Journal of Engineering and Applied Sciences 13 (Special Issue 4): 3887-3891, 2018
ISSN: 1816-949X


# A Study on New Topology for Cost Reduction of Permanent Magnet Motor

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**Abstract:** In this study, we have studied Spoke type Ferrite Magnet Synchronous Motor (SFMSM) differentiated from conventional Surface Permanent Magnet Synchronous Motor (SPMSM) in order to effectively cope with cost reduction which is continuously occurring in the motor industry including home appliance. First, the cost competitiveness of SFMSM is analyzed through a magnetic circuit of c - type core. For this purpose, the ratio between the surface area of the Permanent Magnet (PM) and the area of the air gap is defined as the concentration factor k. Using this k, we have clarified why SFMSM is superior in terms of efficiency and cost compared to the non-concentrating SPMSM. In addition to this, two problems of SFMSM, that is the deterioration of magnetization performance and the analysis error of two - dimensional analysis due to axial leakage magnetic flux were also identified. The results of this study can be used as a guideline for the design and development of SFMSM which have been widely applied in various industrial fields.

**Key words:** Spoke type ferrite magnet synchronous motor, axial leakage magnetic flux, magnetization performance, dimensional , development , non-concentrating

## INTRODUCTION

Surface Permanent Magnet Synchronous Motor (SPMSM) shows excellent efficiency and small leakage fluxes between poles, it has the advantage of mass production. In particular, the SPMSM with ferrite magnet has largely been used in small products and electric home appliances due to its low cost (Li *et al*., 2013, Zhao *et al*., 2015). However, due to the technical saturation of SPMSM, it is difficult to effectively respond to the continuous cost reduction demand in the home appliance field. In order to solve this problem, various motors such as switched reluctance motor and induction motor have recently been studied as candidates to replace SPMSM. Especially, the Spoke type Ferrite Magnet Synchronous Motor (SFMSM) that has been largely investigated in recent years because it has high power density and low cost by using a concentrated flux structure (Lee *et al*., 2004, Kim *et al*., 2012). SFMSM can generate more magnetic flux with less Permanent Magnet (PM) usage than SPMSM through a flux concentrating structure. In this study, a method of designing PM motors with high cost competitiveness using SFMSM was discussed. In addition, two side effects caused by the concentrated flux structure were researched.

## MATERIALS AND METHODS

**Benefit of flux concentrating structure of SFMSM:** SFMSM is a type of Interior Permanent Magnet Motor (IPM). In order to maximize the surface area of the PM perpendicular to the direction of flux, PMs are arranged in the form of a spoke on the rotor core. Figure 1a, the surface area of the PM generating the magnetic flux is larger than the polepitch corresponding to the area of the air gap per pole. In contrast, the SPMSM has a surface area of the PM that is slightly smaller than the pole pitch, as shown in Fig. 1b.

In order to understand the advantage of the flux concentrating structure in which the surface area of the PM is larger than the pole pitch area, the magnetic flux generated from the PM inserted in the c-type core as shown in Fig. 2, represented as Eq. 1:

$$\varphi_m = \frac{A_m A_g l_m B_r}{\mu_r A_m l_g + A_g l_m} = \frac{A_g l_m B_r}{\mu_r l_g + \left(\frac{A_g}{A_m}\right) l_m} \quad (1)$$

Where:
$B_r$ = The residual magnetic flux density of PM
$A_m$ = The surface area of PM
$\mu_r$ = The relative permeability of PM
$l_m$ = The thickness of PM
$A_g$ = The area of air gap
$l_g$ = The length of air gap

The ratio of the surface area of the PM $A_m$) to the area of the air gap ($A_g$) is defined as a concentration factor k and substituted into Eq. 1 as shown in Eq. 2:

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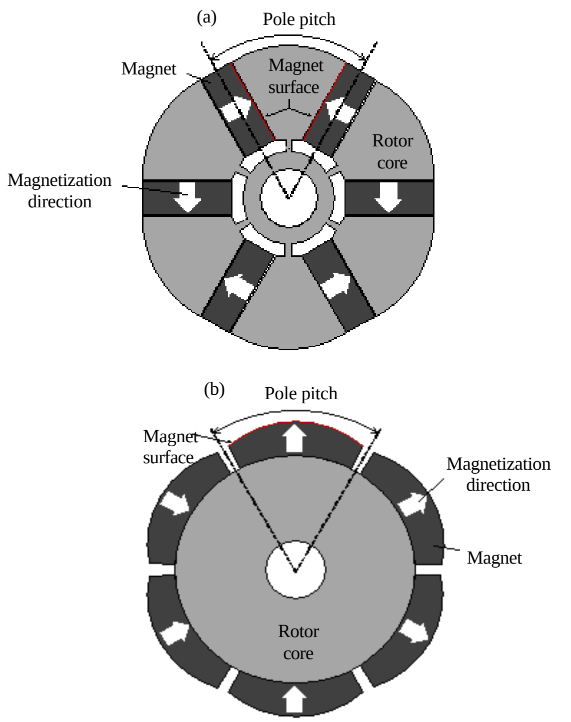


Fig. 1: Comparison of rotor shape according to motor type rotor of SFMSM: a) Rotor of SFMSM and b) Rotor of SPMSM

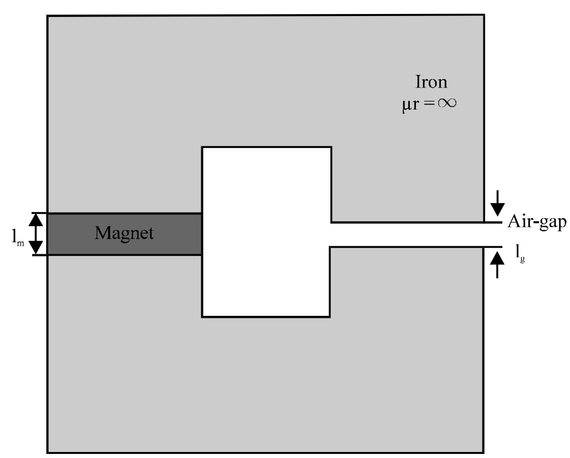


Fig. 2: C-type core including a PM

$$\varphi_m = \frac{A_g l_m B_r}{\mu_r l_g + \left(\frac{A_g}{A_m}\right) l_m} = \frac{A_g l_m B_r}{\mu_r l_g + \frac{l_m}{k}} \quad (2)$$

SFMSM is a motor whose concentration factor k in the denominator of Eq. 2 has a value significantly greater than one. In order to see the effects of increasing the concentration factor k, we compare two cases where the area of air gap is the same and the surface area of the PM is different. Figure 3 a and b show two PMs having the same volume. It is assumed that two PMs are inserted into the c-shaped core of Fig. 2 and the cross-sectional areas of the air gap are all the same. The total magnetic flux generated through the air gap is shown in Fig. 3c. As can be seen from the Fig. 3c, the surface area of the PM increases even if the same volume of PM is used and the total magnetic flux increases as the concentration factor k increases. As a result, the SFMSM having the concentration factor k larger than 1 can obtain the same output density and efficiency characteristics even when the PM is smaller than that of the SPMSM having the concentration factor k of 1 or less.

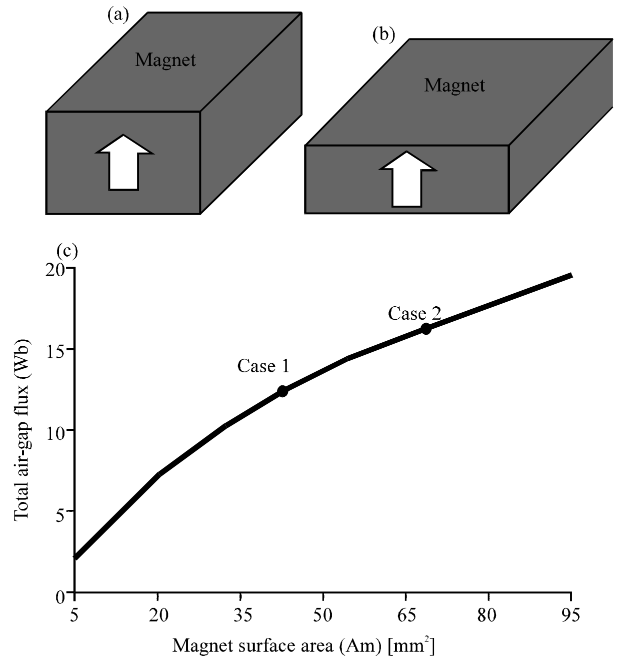


Fig. 3: Comparison of generator flux according to the surface area of permanent magnets having the same volume: a) Case 1: thick model and (b) Case 2: thick and wide model, © total magnetic flux genrated from PM

## RESULTS AND DISCUSSION

**Side effects due to flux concentrating structure of SFMSM:** In order to reduce the cost and improve the output density of SFMSM, it is desirable to maximize the concentration factor k. However, if the concentration

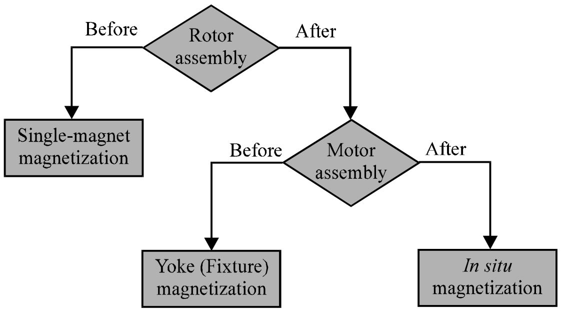


Fig. 4: Magnetization methods of PM motor

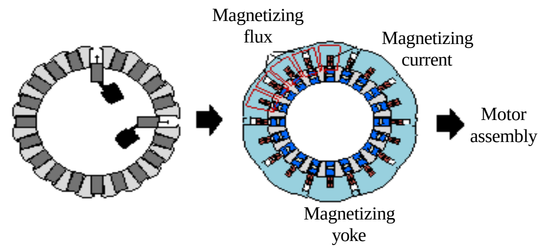


Fig. 5: Process of magnetization process after assembly using magnetizing yoke

factor k is increased, it is advantageous in terms of magnetic flux generation but the following two side effects occur. First, as the concentration factor k increases, the magnetization performance, one of the mass production processes, is degraded. This is a phenomenon that did not occur in the SPMSM where the flux concentration factor k is <1. Second, as the concentration factor k increases, the leakage flux generated through the axial direction between the rotor cores which does not also occur in the conventional SPMSM, increases. This axial leakage flux causes the output of the SFMSM to deteriorate. And it is impossible to accurately analyze the SFMSM by using 2D Finite Element Analysis (FEA) that cannot consider the axial component. In order to predict the performance of SFMSM accurately, 3D FEA is needed and this causes the performance analysis and design of SFMSM to be difficult.

**Magnetization performance after assembly:** In order for the PM motor to operate as a motor, a process of magnetizing the PM generating the field magnetic flux is required. There are three ways to magnetize PMs of the motor as shown in Fig. 4 (Jewell and Howe, 1993).

The first is a single-PM magnetization method in which PMs are assembled after magnetizing the single PM. This is the most reliable way to guarantee 100% magnetization. However, there is a problem in that the mass production process such as rotor assembly and motor assembly becomes complicated due to the attractive force of the magnetized PM.

The second is a yoke magnetization method in which rotor assembly is magnetized by a special magnet yoke. This method is also possible to reach 100% magnetization. However, in order to obtain 100% magnetization by using this method, it requires a properly designed magnetization yoke and sufficient magnetizing current. Excellent magnetization performance and mass productivity are not bad, so, it is the most used method in the real industry.

Finally, a rotor assembly that is not magnetized is inserted into the stator and then magnetized with a stator coil. This method is the most mass-producible but it is difficult to obtain 100% magnetization due to structural problem.

In this study, the magnetization performance of SFMSM with concentration factor k greater than 1 was discussed based on the second magnetization method which is the mainstream of industry. Figure 5 shows a simple process diagram of the after rotor assembly magnetization method.

Figure 6 shows the cause of the degradation of the magnetization performance of the SFMSM. There are two main causes of the degradation of the magnetization performance of the SFMSM. First, it is the division phenomenon of the magnetizing flux. As shown in Fig. 6a in SPMSM, the magnetic flux for magnetization generated in the yoke passes completely through one PM. However, in the SFMSM, the magnetizing flux is divided into 1/2 of the PM placed on the left and right with respect to the rotor core as shown in Fig. 6b. For complete magnetization, a magnetic flux higher than a certain value is required. The splitting phenomenon that occurs when SFMSM is magnetized deteriorates magnetization performance because it makes it difficult to obtain magnetic flux for complete magnetization. The second is the increase of magnetic saturation in the rotor core as the concentration factor k increases. All magnetic flux for magnetization as shown in Fig.6b, must pass through the top of the rotor core. As the concentration factor k increases and the surface area of the PM increases, the required magnetizing flux increases. All of these increased magnetizing flux must pass over the rotor core with limited width. This increases the degree of magnetic saturation on the rotor core and degrades the performance of the

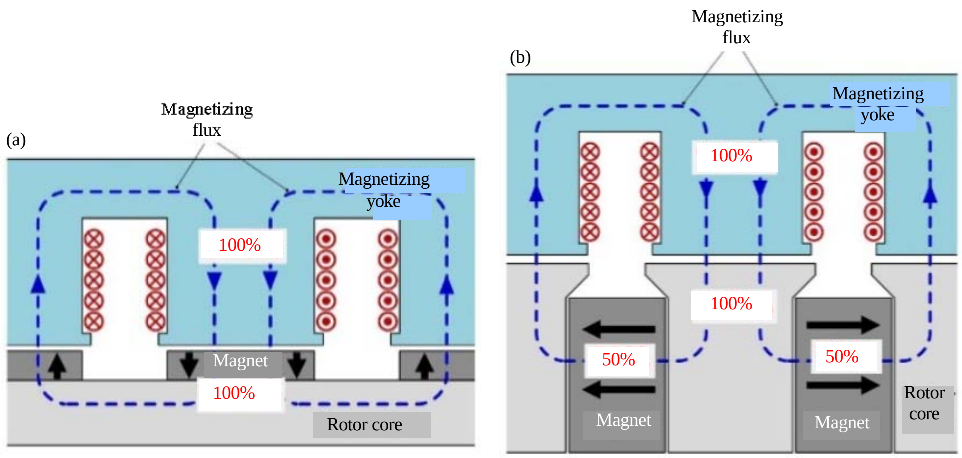


Fig. 6: Causes of magnetization performance degradation of SFMSM

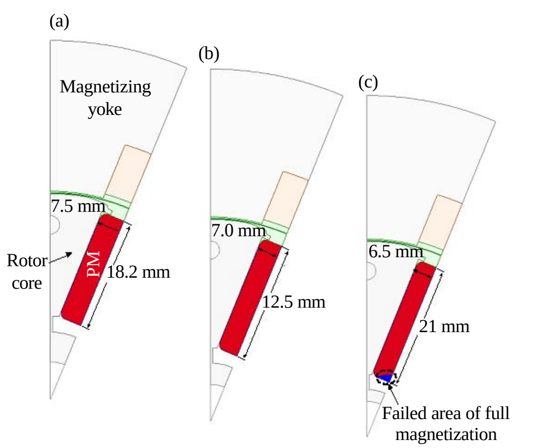


Fig. 7: Comparison of magnetization performance with increasing concentration factor k: a) k = 1.4; b) k = 1.5 andc) = 1.62

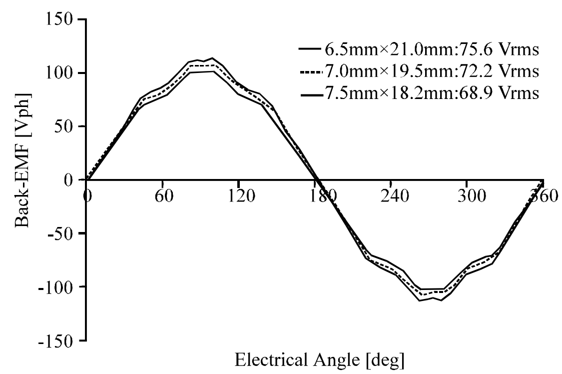


Fig. 8: Comparison of magnetic flux and output according to increasing of concentration factor k

overall magnetic circuit. As a result, the combination of these two causes degrades the magnetization performance of the SFMSM.

Figure 7 shows the results of the magnetization analysis of SFMSM with increasing concentration factor k. The analysis results are obtained under the same conditions for the same magnetizing yoke and magnetizing current. As shown in 7a and b all regions of PM were 100% magnetized under the same magnetization conditions. However, in Fig. 7c where the concentration coefficient k is 1.62, it is confirmed that a part of the bottom of the PM does not fully magnetized. As a result, it can be confirmed that the concentration factor k affects the magnetization performance.

Figure 8 shows the analysis results of back EMF for each rotor in Fig. 7. Since, all rotors have the same outer diameter at this time, the same stator was used for back EMF analysis. As shown in Fig. 8, it can be seen that as the concentration factor k increases the no-load back-EMF corresponding to the output of the motor increases. In particular, the usage of PMs used in all three models is the same.

**Axial leakage flux occurred in rotor cores:** Figure 9a shows the rotor shape of SFMSM with a concentrated flux structure. In SFMSM, the rotor core is separated by magnetized PMs which are nonmagnetic material. Although the rotor core is connected by a bridge or a rib in order to prevent scattering of the rotor core, it is designed by the thinnest layer possible because it is a leakage path of decreasing its performance. Therefore, it causes magnetic saturation and the separation of the rotor core is considered as a magnetic point of view. In addition, the magnetic potential in neighbored rotor cores represents opposite polarities for each other because the flux generated from PM is to be concentrated on a single

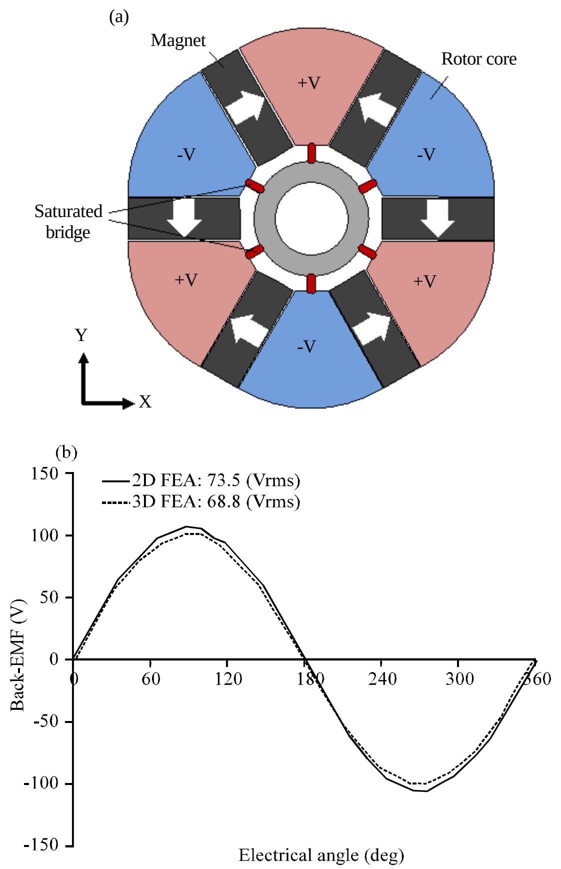


Fig. 9: Causes of axial leakage magnetic flux and its effect: a) Case: magnetic potential difference and b) Effect: difference between 2 and 3D analysis

rotor core. As a result, there exists a difference of magnetic potential among neighbored rotor cores and it causes the leakage magnetic flux in the axial direction between neighbored rotor cores (Lee *et al*., 2017).

Thus, the axial leakage flux generated in the rotor core of the SFMSM cannot be accurately considered by the 2D FEA. Thus, as shown in Fig. 9b, there is a significant error between the 2D analysis which cannot take axial directions into account and the 3D analysis which can take axial considerations. The performance deterioration due to the axial leakage magnetic flux is a phenomenon that must be considered when designing the SFMSM. As the lamination is smaller, the errors between 2D and 3D analysis due to axial leakage increase and more than 10% in the case of thin type. Finally, as the concentration factor k increases, the area of the rotor core viewed from the axial direction increases. This has the effect of reducing the magnetoresistance of the axial leakage path and consequently the axial leakage flux increases.

## CONCLUSION

In this study, we have studied SFMSM which can reduce cost than conventional SPMSM. The flux concentration factor k was introduced and clarified as to how the SFMSM is superior to the SPMSM in terms of price and performance. In addition, we have also discussed two problems caused by increasing the concentration factor k: the deterioration of the magnetization performance and the deterioration of performance due to the axial leakage magnetic flux.


## ACKNOWLEDGEMENT

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT and Future Planning) (No. 2016R1C1B1015111).


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