Unit	Value
z_t	-	5
b	mm	14
b_c	mm	12
ω	rad/sec	4188.8
μ_r	-	∞
σ_c	S/m	5.8×10^7

Fig. 1. Reference model for investigating effect of conductor size on ac resistance.

studied an analytical method of calculating the ac resistance of rectangular conductors connected in series through Ampere's law and Faraday's law [3]. However, since this approach is for the case where conductors of the same type are connected in series. Since the MSO coil has a degree of freedom regarding the height of the conductors in each layer, we proposed a formula to calculate the ac resistance when the heights of the conductors in each layer are different.

The following procedure is required to calculate the ac resistance of conductors with different heights for each layer. The reduced conductor height calculated for each layer is as follows:

$$\xi_k = h_{ck}\sqrt{\frac{1}{2}\omega\mu_0\sigma_c\frac{b_c}{b}} \tag{1}$$

where ξ_k is the reduced conductor height for each layer, h_{ck} is the conductor height for each layer, ω is the electrical angular frequency of the input current, μ_0 is the permeability of the vacuum, σ_c is the conductivity of the conductor, b_c is the width of the conductor, and b is the width of the slot.

The resistance factor of the kth layer is as follows:

$$k_{Rk} = \varphi(\xi_k) + k(k-1)\psi(\xi_k) \tag{2}$$

where k_{Rk} is the resistance factor, and the functions $\varphi(\xi_k)$ and $\psi(\xi_k)$ are as follows:

$$\varphi(\xi_k) = \xi_k\frac{\sinh 2\xi_k + \sin 2\xi_k}{\cosh 2\xi_k - \cos 2\xi_k} \tag{3}$$

$$\psi(\xi_k) = 2\xi_k\frac{\sinh \xi_k - \sin \xi_k}{\cosh \xi_k + \cos \xi_k}. \tag{4}$$

Equation (2) shows that the resistance factor is smallest on the bottom layer and largest on the top layer. The total resistance considering ac resistance is as follows:

$$R_{\mathrm{AC}} = \sum_{k=1}^{z_t} k_{Rk}R_{\mathrm{DC},k} \tag{5}$$

where R_{AC} is the ac resistance of the conductor, z_t is the total number of layers of conductor, and $R_{\mathrm{DC},k}$ is the dc resistance of the conductor for each layer.

B. Conductor Design Method for Reducing AC Resistance

In this section, a conductor design method that can reduce ac resistance is introduced and verified through the analytical method and 2-D FEA. When conductor design is conducted, the fill factor of the conductors within the slot is maintained.

In conductor design, the heights of the conductor for each layer are modeled using a quadratic function while maintaining a constant overall height. This approach enables the exploration of how changes in the size and height of the conductor

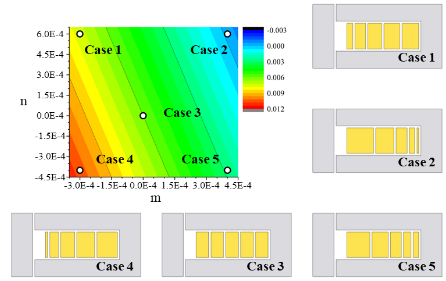

Fig. 2. When m and n change, l and conductor shape in slot.

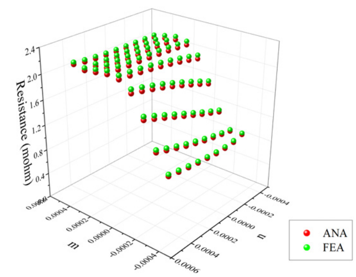

Fig. 3. Change of ac resistance according to the change of m and n.

affect ac resistance

$$h_{ck} = mk^2 + nk + l \tag{6}$$

$$\sum_{k=1}^{z_t} h_{ck} = \text{const.} \tag{7}$$

By (7), l is determined if m and n change in (6) and (7).

Fig. 2 shows l and the shape of the conductor in the slot as m and n change. The conductor consists of a total of 5 layers, the overall conductor height and size of each case is the same. However, each case has different conductor shapes. Case 3 has all the same size conductors. Case 3 has the smallest DC resistance because all conductors in the slot are all the same size. Cases 1 and 5 have a small height of the conductor close to the air gap, whereas cases 2 and 4 have a high height of the conductor close to the air gap.

Using the proposed formula (5), ac resistance was estimated according to the change of m and n. Furthermore, FEAs were conducted for several points to verify the validity of (5). When performing the 2-D-FEA, the commercial tool JMAG was used. Also, the nonlinearity of the core was ignored, and the coil side was only considered except for the coil end. As shown in Fig. 3, comparing the results through the analytical method and FEA, it can be confirmed that the overall trend is consistent. In addition, it can be confirmed that the ac resistance tends to reduce as m and n become smaller. In other words, it means that the AC resistance decreases as it becomes more similar to the conductor shape of cases 1 and 5 of Fig. 2. However, this may increase the current density and cause thermal problems in the motor, so it is necessary to limit the current density by considering the motor's cooling type.

III. Conductor Design Considering AC Resistance for High Efficiency of PMSM Using MSO Coils

A. Base Model

The specifications of the base model are listed in Table I. The base model is a motor used in P2 parallel HEVs, and MSO coils are applied.

TABLE I
SPECIFICATIONS OF BASE MODEL

Parameters	Value	Unit
Pole / Slot	18 / 24	-
Stator outer diameter	280	mm
Stack length	50	mm
Maximum power	40	kW
Maximum torque	190	Nm
Base speed	2000	rpm
Maximum speed	4000	rpm
Slot fill factor	70	%

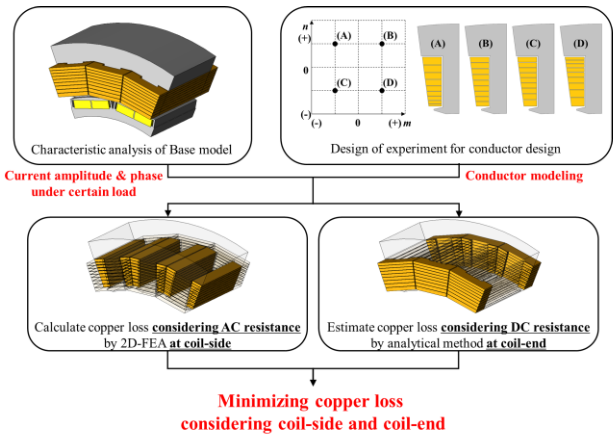

Fig. 4. Conductor design process considering ac resistance.

B. Conductor Design Process Considering AC Resistance

The conductor design process considering ac resistance is shown in Fig. 4. First, the characteristics of the base model are calculated by conducting the current vector control under given constraints [4]. In this process, the magnitude and phase of the current were calculated to operate certain loads: (at 2150 r/min, 90 Nm) and (at 4000 r/min, 60 Nm). Second, the design of the experiment for conductor design based on Latin hypercube sampling is conducted. Here, the variables m and n related to the conductor size are used. Third, for each sample, the copper loss is separately calculated by dividing the coil into two parts: coil side and coil end [2]. In the coil side, to calculated accurately ac resistance by considering the nonlinearity of the core and the effect of the field and armature, 2D-FEA is conducted. On the other hand, in the coil end, the copper loss is calculated through analytical method because the ac resistance is negligible in the coil end [4]. Finally, to minimize the copper loss, the multiobjective optimization with the kriging surrogate model is conducted.

The objectives and constraints for optimizing can be defined as follows:

$$\min : \begin{cases} f_1(x) = W_{c1} \\ f_2(x) = W_{c2} \end{cases} \tag{8}$$

where f_i is the objective function, x is the design variables related to conductor size, and W_{c1} and W_{c2} are, respectively, the copper loss at (2150 r/min, 90 Nm) and (4000 r/min, 60 Nm). At (2150 r/min, 90 Nm), the magnitude and phase of the current are 71.0 Arms and 12.2°, respectively.

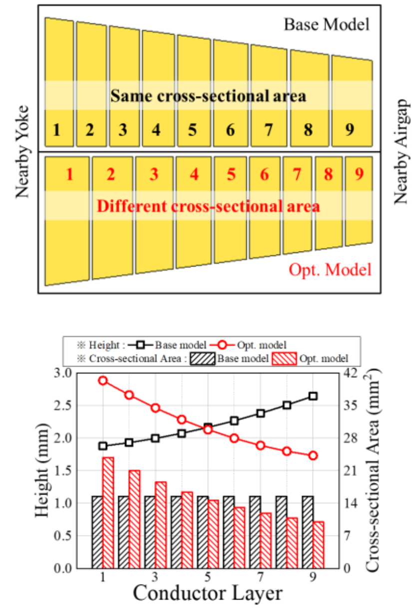

Fig. 5. Conductor shape and dimensions of base model and optimum model.

Also, at (4000 r/min, 60 Nm), the magnitude and phase of the current are 72.3 Arms and 53.9°, respectively.

Constraints were determined considering manufacturability and current density. For manufacturability considerations, the minimum conductor thickness is 0.5 mm. The current density limit is 10 Arms/mm^2, which is the typical current density under continuous operation conditions of a liquid-cooled motor [5]. The constraint g_1 and g_2 can be defined as follows:

$$g_1(x) = 0.5 - \min(h_{c1} \sim h_{c9}) \leq 0 \tag{9}$$
$$g_2(x) = \max(J_{c1} \sim J_{c9}) - 10 \leq 0. \tag{10}$$

C. Design Result Through the Proposed Design Process

In this section, the results of applying the proposed conductor design process to the base model are presented. Fig. 5 shows the conductor shape and dimensions of each layer for the base model and optimum model. Here, the dimensions of the conductors represent the height and cross-sectional area of each layer. As can be seen in Fig. 5, the height of the conductor of the two models changes in different ways as the number of layers increases. The base model gradually increases the height of the conductor as the number of layers increases, but the optimum model shows that the height of the conductor gradually decreases. As explained in Section II, these changes are intended to reduce ac resistance. Also, as the number of layers increases, the cross-sectional area of the conductor is constant in the case of the base model, but the cross-sectional area of the conductor decreases in the case of the optimum model. For this reason, the dc resistance of the optimum model is 13.9 mΩ, which is larger than that of the base model, which is 12.8 mΩ. Figs. 6 and 7 show the tendency of copper loss and ac resistance factor according to the load obtained through the surrogate model. In Figs. 6 and 7, the black and red balls represent the base and optimum models, respectively. In addition, the boundary line shown in magenta in Figs. 6 and 7 indicates the areas,

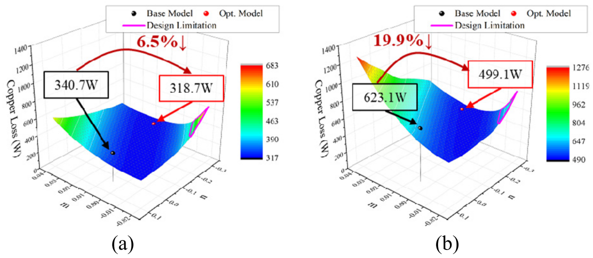

Fig. 6. Tendency of copper loss according to change of m and n at (a) (2150 r/min, 90 Nm) and (b) (4000 r/min, 60 Nm).

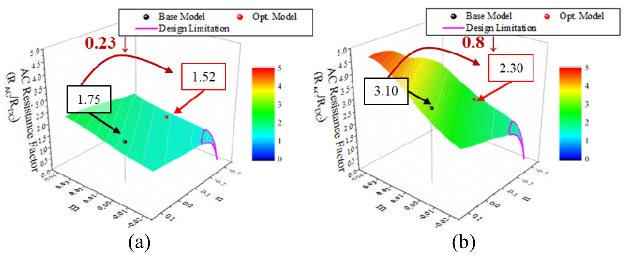

Fig. 7. Tendency of ac resistance factor according to change of m and n at (a) (2150 r/min, 90 Nm) and (b) (4000 r/min, 60 Nm).

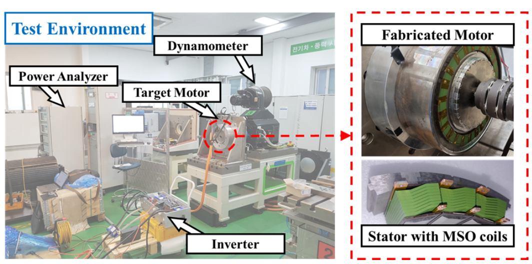

Fig. 8. Test environment and fabricated motor with MSO coils.

where the design is limited by constraints. As seen in Fig. 6, at (2150 r/min, 90 Nm) and at (4000 r/min, 60 Nm), the copper loss decreased by 6.5% and 19.9%, respectively. The ac resistance factor is the ratio of dc copper loss to ac copper loss and is shown in Fig. 7. As seen in Fig. 7, at (2150 r/min, 90 Nm) and at (4000 r/min, 60 Nm), ac resistance factor decreased by 0.23 and 0.8, respectively. Therefore, the proposed design method can reduce copper loss by considering ac resistance in high fill factor windings, such as MSO coils. In other words, the proposed design method can improve the efficiency of PMSMs using high fill factor windings.

IV. Experimental Verifications

To verify the validity of the proposed design method, the optimum model was fabricated and tested. Fig. 8 shows the experimental setup for testing the prototype motor with MSO coils designed through the proposed method. To verify the performance of the motor, the motor efficiency was measured through load tests.

Fig. 9 shows the comparison between FEA and load test results, where the FEA results reflect measured mechanical loss. When comparing the load test results with the FEA

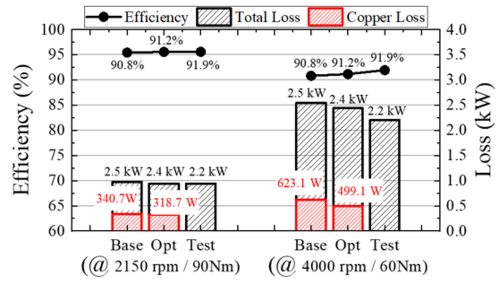

Fig. 9. Comparison between FEA and load test results.

results, the errors were 0.1%p and 0.7%p at (2150 r/min, 90 Nm) and (4000 r/min, 60 Nm), respectively. Also, by reducing the ac copper loss, the effect of the efficiency improvement is confirmed. This effect was especially noticeable at (4000 r/min, 60 Nm). Therefore, the validity of the proposed design method was verified by the comparison FEA and load test results.

V. Conclusion

A conductor design method considering ac resistance was proposed to improve the efficiency of PMSMs using high fill factor windings. First, the effect of ac resistance reduction through conductor design was verified using analytical methods for E- and I-shaped cores. Next, copper loss was reduced by applying the proposed design method to a PMSM with MSO coils. Finally, the validity of the proposed method was verified through testing the prototype motor. Therefore, the proposed conductor design method can improve motor efficiency by reducing ac resistance in high fill factor windings.

For future work, the impact of increased current density due to the proposed method on the motor's thermal characteristics will be investigated using a thermal equivalent circuit model.

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