Iron Loss Analysis of an SR Motor Accounting for Hysteresis and Eddy Current Distribution

1. Introduction

Switched reluctance motors (hereafter referred to as an "SR motor") are highly durable, robust, and have low costs since they do not use permanent magnets. Since the magnetic flux density waveform of an SR motor's iron core differs from those of AC motors, such as PM synchronous motors and induction motors, it has been pointed out that accuracy cannot be achieved using conventional iron loss evaluation methods[1][2]. We used a new method which can evaluate iron loss in high accuracy even with magnetic density wave form for SR motors, and gained positive results when comparing with actual measurements. This paper reports on the findings of this research.

2. Conventional Issues and Proposed Methods

2.1 Issues Regarding SR motor Iron Loss Evaluation

Traditionally, the Steinmetz's empirical law or expanded methods based on this law have been widely used (hereafter referred to as "conventional methods"). With these methods, each coefficient of the empirical law is determined using the iron loss characteristics which are measured with sinusoidal magnetic flux applied to an electromagnetic steel sheet using the Epstein's method or single sheet test method. However, the magnetic flux density history of the iron core in the SR motor varies widely from the sine-wave-shaped magnetic flux. For example, magnetic flux density history for the stator ends is as shown in fig. 1. As this figures shows, magnetic flux density is not composed of a sine wave, but higher harmonic components. These harmonic components draw DC bias-magnetized minor loops in an electromagnetic steel sheet with magnetic hysteresis. It is known that in DC bias- magnetized minor loops, hysteresis loss increases much greater than in major loops with equal amplitudes or minor loops that are not DC bias-magnetized [3]. Therefore, there is the issue of underestimating hysteresis loss with a conventional method which uses iron loss characteristics measured without DC biased magnetization. Concurrently, since eddy current has been estimated based on the iron loss characteristics measured without DC biased magnetization in conventional methods, it is considered that the permeability distribution of electromagnetic steel sheet is different from when the DC biased magnetization is applied and the calculation accuracy of the eddy current loss is also affected.

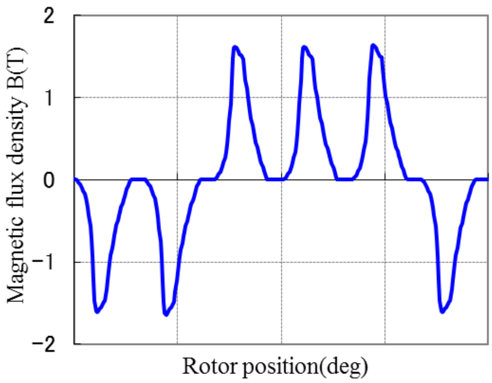


Fig. 1 Example of Magnetic flux density history

2.2 Proposed Eddy Current Loss Analysis Methods

Due to SR motors having high rotational velocity and high synchronous frequencies, the eddy currents in the laminated steel sheet thickness direction are not uniform, and have a concentrated distribution. As stated previously, because of DC biased magnetization, the eddy current distribution differs from the distribution in sinusoidal magnetic flux with no DC biased magnetization, and eddy current distribution in the steel sheet thickness direction must be accurately obtained. In this paper, we used a method to derive eddy current losses. This was done by accounting for skin effect by inputting the magnetic flux density history for each element obtained from a 2D transient response analysis in the 1D analysis that simulates the laminated steel sheet thickness direction, as shown in fig. 2 (hereafter referred to as 1D method) [4][5].

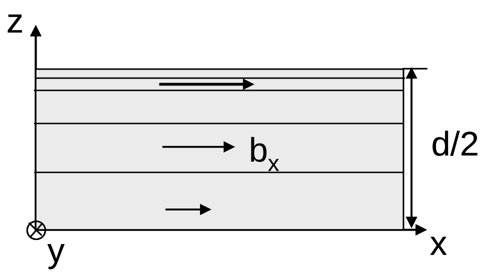


Fig. 2 Conceptual diagram of a lamination analysis (1D method)

2.3 Proposed Hysteresis Loss Analysis Method

There are a few known magnetic hysteresis modeling methods that can account for minor loops with DC biased magnetization, but for this proposed method, an isotropic vector play model[6][7] is used. Isotropic vector play models are applied to the post-processing for magnetic field analyses.

The vector hysteron $\overrightarrow{p_\zeta}(\vec{B})$ is used in the isotropic vector play model. The magnetic field is determined from the hysteron and shape function f_ζ as shown in (1), (2). The shape function is identified from symmetric loops of target electromagnetic steel sheets [8]. $\vec{B}$, which is input in the isotropic vector play model in (1), is the value for each element in the steel sheet thickness direction, which was obtained from the 1D method mentioned in 2.2. The influence of the skin effect for the hysteresis loss is accounted for by the 1D method. The symmetric loops for 50H1300 used for this calculation are displayed in fig. 3.

$$\overrightarrow{p_\zeta}(\vec{B}) = \vec{B} - \frac{\zeta(\vec{B} - \overrightarrow{p_\zeta^0})}{\max\left(\left|\vec{B} - \overrightarrow{p_\zeta^0}\right|, \zeta\right)} \quad \text{.............................(1)}$$

$$\vec{H}(\vec{B}) = \sum f_\zeta\left(\overrightarrow{p_\zeta}\left(\vec{B}\right)\right) \quad \text{..(2)}$$

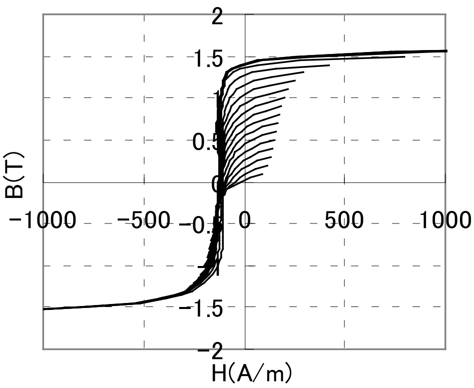


Fig. 3 50H1300 loop (lower side)

3. Basic Characteristic Analysis of the Test Machine

This section will now show the results of comparing the magnetic field analysis with the physical measurements in regards to the specifications of an SR motor, as well as inductance, current, and torque characteristics.

3.1 Test Machine Specifications

The cross-section geometry for the SR motor (hereafter referred to as "test machine") used in this research is shown in fig. 4, and the specifications are shown in table 1. For a compact SR motor with a rated power of approximately 1kW, the number of salient poles for the stator and rotor are a combination of 12/8.

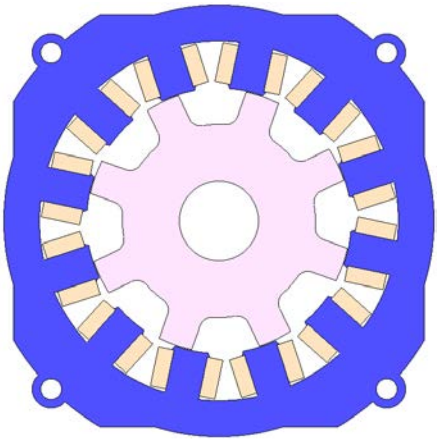


Fig. 4 Geometry of testing machine

Table 1 Testing machine specifications

Number of Poles	12/8
Stator Outer Diameter(mm)	136
Rotor Outer Diameter(mm)	83
Gap Length(mm)	0.3
Stack Length(mm)	70
Number of Phase	3
Phase Resistance (ohm)	0.44
Material of Core	50H1300

3.2 Comparing Inductance between the Physical Measurements and the Analysis

In a SR motor, the angular direction for inductance which changes with rotation are important characteristics to determine torque and current characteristics. Inductance was compared first to verify the applicability of the model. Results are shown in fig. 5. The physical measurements and the analysis results are generally the same, but a slight difference can be seen. The cause of the difference is thought to be the following.

- A 2D analysis is used, leakage flux in the motor ends, such as coil ends, cannot be accounted for, and inductance is underestimated at the non-facing position (0 deg. in fig. 5).
- B-H curve used in the analysis differs from the B-H curve for the actual machine.

In the torque and iron loss calculations below, the causes above are adequately corrected.

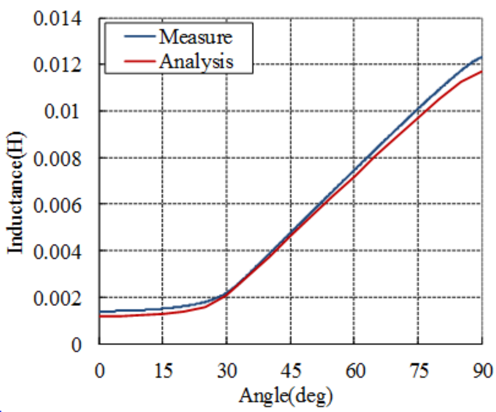


Fig. 5 Inductance comparison

3.3 Comparing Torque Between the Physical Measurements and the Analysis

Continuing, torque is compared. The temperature of a winding was measured during a physical measurement to determine the resistance of the analysis model. Temperature of the winding during a measurement was 70 to 90deg. Results are shown in fig. 6. It shows both results match well at low speeds, but at 3,000r/min, the analysis results for torque were overestimated by 12%. As stated below, this difference is equal to iron loss at 3,000r/min, so the difference seems to be caused by not accounting for iron loss in a magnetic field analysis.

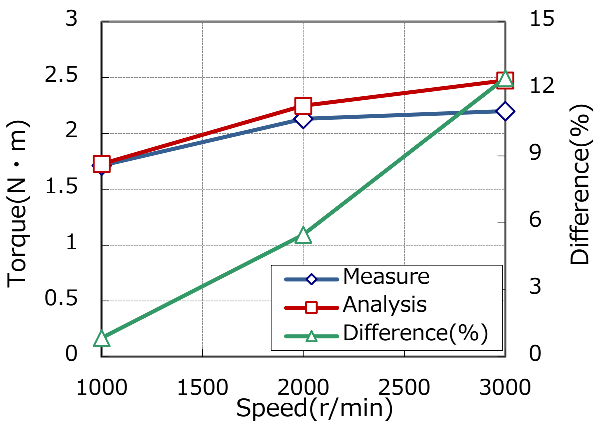


Fig. 6 Torque comparison

4. Test Machine Verification for Iron Loss

4.1 Calculation Result Comparison for Iron Loss Using a Conventional Method and Proposed Method

Calculation results for iron loss using a conventional method and proposed method are compared to the measured values and shown in fig. 7. The results show that both conventional and proposed methods have only small difference with actual measurements at 1,000 and 2,000r/min. However, at 3,000r/min, while the proposed method is nearly identical to the actual measurements, the conventional method underestimates iron loss by 25%. Iron loss at 3,000r/min is approximately 100W, and the value converted to the equivalent torque is approx. 0.3Nm. This value is almost the same as the difference between actual measurement and magnetic field analysis for torque in fig. 6, and the cause for the overestimation of torque is very likely due to not accounting for iron loss in the magnetic field analysis.

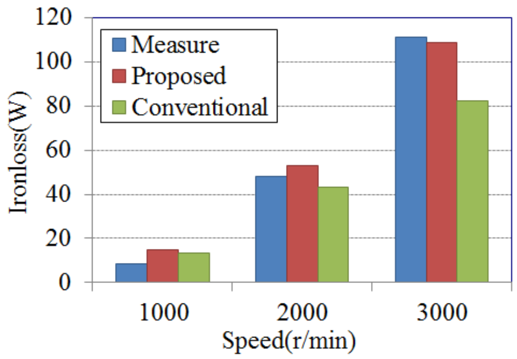


Fig. 7 Iron loss comparison

4.2 Analyzing Hysteresis Loss and Eddy Current Loss

In this section, we will clarify the cause of iron loss being underestimated using a traditional method by analyzing iron loss at 3,000r/min in a conventional method and the proposed method. A breakdown of iron loss for each method is shown in fig. 8. According to this figure, in the conventional method, hysteresis loss is underestimated by nearly 40% more than the proposed method, and eddy current loss is also underestimated by 20%. Next, hysteresis loss distribution is shown in fig. 9. From the figure, it can be seen that losses are high in the stator salient pole ends (hereafter referred to as "point A") and in the rotor salient pole ends (hereafter referred to as "point B"). Magnetic fields for point A and point B obtained in the isotropic vector play model and magnetic flux density history are shown in fig. 10. This figure that shows both points A and B are comprised of DC bias-magnetized minor loops. When the maximum magnetic flux density for point A exceeds 1.5T, and the minor loop is greatly extended to the magnetic field direction. Due to this, it can be seen that hysteresis loss is underestimated in the conventional method, which uses iron loss characteristics measured in alternating magnetic flux without DC bias magnetization. To qualitatively verify this, a waveform with amplitude and center position of B_{amp} as shown in fig. 11, which mimics magnetic flux density history of an SR motor, is entered in an isotropic vector play model, and the hysteresis loss is calculated. Results comparing with a waveform (for the conventional method) with no direct current bias magnetism in the same amplitude B_{amp} are shown in fig. 12. This shows losses start increasing when the center position exceeds 0.6T and maximum magnetic flux density is 1.2T (that is, when B_{amp} is 0.6T), with DC biased magnetization. It can be quantitatively explained that hysteresis losses increases under DC biased magnetization where maximum magnetic flux density reaches 1.5T as shown in fig. 10.

The authors discuss the cause of increase in eddy current loss in proposed method than the conventional method. Due to this, as with hysteresis loss verification, a waveform with DC biased magnetization when B_{amp} is 0.75T as shown in fig. 11, and a waveform with no DC biased magnetization are input into the 1D method, and eddy current distribution in the steel sheet thickness direction is investigated. Eddy current distribution is shown in fig. 13. When looking at both distributions, the eddy current distribution is high inside the steel sheet with DC biased magnetization. This phenomenon occurs since maximum magnetic flux density is higher with DC biased magnetization than without DC biased magnetization, permeability decreases, and the skin effect is alleviated. This seems to have effectively decreased electric resistance for eddy currents and increased eddy current loss. Conversely, with the conventional method, which handles DC biased magnetization as zero, it appears that eddy current loss was underestimated.

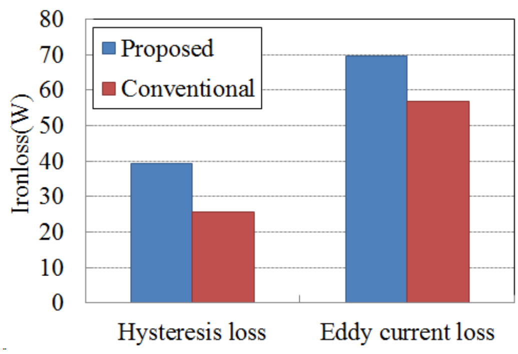


Fig. 8 Iron loss breakdown (3000r/min)

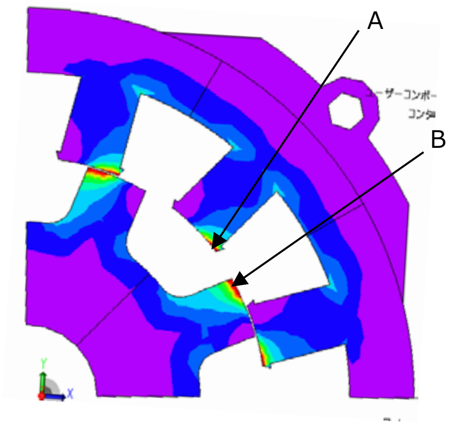
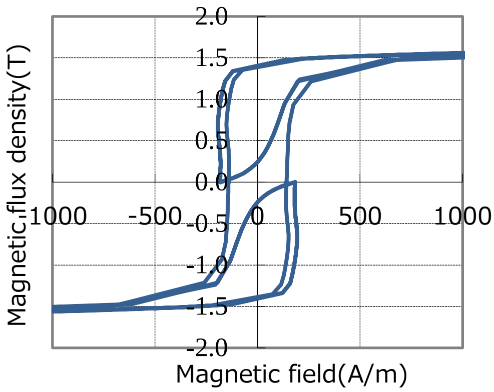
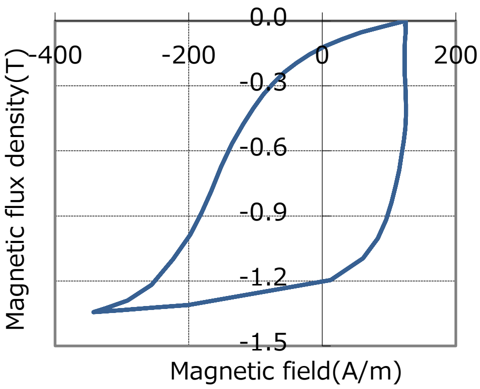


Fig. 9 Hysteresis loss distribution



(a) Point A



(b) Point B

Fig. 10 B-H history

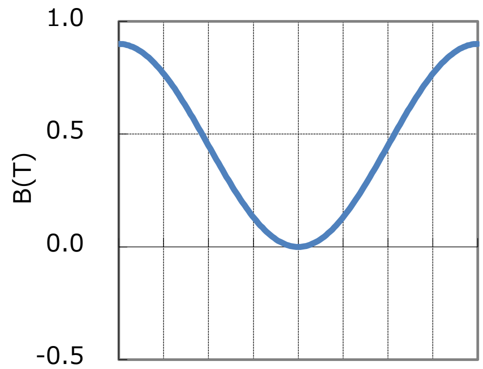


Fig. 11 Direct current bias waveform

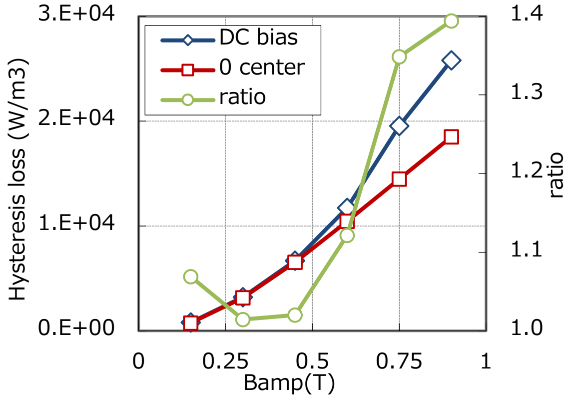
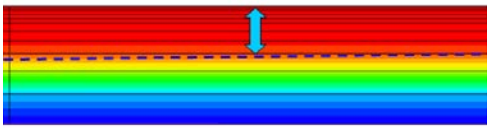
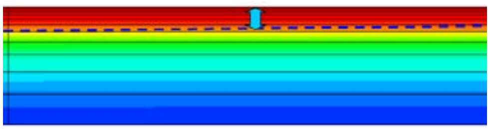


Fig. 12 Effects of direct current bias magnetism



(a) Direct current bias magnetism status



(b) No bias magnetism

Fig. 13 Eddy current distribution for 1D method

5. Conclusion

By using the isotropic vector play model and 1D method the authors successfully demonstrate the improvement in calculation accuracy for iron losses with DC biased magnetization in SR motors. Thus the isotropic vector play model and 1D method is proven to be superior in the calculation accuracy than the conventional method, which employs the Steinmetz's empirical law as its base.

6. References

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Contact
JMAG Div.
info@jmag-international.com