Prediction of Mechanical Loss for High-Power-Density PMSM Considering Eddy Current Loss of PMs and Conductors

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This article proposes an indirect method for predicting mechanical loss by considering the eddy current loss of permanent magnets (PMs) and conductors under the no-load condition. The mechanical loss has been conventionally predicted indirectly through experiments and numerical methods. The conventional method uses the no-load loss measured through experiments and the no-load iron loss calculated through a numerical method. With the increase in the demand for high-power-density motors, the PMs with high energy density and winding technology with high fill factor are required. Thus, the proportion of eddy current losses of PMs and conductors is increasing among the electromagnetic losses. Therefore, we propose an indirect method for predicting the mechanical loss considering the eddy current losses. The accuracy of the proposed method is higher than that of the conventional method. Moreover, the proposed method is verified by comparing the estimated efficiency of the specimen obtained by using this method with the measured efficiency.

Index Terms—**Eddy current loss, efficiency, mechanical loss, maximum slot occupation coil (MSO coil), permanent-magnet synchronous motor (PMSM).**

I. Introduction

ESTIMATING the efficiency of permanent magnet synchronous motors (PMSMs) is important, as it is related to the thermal characteristics and energy consumption of the motor. Methods to predict various losses in PMSMs are required to estimate the efficiency accurately. The losses in the PMSMs can be classified into electromagnetic and mechanical losses. The electromagnetic loss can be predicted accurately by using material properties, but the mechanical loss is difficult to predict because it is highly dependent on the environment and manufacturing conditions.

The mechanical loss can be divided into bearing loss and windage loss, which is the friction between the fluid and the rotor in the air gap. As the mechanical loss is related to aerodynamic behaviors and manufacturing processes, it has been conventionally predicted via experiments or indirect methods. Although attempts have been made to predict the mechanical loss analytically using fluid properties [1], this method is only suitable for high-speed motors in which the windage loss is dominant. The most reliable way to predict the mechanical loss is to conduct experiments using a nonmagnetized dummy rotor [2]. However, this method is not efficient because it additionally requires the manufacture of the dummy rotor. Therefore, an indirect method using experiments with the designed motor and electromagnetic finite-element analysis (FEA) is preferred [3], [4].

The indirect method uses the no-load loss measured from the specimen driven by an additional motor. As the no-load loss includes not only the mechanical loss but also the no-load iron loss generated by field magnets, the no-load iron loss is separated from the no-load loss, and the mechanical loss can be predicted. However, the method assumes that the eddy current losses of permanent magnets (PMs) and stator conductors are negligible. Due to the demand for high-power-density motors, high fill-factor windings, such as hairpin windings, have been developed to increase the electric loading [5], and PMs having high energy density have been developed to increase the magnetic loading. However, the eddy current losses in PMs and conductors are increased even under the no-load condition because of increased conductor area and magnetomotive force of PMs. Thus, the eddy current losses should be considered when predicting the mechanical loss by using an indirect method.

This article presents a prediction method for mechanical loss by considering the eddy current losses of PMs and conductors under the no-load condition. A more accurate prediction method can be accomplished by separating the no-load eddy current losses as well as iron loss from the no-load loss. The mechanical loss can be predicted more accurately by using this method without manufacturing a dummy rotor. The rest of this article is organized as follows. Section II describes the nature of the eddy current losses under the no-load condition. Section III describes the prediction method for mechanical loss by considering the iron loss and eddy current losses. The experimental method using the dummy rotor, the conventional method using no-load loss and iron loss, and the proposed method are compared in this section. Section IV verifies the proposed method by conducting simulations and experiments. The results of predicting the mechanical loss by using each method are compared in this section. Section V concludes this article.

II. Eddy Current Losses in No-Load Condition

The eddy current losses of PMs and conductors are induced by alternating external magnetic fields. Fig. 1 shows the causes

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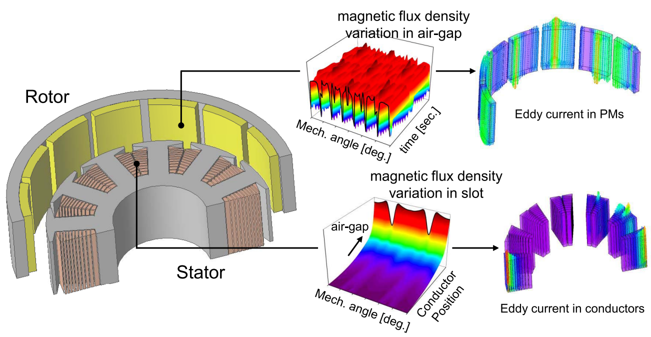


Fig. 1. Causes of the eddy current losses in PMs and conductors.

of the eddy current losses and the eddy current path of PMs and conductors. The eddy currents are induced by the space- and time-harmonic components of air-gap magnetic flux density caused by the field flux and the structure of slots even in a no-load condition. The eddy current loss of conductors is caused by the armature current flowing inside the conductors and the external magnetic field arising due to field magnets. The armature current affects the skin and proximity effect, resulting in eddy current loss. As the rotor rotates without armature currents, the space and time harmonics in the field flux combine to produce asynchronous field components relative to the conductors. Therefore, the magnetic flux leaking into the slot also has harmonic components. This effect generates the eddy current loss in conductors even in no-load conditions.

Due to the complex geometry of the motor, the air-gap magnetic flux density and slot leakage component are difficult to model analytically [8]. In addition, it is difficult to estimate the distribution of current density on conductors because it varies depending on the arrangement of the conductors inside the slot [7]. Thus, the current densities of PMs and conductors are calculated using electromagnetic FEA. The eddy current losses of PMs and conductors are calculated as

$$W_{\text{eddy}} = \frac{1}{\sigma}\int \mathbf{J}\cdot\mathbf{J}^{*}dV \tag{1}$$

where W_{eddy} and σ are the eddy current loss and conductivity for each material, $\mathbf{J}$ is the current density, and the V is the volume for each material.

III. Prediction Methods for Mechanical Loss

This section describes the nature of mechanical loss and the prediction methods for mechanical loss. The conventional, experimental, and proposed methods are compared in this section.

Table I shows the specifications of the specimen, which has 14-poles and 12-slots and an outer rotor, used for verifying the proposed method. The armature winding of a maximum slot occupation coil (MSO coil) is used to show the effect of the eddy current loss in conductors over its large conductor area as shown in Fig. 2(a) and (b), to verify the proposed method. An MSO coil is a winding technology that enables to increase the fill factor extremely by machining a copper block into a coil that can be fit into the slot [6], [9].

TABLE I
Specifications of the Specimen

Item	Unit	Value
Number of poles	-	14
Number of slots	-	12
Stator diameter	mm	80
Stack length	mm	20.7
DC link voltage	V	48
Max. power	W	600
Rated torque	Nm	1.0
Max. speed	rpm	2,500
Permanent Magnets	-	N38UH

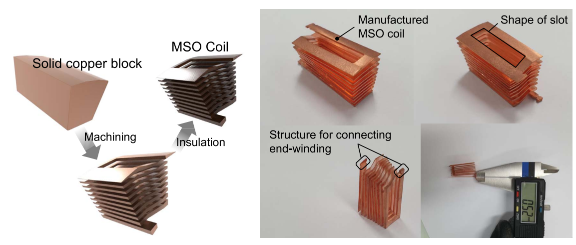
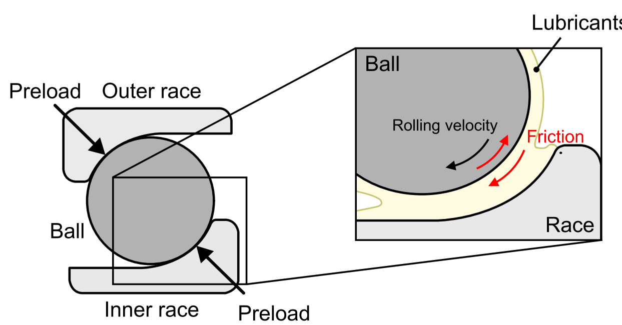


Fig. 2. MSO coil for high fill factor. (a) Manufacturing process of the MSO coil. (b) Manufactured MSO coil for the specimen.



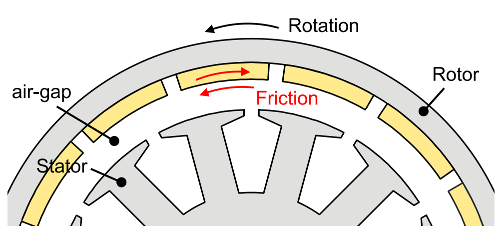


Fig. 3. Causes of mechanical loss. (a) Friction phenomenon in the bearing. (b) Friction phenomenon in the air gap.

The mechanical loss of the motor consists of bearing and windage losses. The bearing loss is caused by the friction occurring between the ball of the bearing and the lubricants, as shown in Fig. 3(a), and the friction phenomenon is similar to viscous friction. The windage loss is caused by the friction between the fluids in the air gap and the rotor, as shown in Fig. 3(b). Therefore, the mechanical loss depends on the rotational speed of the rotor.

A. Conventional Method

The conventional method for predicting the mechanical loss is widely used rather than the experimental method because the method is much efficient than the experimental method that requires manufactured dummy rotor [3], [4]. The conventional method is developed with experiment results and FEA together, unlike the IEC standard based on the experiments [10]. The method assumes that the eddy current losses of PMs and conductors are negligible so that it only considers the iron loss under the no-load condition. The procedure of predicting the mechanical loss by using the conventional method is as follows. The no-load loss is measured by driving the specimen at a constant rotating speed using an additional motor. The torque required to maintain the rotating speed is measured, and the no-load loss can be calculated by multiplying the torque and rotating speed as

$$W_{\text{noload}} = T_{\text{noload}} \cdot \omega_m \tag{2}$$

where W_{noload} is the no-load loss, T_{noload} is the torque required to maintain the specimen at a constant rotating speed in no-load condition, and ω_m is the rotating speed. Subsequently, the mechanical loss at the rotating speed can be predicted by separating the no-load iron loss calculated by using electromagnetic FEA from the no-load loss as

$$W_{\text{mech}} = W_{\text{noload}} - W_i \tag{3}$$

where W_{mech} and W_i are the mechanical loss and calculated no-load iron loss, respectively. The eddy current losses of PMs and conductors are not considered in the conventional method because the method assumes that the eddy current losses in no-load conditions are negligible compared with other losses.

B. Proposed Method

The proposed method predicts the mechanical loss by separating the no-load iron loss and eddy current losses of PMs and conductors from the no-load loss as

$$W_{\text{mech}} = W_{\text{noload}} - W_i - W_{e,\text{PM}} - W_{e,\text{cond}} \tag{4}$$

where $W_{e,\text{PM}}$ and $W_{e,\text{cond}}$ are the no-load eddy current losses of PMs and conductors, respectively. As the no-load iron loss and eddy current losses are dependent of the frequency and magnetic flux density, they should be calculated at each rotating speed.

The process of calculating the iron loss is shown in Fig. 4(a). First, a nonlinear FEA is performed to calculate the magnetic flux density at each element under a certain rotating speed with no armature current. Then, harmonic analysis of the magnetic flux density is conducted to evaluate the amplitude at each frequency. From the iron loss data of the material, the iron loss corresponding to the magnetic flux density and frequency of each harmonic component is calculated. Then, the iron loss for each element is calculated by summing the iron losses of all the associated harmonic components. Consequently, the total iron loss is calculated by summing the iron losses for all elements. The process of calculating the eddy current losses is shown in Fig. 4(b). First, the transient analysis is conducted for calculating the current density of PMs and conductors. Then,

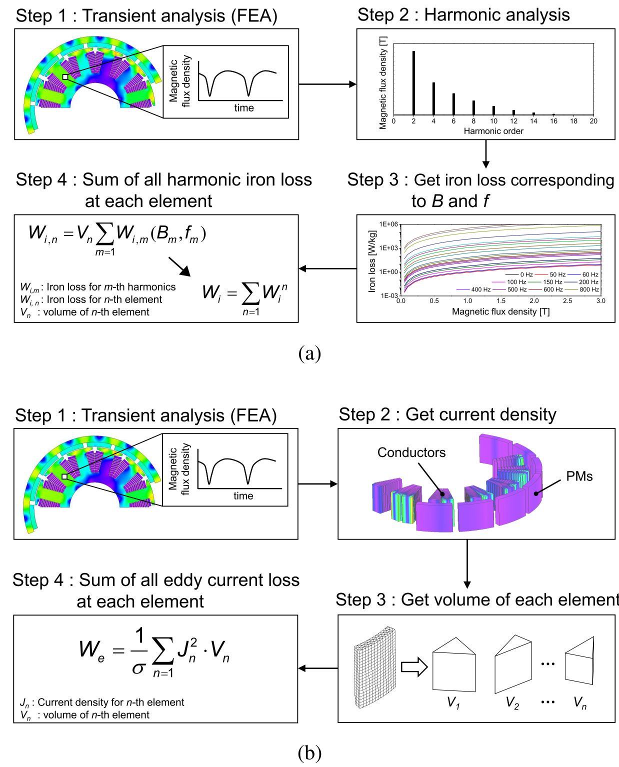


Fig. 4. Process for calculating electromagnetic losses. (a) Flowchart for iron loss calculation. (b) Flowchart for calculating the eddy current losses.

the eddy current losses for each element are calculated by using the current density, volume of element, and conductivity of each material. Consequently, the total eddy current loss is calculated by summing the eddy current losses for all elements.

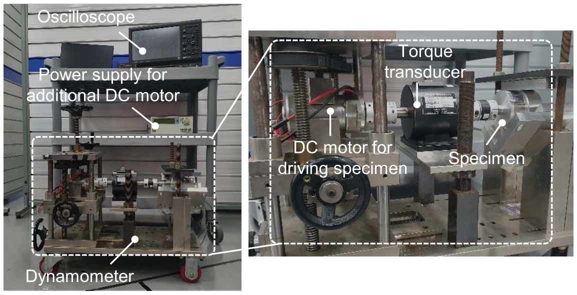
As the conventional method only separates the no-load iron loss from the no-load loss, the mechanical loss is higher than that obtained through the proposed method. Then, the efficiency of the motor is lower than that obtained by using the mechanical loss predicted by the conventional method.

IV. Experimental Verification

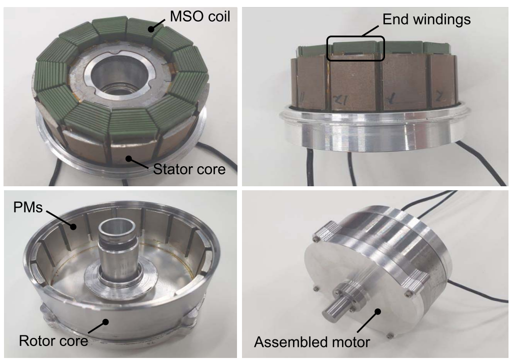
This section compares the experimental results obtained by using the conventional and proposed methods. The mechanical losses predicted by each method are compared with the mechanical loss measured from the experiments. Each mechanical loss is used to calculate the efficiency of the motor at the rated power, and the calculated efficiency is compared with the measured efficiency to verify the effectiveness of the proposed method.

A. Measurement of the No-Load Loss and Mechanical Loss

Fig. 5(a) shows the configuration of the experimental setup for measuring the no-load loss and Fig. 5(b) shows the specimen manufactured with MSO coil. The specimen with a magnetized rotor, a torque transducer, and an additional dc motor for the external driving of the specimen were connected in series. The capability of the torque transducer is 10 Nm and the precision is 0.1%, and the resolution of the tachometer for measuring the rotating speed is 0.02%. The experiments



(a)



(b)

Fig. 5. Experimental setup to measure the mechanical loss. (a) Configuration of the experiment. (b) Specimen manufactured with MSO coil.

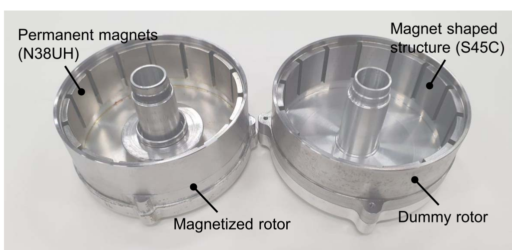


Fig. 6. Dummy rotor for measuring the mechanical loss.

were conducted after rotating the specimen for 30 min to minimize the effect of the temperature change on the bearing because the lubricants in the bearing are highly affected by the temperature. The experiments were conducted up to a speed of 2500 r/min, which is the maximum speed of the specimen.

The mechanical loss according to the rotating speed was measured by conducting experiments, to verify the proposed method. As the no-load electromagnetic loss is generated by the field magnets, the mechanical loss can be measured directly by measuring the no-load loss of the specimen with dummy rotor [2], [4], [10]. Although there is a segregation method of the mechanical loss suggested by the IEC standard, the method using the dummy rotor is more effective because the method suggested by the IEC standard includes uncertainty by measurements [10]. The dummy rotor was manufactured with non-magnetized materials such as S45C shown in Fig. 6, but its weight was the same as that of the magnetized rotor. The experiments were conducted by installing the specimen with the dummy rotor in the experimental setup of Fig. 5(a). The speed range of the experiments was the same as that of the experiments for measuring the no-load loss.

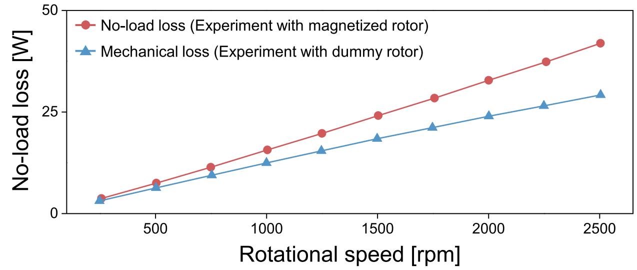


Fig. 7. Measured no-load loss and mechanical loss of the specimen.

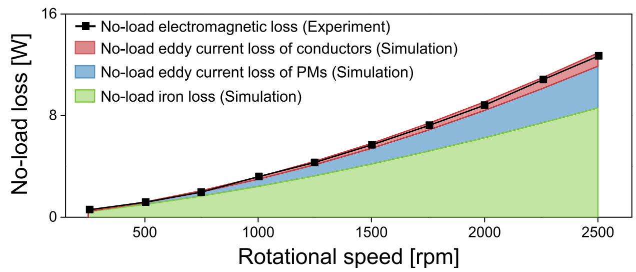


Fig. 8. Comparison of the calculated no-load iron loss and eddy current losses with the measured no-load loss.

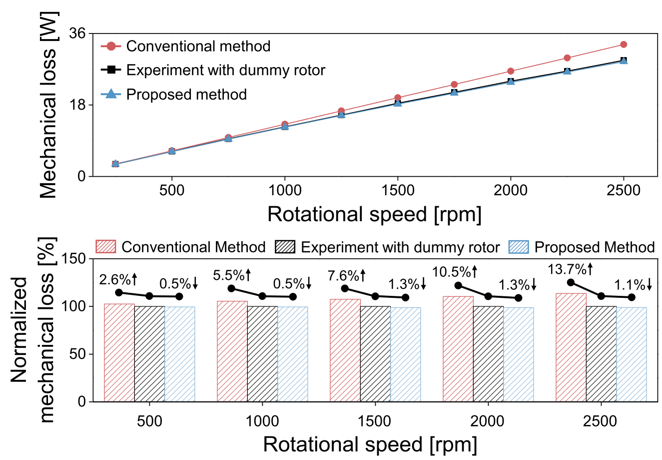


Fig. 9. Comparison of the predicted mechanical loss by using the conventional and proposed methods with the measured mechanical loss.

Fig. 7 shows the measured no-load loss from the experiment with magnetized rotor and mechanical loss from the experiment with dummy rotor. Each loss increases as the rotating speed increases. As the no-load loss includes the electromagnetic loss, the mechanical loss is lower than the measured no-load loss.

B. Verification of Proposed Method

Fig. 8 shows the results of comparing the calculated no-load iron loss and eddy current losses of PMs and conductors with electromagnetic loss, which was calculated by separating the measured mechanical loss from the measured no-load loss. The eddy current loss of the end windings was not considered because the end windings are less affected by the radial flux [11]. It can be seen that the eddy current losses cannot be negligible compared with the iron loss. Fig. 9 shows the result of comparing the predicted mechanical

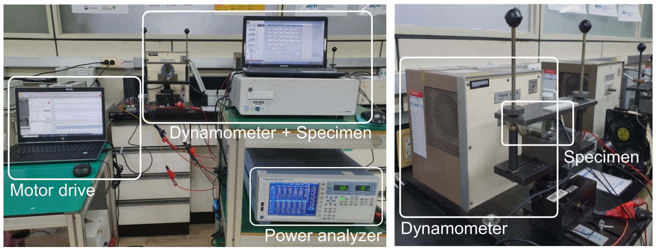


Fig. 10. Experimental setup for measuring the efficiency of specimen.

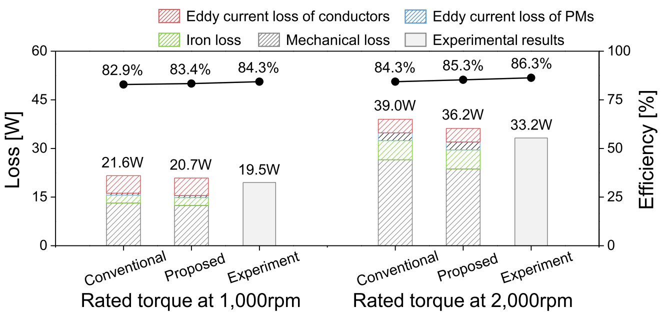


Fig. 11. Comparison of estimated efficiency by using each method and measured efficiency of the specimen.

loss by using the conventional and proposed methods with the measured mechanical loss. The mechanical loss obtained by the conventional method was higher than that of the proposed method because the eddy current losses are expected to be included in the mechanical loss. By comparing the predicted and measured mechanical losses, it is concluded that the proposed method is suitable for predicting the mechanical loss.

Experiments for measuring the efficiency of the specimen were conducted to verify the efficiency estimated using the mechanical loss predicted by using the proposed method. Fig. 10 shows the experimental setup for measuring the efficiency of the specimen. The experiments were conducted at the rated torque and different rotational speed of 1000 and 2000 r/min. The estimated efficiency was evaluated by using the iron loss and eddy current losses, which were calculated by using FEA, and the mechanical loss predicted by using each method. Fig. 11 shows the results of comparing the estimated and measured efficiencies. The estimated efficiencies were calculated by using electromagnetic losses evaluated by FEA under each load condition and mechanical losses predicted by using each method. The eddy current loss of end windings was not considered, but the copper loss by armature current was considered for calculating the efficiency. As the eddy current losses under no-load conditions were not separated in the mechanical loss of the conventional method, the mechanical loss of the proposed method is lower than that of the conventional method. Therefore, the errors of efficiency between the proposed method and the experiment result were lower than that of the conventional method.

V. Conclusion

This article proposes an indirect method for predicting mechanical loss by considering eddy current losses under the no-load condition. As PMs with high energy density and windings with high fill factor are used to increase the efficiency of the motor, the eddy current losses of PMs and conductors occur even under the no-load condition. Thus, the proposed method predicts the mechanical loss by considering the eddy current losses and the no-load iron loss. The proposed method was verified via a comparison with the mechanical loss measured using experiments. The experiments were conducted by using a dummy rotor manufactured with non-magnetized materials. The proposed method predicted the mechanical loss more accurately than the conventional method, which predicts the mechanical loss by considering only the no-load iron loss. Moreover, the proposed method was verified via a comparison of the efficiency estimated by using this method with the measured efficiency. The mechanical loss could be predicted by using the designed motor and numerically calculated electromagnetic losses.

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