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Reliability Analysis of Permanent Magnet and Air-gap Flux Density of Spoke-type IPMSM for Driving Cooling Fans

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Abstract

One of the key electrical components in a car, a motor has been actively studied based on its reliability. In recent years, as the proportion of the motor has increased in a car, development of the motor with a high output and a low price has been required. IPMSM can cause a high torque per unit current by using a reluctance torque generated from the difference in the magnetic resistance, which is suitable for the motor which requires a high output. In particular, since the spoke-type IPMSM with a concentrated flux structure can utilize non-rare earth metal-based ferrite magnets which are cheaper than rare earth metal-based permanent magnets such as neodymium, this can lower the motor price. In this paper, we study driving characteristics by analyzing the magnetic flux density and cogging torque that causes noise and vibration in accordance with the rotor shapes (Magnet, Rib) of the spoke-type IPMSM.

Keywords: Engine Cooling Fan, Fan Motor, Ferrite Magnet, Interior Permanent Magnet System Synchronous Motor (IPMSM), Spoke Type, Vehicle Motor

1. Introduction

These days, rare-earth resources have been used frequently in electrical and electronic equipments[1]. Rare earth metal-based permanent magnets are used to improve efficiency at low speed. Until recently, there have been some issues surrounding the raw materials used in the rare earth-based magnets, such as increased price and limited export of rare earth based-magnets. Since rare earth metal-based magnets are still expensive and the prices are unstable, they may not be desirable for motors. Therefore, it is important to develop IPMSM, which does not use rare metal-based magnets[2]. Among other IPMSMs, the spoke-type IPMSM with a high reluctance torque and concentrated flux structure especially has a high torque per unit volume The spoke-type IPMSM has been studied for applications where a high torque is required. However, the spoke-type IPMSM has some problems. First, it causes local demagnetization at the edge of the permanent magnet by an external magnetic field. Secondly, because of the distortion of the air-gap magnetic flux density distortion, cogging torque increases, thereby decreasing motor performance, changing operation regions and generation noise and vibration[3,4].

Structurally, the spoke-type IPMSM may have Rib structure in the outermost of a rotor. This Rib structure of the rotor affects the operation range, properties and safety factor of the motor. In addition, it is related to demagnetization phenomenon that affects the motor characteristics[5]. This paper investigated the impact of air-gap magnetic density on cogging torque in accordance with the rotor shapes (magnet, rib) of the spoke-type IPMSM and interpreted demagnetization of ferrite magnets.

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2. Air-gap Magnetic Flux Density in accordance with Rotor Shapes

In this chapter, we set up a rib and a permanent magnetics as variables to analyze the characteristics of motors in accordance with rotor shapes of the spoke-type IPMSM. Figures 1 and 2 show the effect of changes in the width and thickness of the permanent magnet has on the air-gap flux. By the way the result of analysis by arbitrarily specifies the size of the magnet. Since the width of the permanent magnet has more effects on the motor output and is more advantageous for increasing magnetic flux per unit volume than the thickness, we only designated the width as a variable.

In case of the rib, the spoke-type IPMSM may have a rib structure in the outermost of the rotor. The rib structure affects the operation range, properties and safety factor of the motor. In addition, it is related to demagnetization phenomenon that affects the motor characteristics[5]. Figure 3 shows a basic model and Table 1 shows the specifications. Figure 4 shows the shape variables for the width and rib of the permanent magnet.

2.1 Model Properties

The analytical model was designed by applying numerical analysis method such as a finite element method to the

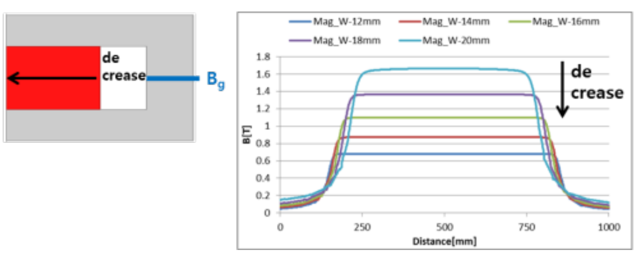


Figure 1. Air-gap flux density in accordance with the width of the permanent magnet.

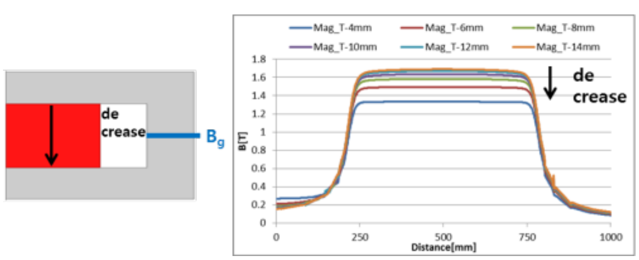


Figure 2. Air-gap flux density corresponding to the thickness of the permanent magnet.

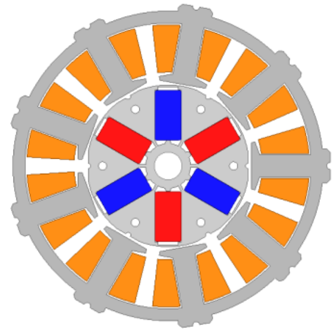


Figure 3. Spoke-type IPMSM model.

Table 1. Specification of analysis model

Items	Value
Output	250 [W]
DC link voltage	13.5 [V]
Rated speed	2000 [RPM]
Rated Torque	1.2 [Nm]
Number of poles	6 [poles]
Number of phases	3 [phase]
Stack length	25 [mm]
Air-gap length	[mm]

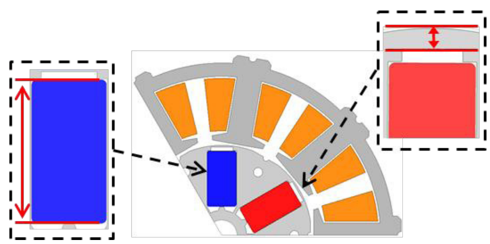


Figure 4. Shape variables of a permanent magnet and Rib.

Table 2. Design Parameters

Variable	Range	Step	Unit
Magnetic Width	14.5 ~ 15.0	0.1	mm
Rib Thickness	0.82 ~ 1.52	0.1	mm

design directly. In the spoke-type IPMSM, the permanent magnets are inserted at both ends of one pole of the rotor and present symmetrically and the magnetic pole consists of core surface of the rotor between the permanent magnets. Therefore, this structure can increase air-gap magnetic flux density by increasing the cross-sectional area of the permanent magnets relative to the surface of the rotor are constant[6]. Therefore, we selected an appropriate length for air-gap in consideration of the loading ratio and set up the output required for loading vehicle engine cooling fan and the maximum value of output phase voltage in accordance with an inverter PWM modulation system. In addition, we minimized the stack length to reduce the inertia for driving the fan and designed in accordance with rated speed.

2.2 Variables of Rotor Shapes

As shown in Figure 4, we attempted to analyze the impact on the air-gap flux density through changes in the width of permanent magnets, a design variable of the magnetic circuit of the spoke-type IPMSM and rib through which.

3. Cogging Torque Characteristics in Accordance with the Air-gap Flux Density

In this section, we investigated the characteristics of cogging torque in accordance with distribution of air-gap magnetic flux density. For this purpose, we analyzed dimensional changes in permanent magnetic which are the design variables of magnetic circuit from the data of the same rotors and the effects of the rib structure on the air-gap magnetic flux density after analyzing the characteristics essential to the design of the spoke-type IPMSM. Afterwards, we investigate the driving characteristics of the spoke-type IPMSM using the finite element method.

3.1 Characteristics of the Magnetic Circuit of the Spoke-type IPMSM

The reason for analyzing the characteristics of the magnetic circuit of the IPMSM with a permanent magnetic is to know the size of the air-gap magnetic flux. The spoke-type IPMSM has used more permanent magnets than a common bar-type IPMSM. However, a large magnetic flux can be created in the air-gap despite using less permanent magnet by the performance of the permanent magnet and reducing the cross-sectional area of the air-gap can lead to a large magnetic flux in the air-gap as well. Therefore, an analysis of the characteristics of the magnetic circuit is necessary.

Provided that the magnetic flux flows in the magnetic circuit including the permanent magnetic in Figure 5. an equation (1) can be obtained from applying Ampere's law.

$$\oint H \times dl = H_m l_m + H_{c1} l_{c1} + H_{c2} l_{c2} + H_{c3} l_{c3} + 2H_g l_g = 0\ [A] \quad (1)$$

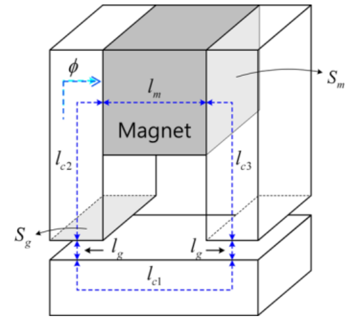


Figure 5. The magnetic circuit including a permanent magnet

Assuming that the magnetic permeability of the core is very large, H_{c1}, H_{c2}, H_{c3} are relatively small enough to be negligible and thereby a simple equation (2) can be obtained.

$$H_m l_m \approx -2H_g l_g \quad [A] \quad (2)$$

Moreover, since the total magnetic flux of the air-gap and total magnetic flux of the permanent magnet are the same if the leakage is ignored, the relationship between the magnetic flux density B_g of the air-gap and the magnetic flux B_m inside the permanent magnet is shown in the equation (3).

$$B_g = \frac{S_m}{S_g} B_m \quad [T] \quad (3)$$

$$S_m B_m = S_g B_g \quad (4)$$

Here, B_m, B_g represents the magnetic flux density of the permanent magnet and air-gap, respectively and S_m, S_g represents the cross-sectional area of the permanent magnet and air-gap, respectively.

The equation (5) can be obtained by substituting the equation (3) to the equation (2) and the smaller the air gap is, the closer value to the residual magnetic flux density of the permanent magnet B_m becomes. In addition, the intensity of the magnetic field may be referred to as a critical value since it is directly related to the cross-sectional area and air-gap length of the permanent magnet.

$$H_m \approx -2 \frac{B_m}{\mu_0} \frac{S_m}{S_g} \frac{l_g}{l_m} \quad [A/m] \quad (5)$$

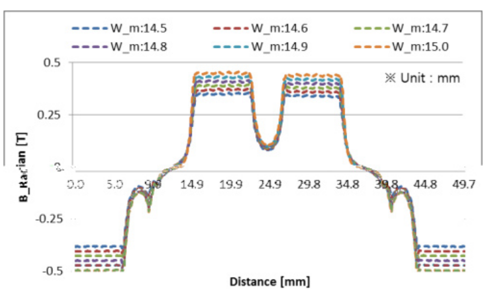
3.2 Characteristics in accordance with the Width of the Permanent Magnet

As shown in the equation (3), increasing the air-gap magnetic flux as a result of increasing the cross-sectional area of the permanent magnet is shown in Figure 6.

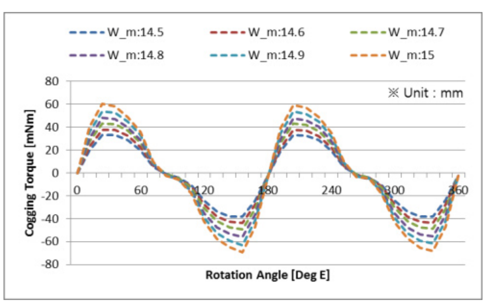
Accordingly, the phenomenon that the cogging torque was increased appeared and it is necessary to investigate the relationship between the impact on efficiency and torque by analyzing torque ripple through the load analysis.

3.3 Characteristics in accordance with the Rib Thickness

Figure 7 shows the characteristics of the air-gap flux density and the cogging torque in accordance with the rip within the rotor. As the thickness of the rib got thinner, the level of the air-gap magnetic flux was increased, thereby increasing the cogging torque as well. Cogging torque is generated due to the original slot and is proportional to the square of the rotor. Therefore, the characteristics of the cogging torque are changed by the air-gap magnetic flux rather than the difference in the magnetic resistance. Moreover, as shown in Figure 7(a), the distorted portion with the pitted center in the waveform of the air-gap magnetic flux can be seen as a unique feature. This can also be seen as a figurative feature because the magnetic flux from the permanent magnet directly enters into the air-gap in the case of the spoke-type IPMSM. Due to this feature, the waveform of the air-gap flux density is difficult to control directly by the shape or the magnetization direction of the permanent magnet.

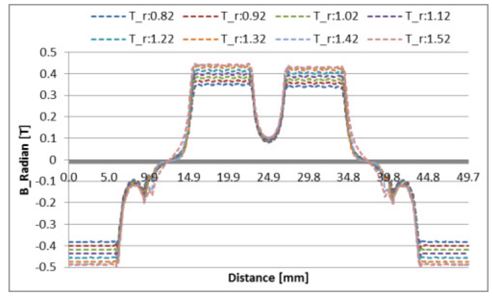


(a)

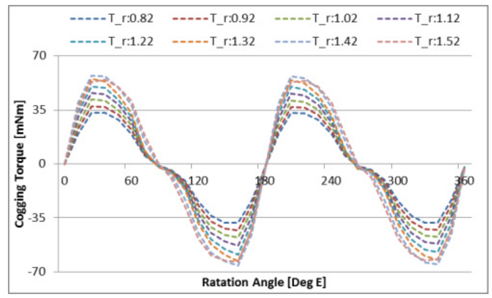


(b)

Figure 6. Result analysis of the characteristics in accordance with the width of the permanent magnet **(a)** Air-gap magnetic flux density **(b)** Cogging torque.



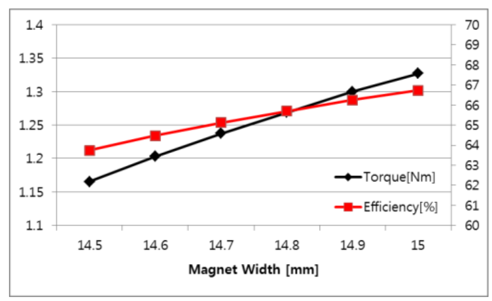
(a)



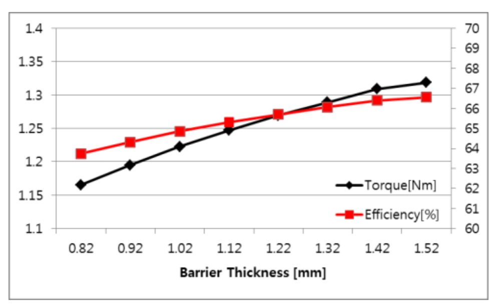
(b)

Figure 7. Result analysis of the characteristics in accordance with the rotor rip **(a)** Air-gap magnetic flux density **(b)** Cogging torque.

3.4 Result of the Parametric Analysis in accordance with Shapes



(a)



(b)

Figure 8. Torque and efficiency of the rotor in accordance with shapes **(a)** Width of the permanent magnet **(b)** Rib thickness.

3.5 Demagnetization Interpretation

The characteristics of the permanent magnet vary according to temperature, magnetic circuit and external magnetic field. In the case of a non-rare earth metal-based ferrite magnet, a large reverse field at low temperature can lead to irreversible demagnetization. If the reverse field below the knee point takes place in the B-H curve of the permanent magnet, irreversible demagnetization occurs[5]. In addition, the properties are changed by heat and the lower the temperature, the coercive force is. The material of the permanent magnet used in this paper is 7BE and the B-H curve is shown in Figure 8. As described above, demagnetization of the ferrite magnet can take place if the temperature becomes low. This can be referred to demagnetization at low temperature and the operation point become below the knee point due to changes in the residual magnetic flux and the coercive force according to the temperature.

By looking at the demagnetization ratio per unit area according to the width of the permanent magnet as shown in Figure 8, it can be seen that the larger the width of the permanent magnet, the more demagnetization is generated. The reason for this phenomenon is that the permanent magnet is close to the air-gap due to an increase in the width. Furthermore, the demagnetization ratio is increased due to the reverse magnetic field by the magnetomotive force of a stator. Figure 9 shown the demagnetization ratio in accordance with the rip thickness and the larger the rib thickness is, the smaller demagnetization ratio is. We analyzed the thickness at an interval of 0.2mm to 0.58mm and the part marked by zero in the horizontal axis represents the model in which the rib is not present. The main reason why this model without the rib has the largest demagnetization is that the magnetomotive force of the stator does not leak into the rib and affects the permanent magnet. On the other hand, in the model in which the rib is present, the magnetomotive force of the stator leaks into the rib and affects the permanent magnet less.

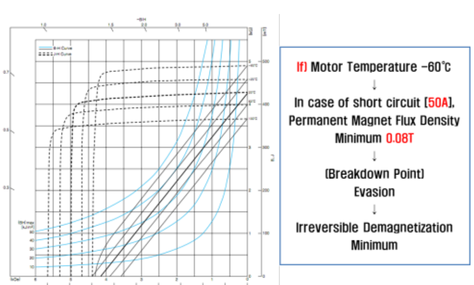


Figure 7. B-H curve.

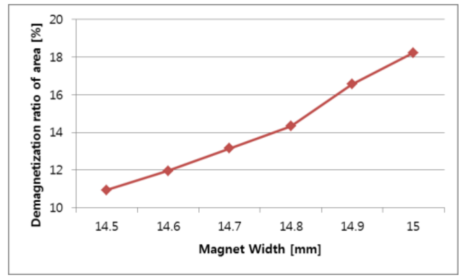


Figure 8. Demagnetization ratio per area in accordance with the width of the permanent magnet.

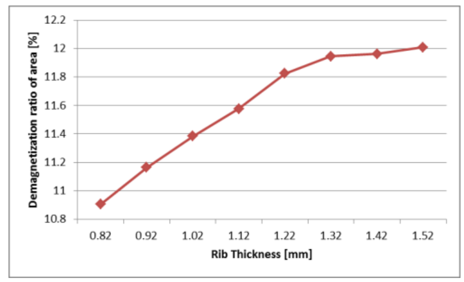


Figure 9. Demagnetization ratio per area in accordance with the rip thickness.

4. Conclusion

This paper concerns a concentrated flux structure spoke-type IPMSM and analyzes the characteristics of the motor by analyzing the air-gap magnetic flux density and cogging torque. To analyze the factors affecting the air-gap magnetic flux, we focused on changes in the rotor shapes and carried out analysis of the cogging torque, torque, efficiency and demagnetization through changes in the cross-sectional areas and rib thickness. Especially, large proportion in width than the thickness of the output by the cross-sectional area of the permanent magnet. Since as a concentrated flux, the spoke-type IPMSM can use non-rare earth-based permanent magnets which are more advantageous than rare earth-based permanent magnets in terms of price, it is suitable for automotive electronics areas which regard weight and price as important. However, the spoke-type IPMSM has disadvantages in terms of cogging torque, flux leakage and demagnetization. Therefore, in this paper, we propose a solution to this problem.

5. Acknowledgement

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