

Development for Practical High-Performance Ferrite Magnet Motors

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Abstract

Rare-earth magnet parts are indispensable for making compact and energy efficient PM motors. There are, however, problems such as price fluctuation and the concern regarding stable supply as a rare-earth material. As such, it prompted R&D activities on the rare-earth-less or rare-earth-free motors.

As a candidate for a rare-earth-less motor, we developed an Interior Permanent Magnet Synchronous Motor (IPMSM) with ferrite magnets that are available at a relatively low price under steady supply. At this time, we performed a motor efficiency measurement and analysis of irreversible demagnetization and magnetization of the IPMSM with ferrite magnets (F-IPMSM). We further evaluated the performance of the F-IPMSM with due consideration to the productivity and then made a prospect for practical use. In the future, we will continue to work on improving torque performance and efficiency, and will aim to commercialize these products.

1 Preface

Recently, against the background of environmental concerns and growing demands to address saving energy, Permanent Magnet Synchronous Motors (PMSMs) are actively used in various industrial fields because it realizes a compact design and high efficiency. The rare-earth magnets used in the PMSMs, however, have inherent problems such as price fluctuation and the concern with the stable supply of rare-earth materials. The industrial market, therefore, calls for the development of alternative new technologies. As an alternative for the rare-earth magnet, we have developed the Interior Permanent Magnet Synchronous Motor (IPMSM) with ferrite magnets that are available at a relatively low price under stable supply, and we could realize the rotor structure of the IPMSM with ferrite magnets (F-IPMSM) which could achieve the same performance as the IPMSM with rare-earth magnets (R-IPMSM)⁽¹⁾.

This paper introduces various performance evaluations performed for practical use of the F-IPMSM.

2 Evaluation of the Prototype Model

Fig. 1 shows the rotor structure of the F-IPMSM

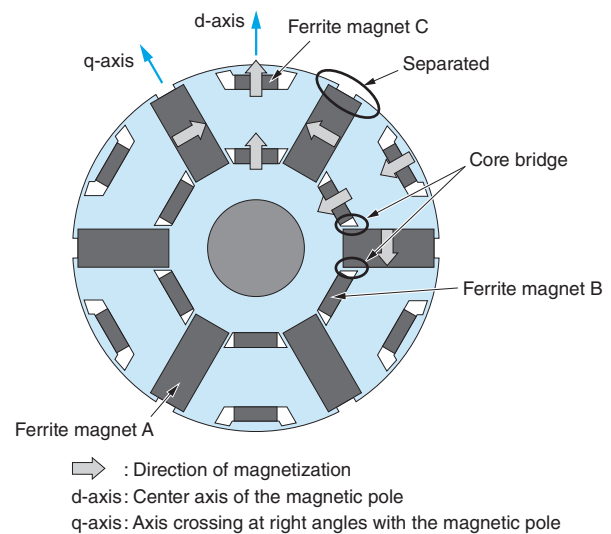


Fig. 1 Rotor Structure of the F-IPMSM

Ferrite magnet A is arranged in a spoke state. In order to reduce the leakage of magnetic flux, the core on the outer diameter side of the ferrite magnet A is separated and the between ferrite magnet A and B is joined through a narrow core bridge.

and Table 1 shows the motor specifications. The F-IPMSM proposed comes with the ferrite magnet A arranged in a spoke state to secure a large magnet surface and with the ferrite magnet B to reduce leakage of the magnetic flux. Further, in order to increase

Table 1 Motor Specifications

The motor specifications are shown below.

Items	Specifications
Number of poles	6
Number of slots	36
Stator outer diameter	φ220mm
Stack length	108mm
Base speed	1000min ⁻¹
Maximum speed	4000min ⁻¹
Maximum speed (at the limit of rotor strength)	7200min ⁻¹
Output power	10kW
Residual flux density (Ferrite magnet)	0.45T

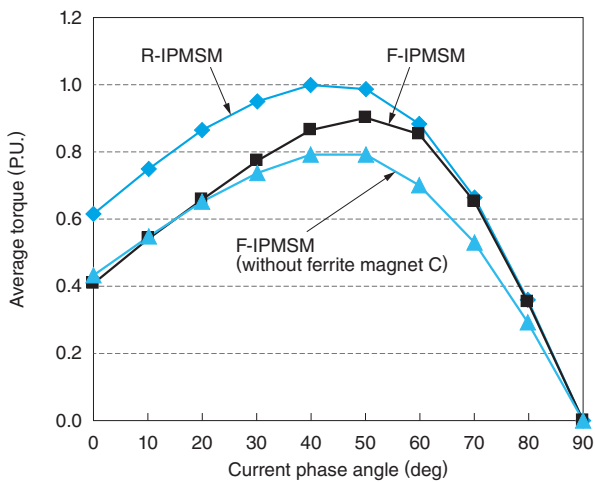


Fig. 2 Torque Characteristics (Analysis Result)

By generating reluctance torque effectively, the F-IPMSM could generate about 90% torque performance of that of the R-IPMSM. If the ferrite magnet C is not arranged, reluctance torque decreased and the resultant torque performance is reduced to approximately 80%.

the saliency ratio by decreasing the d-axis inductance, the ferrite magnet C is arranged. These arrangements realized the effective generation of the reluctance torque. While the residual flux density of the ferrite magnet is one third of that of the rare-earth magnet, the F-IPMSM could generate about 90% torque under the same conditions of current and size of conventional R-IPMSM as indicated in Fig. 2.

2.1 Evaluation of Efficiency

Fig. 3 shows the efficiency map of the R-IPMSM and the F-IPMSM. According to this figure, it could confirm that the maximum efficiency of both IPMSMs is about equal. As indicated above, the torque of the F-IPMSM is smaller than that of the R-IPMSM under the same current condition. As a result, the current of the F-IPMSM tends to increase during low-speed

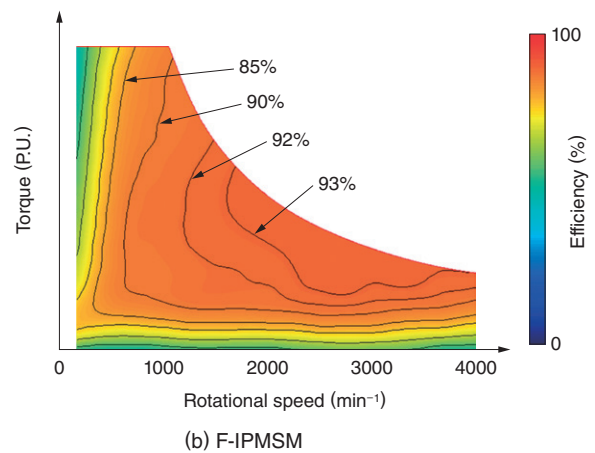
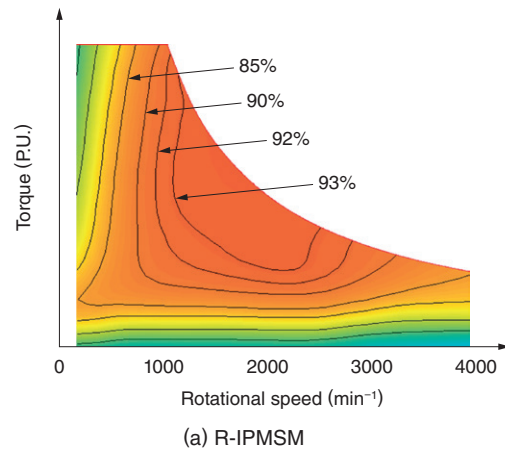


Fig. 3 Efficiency Map (Measured Result)

The F-IPMSM could obtain a maximum efficiency that is almost equivalent to the level of the R-IPMSM. High efficiency area will be shifted to the high speed region.

and the large-torque region and efficiency tends to decrease due to an increase in the copper loss. During the high-speed region, however, it shows that the efficiency of the F-IPMSM is higher than that of the R-IPMSM because the field-weakening current is small.

2.2 Analysis of Irreversible Demagnetization

Compared with the rare-earth magnet, the coercivity of the ferrite magnet is as low as around one third. For this reason, evaluation of irreversible demagnetization is indispensable. Fig. 4 shows the result of analysis of demagnetizing field distribution. As shown in Fig. 4, a large demagnetizing field is observed on the corner of the ferrite magnet A. As indicated by Expression (1) below, the influence of demagnetization is evaluated based on the decreasing rate of the induced voltage and the result is shown in Fig. 5.

$$\delta_e = \frac{E_a - E_b}{E_a} \times 100 (\%) \dots \dots \dots (1)$$

where,

δ_e : Decreasing rate of induced voltage

E_a : Induced voltage before demagnetizing

E_b : Induced voltage after demagnetizing

According to Fig. 5, we could confirm that demagnetization is negligibly small under the condition of the rated current. In the event that the motor current exceeds the rated level (inverter's limit current), however, we could see that there is a decrease in the induced voltage of approximately 0.5% in during a low temperature operation period.

2.3 Analysis of Magnetization

In manufacturing the prototype model in Fig. 1, we put the magnetized ferrite magnets into the rotor core. For the mass production for practical use of the F-IPMSM, however, setting up a manufacturing

process for magnetizing after the rotor assembly is required. In order to verify that ferrite magnets are completely magnetized after the rotor assembly, we performed an analysis of magnetization.

Fig. 6 shows the result of the analysis of magnetization for the prototype model in Fig. 1. In this case, the required condition for complete magnetization is defined as when the intensity of the magnetic field generated in the direction of the magnetization orientation of each magnet is more than three times the coercivity. As shown in Fig. 6 (b), we see that the inner diameter side of the ferrite magnet A and both ends of the ferrite magnet B do not satisfy the required condition.

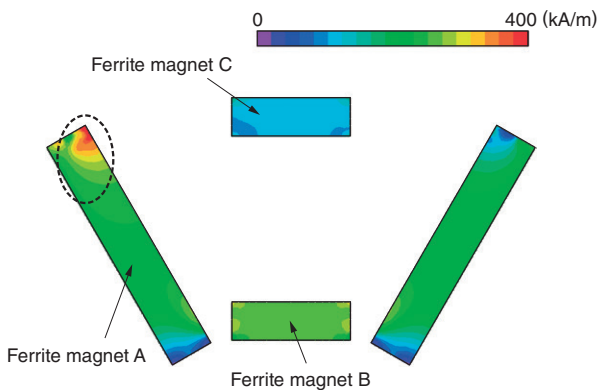


Fig. 4 Demagnetizing Field Distribution (Analysis Result)

When a maximum current is carried, a large demagnetizing field is observed on the corner on the outer diameter side of the ferrite magnet A.

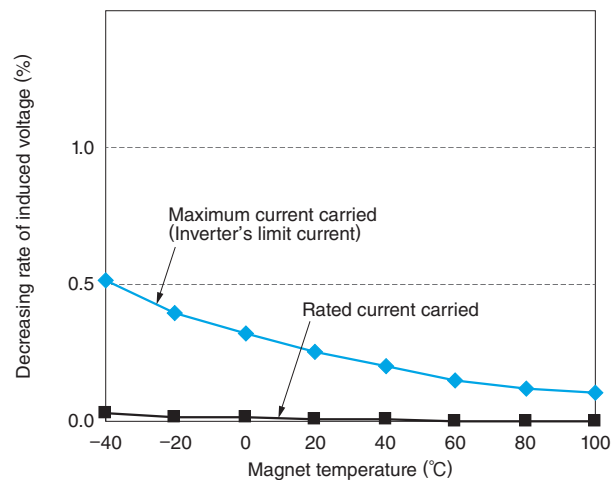
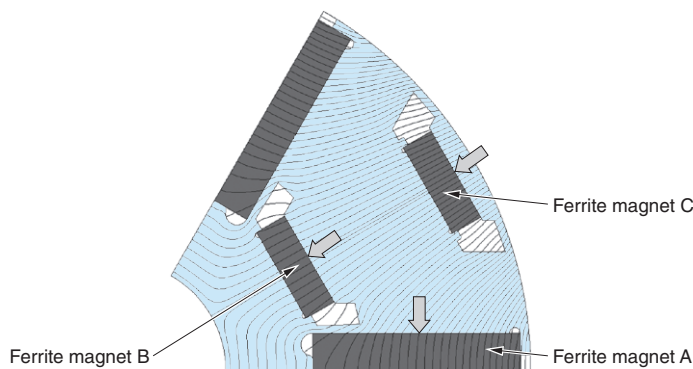
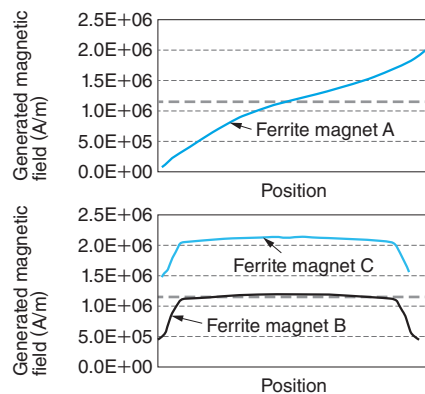


Fig. 5 Decreasing Rate of Induced Voltage

When the rated current is carried, there is almost no influence of demagnetization. When the maximum current is carried, however, demagnetization occurs at a low temperature.



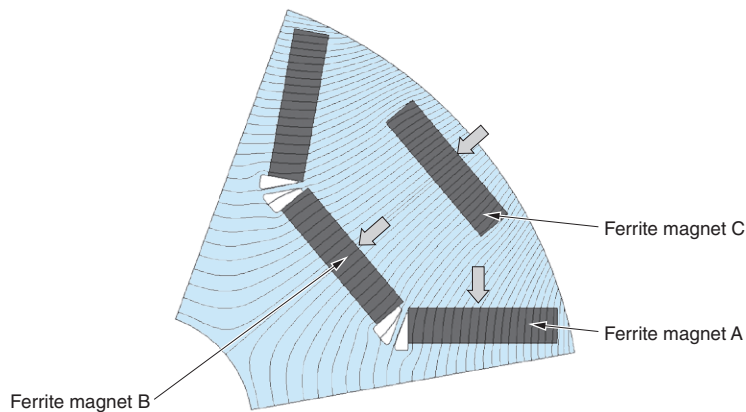
(a) Magnetization analysis model (Present model)



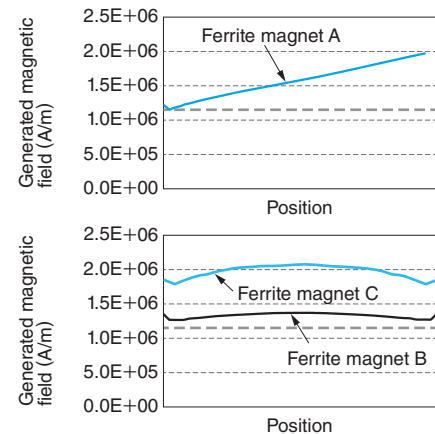
(b) Result of magnetization analysis

Fig. 6 Result of Magnetization Analysis (Present Model)

The arrow mark indicates the direction of magnetization orientation. The generated magnetic field is expressed by the value in this direction. The dotted line indicates the required magnetic field. The ferrite magnet A and B are, therefore, known to involve some sections where the magnetization level is insufficient.



(a) Magnetization analysis model (Improved model)



(b) Result of magnetization analysis

Fig. 7 Result of Magnetization Analysis (Improved Model)

Magnetization was accomplished even on the inner diameter side where the magnetic flux was generally difficult to flow. All of the magnets are able to be magnetized completely.

3 Investigation into Improvements

For achieving magnetizing completely after the rotor assembly, we reviewed the arrangement of the ferrite magnets. As mentioned above, as it is difficult for the magnetic flux to flow into the inner diameter side of the ferrite magnet A in Fig. 1, the width of the magnet was shortened and the angle of the magnet arrangement was changed for the magnetic flux flowing smoothly into the inner diameter side of the ferrite magnet A. In addition, the flux barriers were provided at the inner diameter side of the ferrite magnet A and both ends of the ferrite magnet B for more magnetic flux to flow into the ferrite magnet A and B. In addition, all of the ferrite magnet A, B, and C were designed to have the same size as an approach toward the goal of mass production for practical use.

Fig. 7 shows the result of analysis of magnetization for an improved model. Since the generated magnetic field in the ferrite magnet A, B, and C exceeds the magnetic field of the required condition, it is concluded that magnetizing after the rotor assembly is achieved for an improved model.

4 Postscript

This paper introduced the performance evaluation of the IPMSM with ferrite magnets and our study result for future commercialization. We are one step closer to the final development stage on the F-IPMSM with due consideration to the productivity while obtaining the equivalent performance of the R-IPMSM.

In the future, we will work on torque performance and efficiency improvements and will innovate the manufacturing processes. Further, we will continue the evaluation work on the prototype and work hard to accelerate the study of F-IPMSM application for practical use.

· All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.

《Reference》

- (1) Ota, Matsuhashi, Okitsu, Matsuo: "Development of High-Performance Ferrite Magnet Motor," Meiden Jiho No.341, 2013/No.4, pp.61-64 (in Japanese)