Characteristics of IPMSM According to Rotor Design Considering Nonlinearity of Permanent Magnet

Min-Ro Park[1], Hae-Joong Kim[1], Yun-Yong Choi[1], Jung-Pyo Hong[1], *Senior Member, IEEE*, and Jeong-Jong Lee[2]

[1]Department of Automotive Engineering, Hanyang University, Seoul 133-791, Korea
[2] Intelligent Mechatronics Research Center, Korea Electronics Technology Institute, Bucheon 420-140, Korea

As materials with various properties were developed for improvement of performance and low material cost of Permanent Magnet (PM) motors, the properties of the materials have become major factors that determine the motor performance. As such a material, the recently-developed anisotropic bonded NdFeB PM showed a nonlinear demagnetization curve. Thus in this paper, by considering the nonlinearity of the PM, a process to calculate operating point was proposed, and by applying this process, the characteristics of Interior Permanent Magnet Synchronous Motor (IPMSM) according to different rotor designs were investigated.

***Index Terms*—demagnetization, finite element analysis, nonlinear magnetics, operating point, permanent magnet motors.**

I. INTRODUCTION

PERMANENT MAGNET (PM) motors have been widely used and studied for a long time to acquire high efficiency, high power, and minimization of volume since their output power per unit volume and power factors are high [1], [2]. As a result, there has been extensive research on improving performance of PM [3]-[5]. The Dy free anisotropic bonded NdFeB PM exhibits a high magnetic energy product compared to ferrite PM, and is cheaper compared to sintered NdFeB PM [6]. However, the NdFeB PM shows nonlinearity.

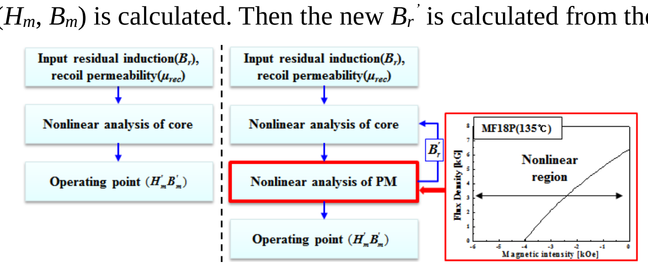
In this paper, considering the nonlinearity of PM as shown in Figure 1, the operating point calculation process was proposed, and the process was applied to 2D magneto static field Finite Element Analysis (FEA) to study the properties of Interior Permanent Magnet Synchronous Motor (IPMSM) for different rotor designs.

II. OPERATING POINT CALCULATION PROCESS

Sintered NdFeB PM shows linear properties at room temperature, but with temperature increase, nonlinear properties are shown. In bonded NdFeB PM (MF18P), the nonlinear properties are shown for all temperatures and become prominent with temperature increase. Therefore, by taking the nonlinear properties of PM into account, it is necessary to find the operating point and design motors.

Figure 1 shows the operating point calculation process considering the nonlinearity of PM. Using initial residual induction (B_r) and recoil permeability (μ_{rec}), the nonlinear analysis of the core is performed and the initial operating point (H_m, B_m) is calculated. Then the new B_r' is calculated from the nonlinear analysis of PM, and using the new B_r', nonlinear analysis of core is conducted again. After sequentially repeating the nonlinear analysis of the core and PM, an operating point (H_m', B_m') of the magnet is found. Figure 2 shows the process of nonlinear analysis on PM in operating point calculation. Using residual induction (B_r), H_m is calculated and corresponding B_m is determined on B-H curve of the PM. Then, the new B_r is calculated using the found H_m and B_m. Using the new B_r, the process to calculate H_m is repeated until B_r converges. The method was applied to each element of the motor via 2D magneto static field FEA. Since the process reflects the nonlinear properties of both the PM and the core, a more accurate operating point can be calculated. In this process, Convergence rate is decided as a value considered reasonable after analyzing the change of B_r according to the convergence rate. Also, the number of iterations is influenced by material data, initial value and convergence rate. In this paper, convergence rate is 0.1% and took less than a minute with about 10,000 meshes to converge.

The process was applied to 6pole 9slot Flux concentrated type IPMSM that uses MF18P PM, and the operating points obtained using linear analysis and nonlinear analysis of the magnet were compared. The analyses were performed at 20℃ and 135℃, and d-axis current of 25A was applied for load analysis. Recoil permeability (μ_{rec}) was maintained at 1.15 for linear and nonlinear analyses. As shown in Figure 3, not much difference was shown at 20℃, where nonlinear properties do not appear significant. However, a significant difference between linear and nonlinear analyses was shown at 135℃, at which nonlinear properties are significant, and a greater difference was observed in load analysis.



(a) (b)

Fig. 1. Operating point calculation process
(a) Nonlinearity of PM not considered, and (b) Nonlinearity of PM considered

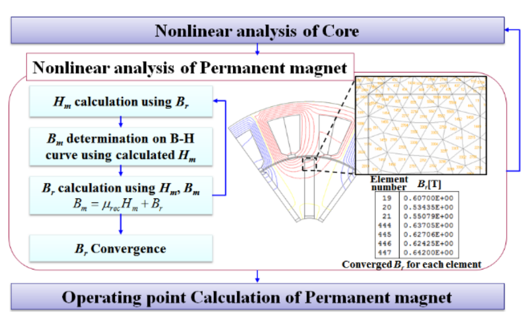


Fig. 2. Nonlinear analysis process of PM

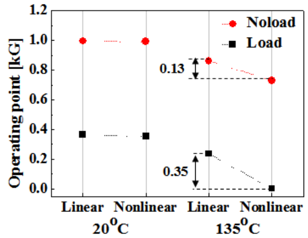


Fig. 3. Comparison of operating points obtained from linear and nonlinear analyses.

III. CHARACTERISTICS ACCORDING TO ROTOR DESIGN

Using the proposed analysis process in the previous section, characteristics changes of IPMSM were studied for rotor design variation. As shown in figure 4, the operating points for 4 types and 3 different numbers of poles were calculated, and for all cases, noload back electromotive force (EMF), their total harmonic distortion (THD), noload back EMF per PM usage and demagnetization characteristics were verified. In all cases, the stator shape, airgap length, stack length, rotor inner and outer diameter, number of series turns per phase, rib thickness, and PM thickness were same.

In the comparison study at 1000rpm, IPM_V type showed the highest noload back EMF with lowest THD. It was shown that noload back EMF increased with the number of poles. The noload back EMF for PM usage showed the same tendency shown for different types and different numbers of poles. And noload back EMF per PM usage, which is the efficiency of PM usage, was the highest for flux concentrated type. More details on these will be explained in the full paper.

The results of demagnetization characteristics are shown in Figure 5. They were evaluated by comparing the noload linkage flux reduction rate between before and after d-axis current was applied. First of all, an improvement of demagnetization characteristics was shown with the increase of number of poles. This is because the armature reaction magnetomotive force (MMF) per pole was reduced with the increased number of poles. Secondly, Flux concentrated and Flux concentrated_V type were shown to convey poor demagnetization characteristics. This is because these 2 models do not have ribs, unlike IPM and IPM_V type, which imposes greater armature reaction MMF on the PM.

IV. CONCLUSION

In this paper, a coupled nonlinear analysis process of the PM and the core was proposed and the operating points for linear and nonlinear analyses were compared to emphasize the need for nonlinear analysis. This process was applied to 2D magneto static field FEA, and noload back EMF, their THD, noload back EMF per PM usage and demagnetization characteristics were calculated for IPM motors with different types and number of poles. As a result, IPM_V type that uses the highest amount of PM showed a high noload back EMF. However Flux concentrated type had the highest noload back EMF per PM usage. Demagnetization characteristics of PM were shown excellent for IPM and IPM_V type and improved with the increase of number of poles. More detailed conclusion will be stated in the full paper.

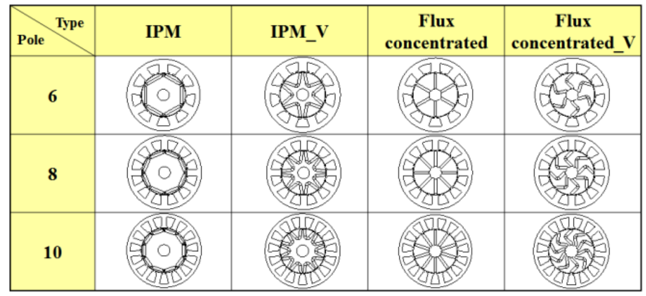


Fig. 4. Models for each rotor design.

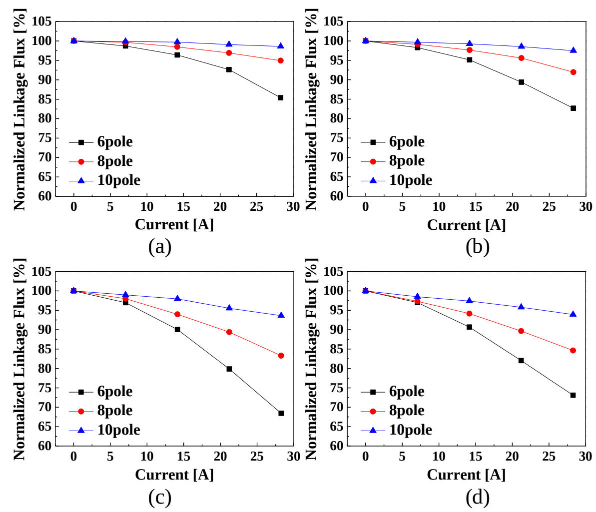


Fig. 5. Demagnetization characteristics for each type.
(a) IPM, (b) IPM_V, (c) Flux concentrated, and (d) Flux concentrated_V

ACKNOWLEDGMENT

This research was supported by the MKE (The Ministry of Knowledge Economy), Korea, under the CITRC (Convergence Information Technology Research Center) support program (NIPA-2013-H0401-13-1008) supervised by the NIPA (National IT Industry Promotion Agency).

This work supported by a research program (The Specialized Research Center on the Future Ground System) funded by the Agency for Defense Development of Korea and we appreciate it.

REFERENCES

[1] K. S. Kim, B. H. Lee, J. W. Jung, and J. P. Hong, "Thermal Analysis of Water Cooled ISG Based on a Thermal Equivalent Circuit Network," *J Electr Eng Technol*, Vol. 9, No. 3, pp. 893-898, 2014

[2] S. J. Lee, S. I. KIM, and J. P. Hong, "A New Anisotropic Bonded NdFeB PM and Its Application to a Small DC Motor," *International Journal of Automotive Technology*, Vol. 15, No. 7, pp. 1183−1187, 2014

[3] K. Noguchi, C. Mishima, M. Yamazaki, H. Matsuoka, H. Mitarai, Y. Honkura, "Development of dy-free NdFeB anisotropic bonded magnet (New MAGFINE)," *Electric Drives Production Conference (EDPC), 2011 1st International*, pp. 181-186, Sept. 2011

[4] N. Hamada, C. Mishima, H. Mitarai, and Y. Honkura, "Development of Nd-Fe-B anisotropic bonded magnet with 27 MGOe," *IEEE Trans. on Magn.*, vol. 39, no. 5, pp. 2953–2955, Sep. 2003.

[5] C. Mishima, N. Hamada, H. Mitarai, and Y. Honkura, "Development of a Co-free NdFeB anisotropic bonded magnet produced from the d-HDDR processed powder," *IEEE Trans. on Magn.*, vol. 37, no. 4, pp. 2467–2470, Jul. 2001

[6] Y. Hayashi, H. Mitarai, and Y. Honkura, "Development of a DC Brush Motor with 50% Weight and Volume Reduction Using an Nd–Fe–B Anisotropic Bonded Magnet" *IEEE Trans. on Magn.*, vol.39, no.5, pp. 2893-2895, 2003.