Optimization Design of Segmented Permanent-Magnet Shape by Analysis of Thermal Characteristics

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Abstract - Recently, research on eco-friendly EV & HEV is in progress. In particular, there is a growing interest in IPMSM, which has high efficiency, power and wide operating range. However, IPMSM is more expensive than different type of motors because of permanent magnets. Dysprosium (Dy) and Terbium (Tb) are used to increase coercive force. Essential for automotive applications requiring high heat resistance. In this paper, the characteristics of IPMSM are analyzed using sintered $Nd_2Fe_{14}B$ as doing high coercivity while reducing rare earth Dysprosium (Dy). The method using rare earth reduction technology is call grain boundary diffusion permanent magnet. Simulation is performed using grain boundary diffusion permanent magnet and reference permanent magnet. Demagnetization characteristics of permanent magnet are largely two divided into temperature and external magnetic field. In order to analyze the properties of rare earth permanent magnets, demagnetization characteristics were compared according to operating temperature. Demagnetization in permanent magnets have a significant effect on motor output power. The reliability is verified by analyzing the demagnetization rate and magnetic flux density of permanent magnet by using external magnetic field. The efficiency map is analyzed according to the operation area

1. INTRODUCTION

- Motors equipped in the vehicle must satisfy high power in confined spaces. Since high power density is required, BLDC using permanent magnets is mainly used. The permanent magnet type synchronous motor of the IPM type has a wide operating range through weak magnetic flux control, and has a high torque using reluctance torque.

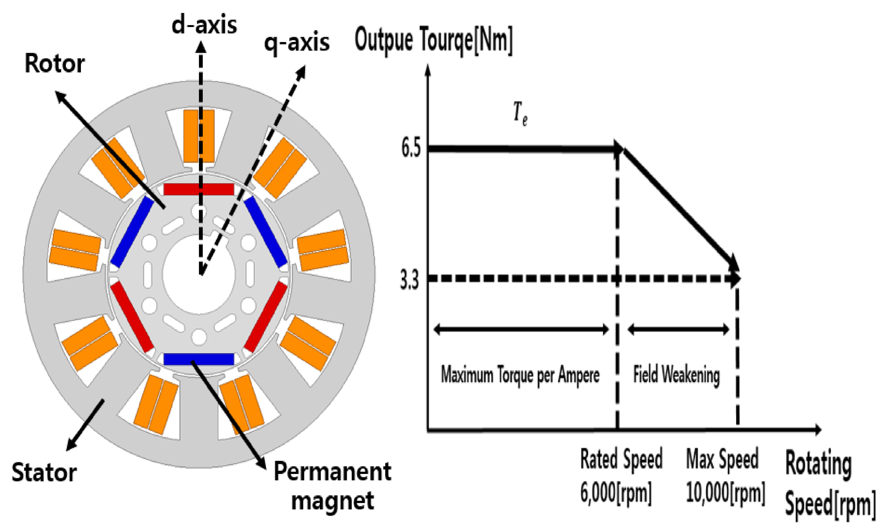


Fig. 1. IPMSM structure

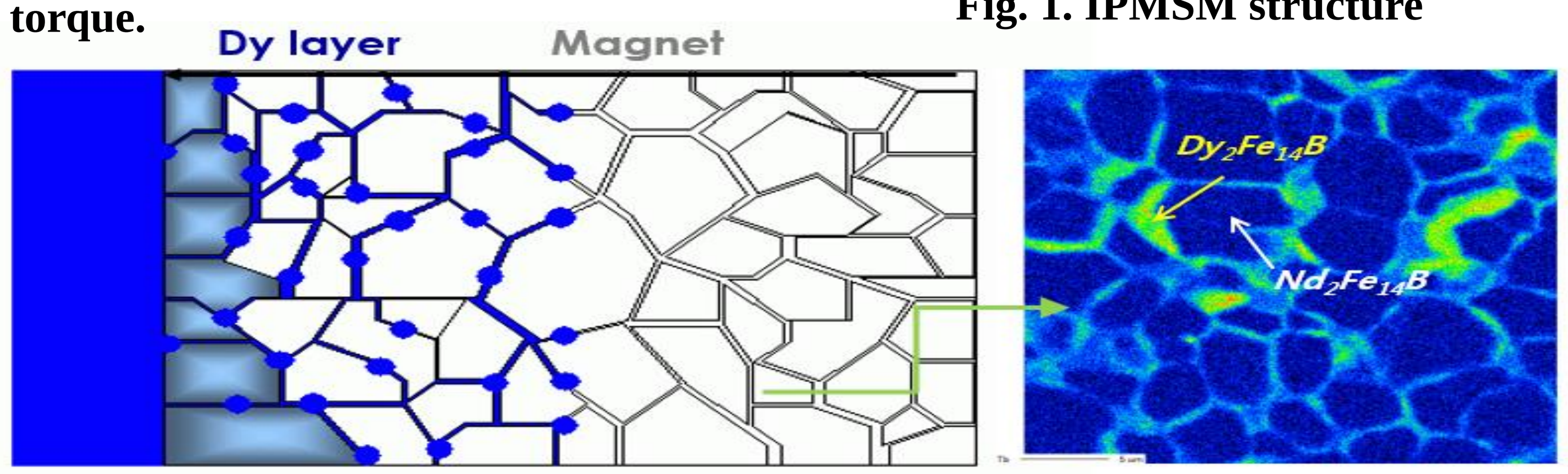
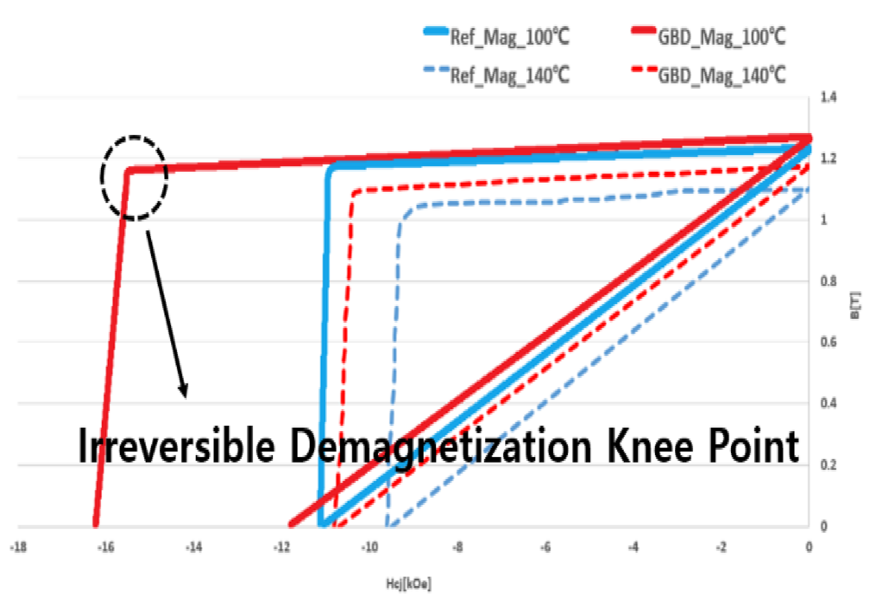


Fig. 2. GBD conceptual diagram and $Nd_2Fe_{14}B$, $Dy_2Fe_{14}B$ grain to the surface of magnet(Source : Star Group IND. CO.,LTD)

- Dysprosium (Dy) and Terbium (Tb) used in permanent magnets are expensive. Dy or Tb are essential for automotive motors that operating at high temperatures. Higher. H_c as number of increases the performance of thermal characteristics in permanent magnets. If used rare earth grain boundary diffusion (GBD), rare earth (Dy) diffuses inward along the grain boundaries of the magnet. This results in a high anisotropic magnetic field along the grain boundaries. Even in using relatively less rare earth (Dy), it has the same coercive force (H_c) as the reference permanent magnet. Grain diffusion (GBD) apply rare earth Dy to the sintered magnet surface. After application, heat treatment several times above 900 ℃. In this process, it has a high anisotropic magnetic field. Has the same effect as Dy of 3% in the permanent magnet manufactured by conventional method. Left figure in Fig. 2. shows the diffusion along the grain boundary on the sintered permanent magnet surface. The right side shows the grain boundary diffusion taken with a scanning electron microscope (SEM).

2. Analysis of the Grain boundary diffusion and demagnetization



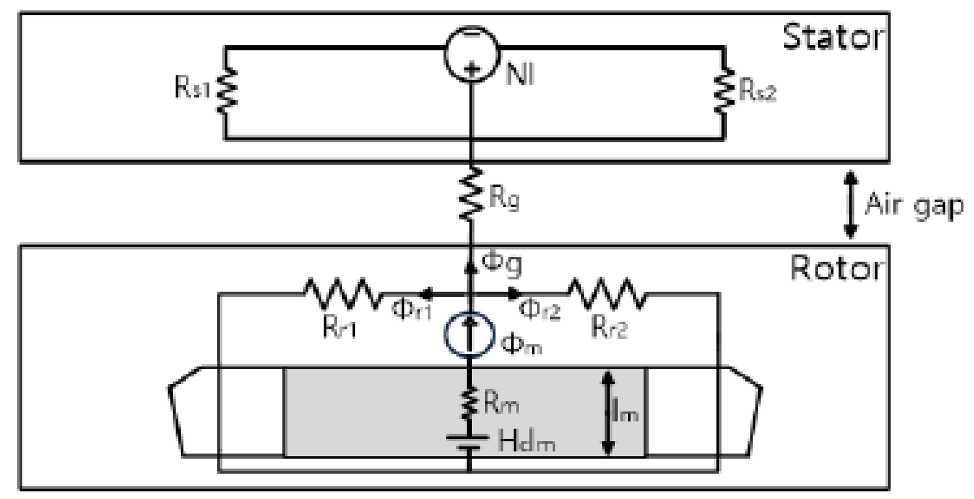
Characteristic Properties(100℃)	Br (T)	Hcj (kOe)	$\%B_r$ (%/℃)	$\%H_cj$ (%/℃)
Ref.Magnet	1.21±0.03	-11.1±0.06	-0.10	-0.56
GBD Magnet	1.26±0.05	-16.2±0.03	-0.10	-0.50
Characteristic Properties(140℃)				
Ref.Magnet	1.05±0.03	-9.5±0.06	-0.11	-0.51
GBD Magnet	1.17±0.05	-10.7±0.03	-0.11	-0.50

Fig. 3. GBD processed magnet and Reference magnet J-H, B-H curve and data sheet

- Fig. 3. shows the J-H and B-H curves of GBD permanent magnets and reference permanent magnets. The operating tem-perature is a value for 100 ℃, 140 ℃. At 100°C, the Hcj of GBD was -16.25[kOe] and the Hcj of the reference permanent magnet was -11.10[kOe], showing a greater value of approxi-mately 31%. The Hcj of GBD at 140°C is -10.9[kOe] and the reference magnet is -9.8[kOe], which is 11% smaller.

$$B_r(T) = B_r(T_0)\cdot[1+\alpha(T-T_0)]$$
$$H_{ci}(T) = H_{ci}(T_0)\cdot[1+\beta(T-T_0)]$$

- Equation shows the residual magnetic flux denstiy($Br(T)$), coercive force($Hci(T)$) of the magnet according to driving temperature. The residual flux density temperature coefficient α[%℃/], coercive force temperature coefficient β [%℃/] show negative values. $T0$ is the reference temperature



$$H_c l_m - NI = R_m\Phi_m + 2R_r\Phi_r + R_g\Phi_g$$
$$\Phi_m = \frac{H_c l_m - NI - 2R_r\Phi_r - R_g\Phi_g}{R_m}$$
$$R_g = \frac{2l_g}{\mu_0 A_g}$$
$$R_m = \frac{2l_m}{\mu_0\mu_r W_m L_{st}}$$

Fig. 4. Magnetic circuit model for IPMSM and equation for decreased the magnetic filed

- Analyzed the characteristics of the permanent magnet demagnetization affected by the magnetomotive force (NI) generated by the electric field on the stator winding. NI is magnetomotive force generated by the stator, Rm, Rr , Rg is permanent magnet reluctance, rotor reluc-tance, air gap reluctance, Φm , Φr , Φg is permanent magnet magnetic flux, magnetic flux to the rotor, magnetic flux to the air gap

3. Simulation and experiment

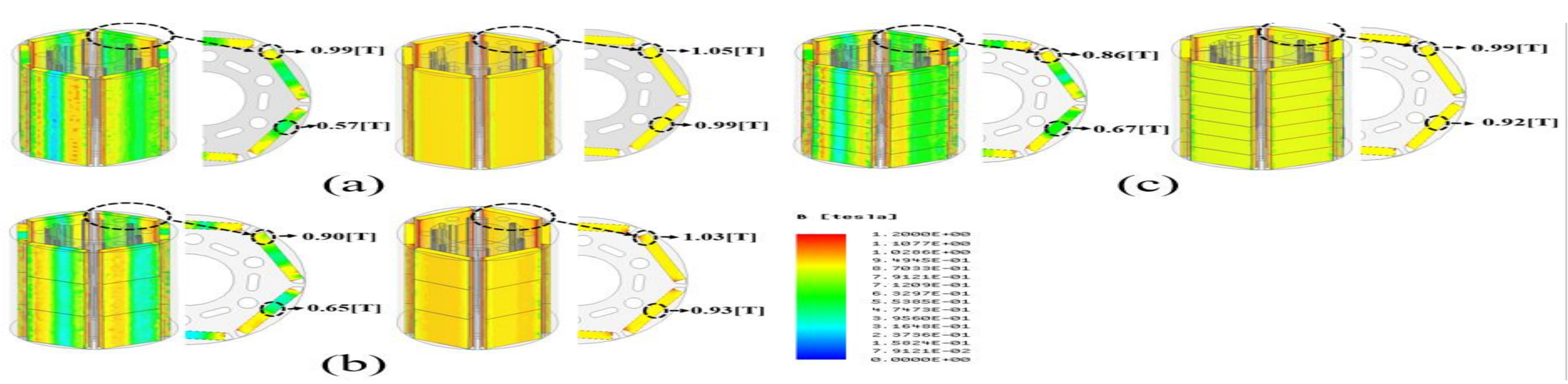


Fig. 5. Magnet flux density according to Reference permanent magnet and GBD permanent magnet, operating temperature 100℃ (Max. B 1.2[T]) (a) Non_segmented magnet (b) 3segmented magnet (c) 7segmented magnet

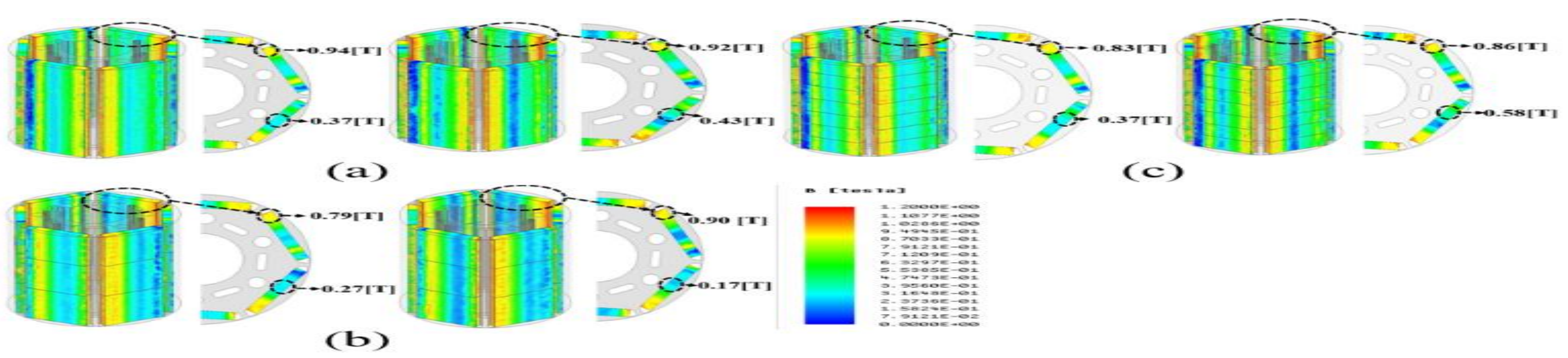
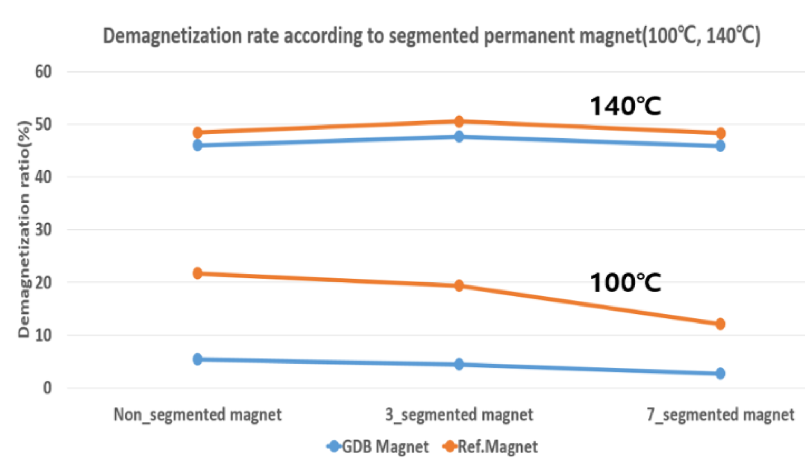


Fig. 6. Magnet flux density according to Reference permanent magnet and GBD permanent magnet, operating temperature 140℃ (Max. B 1.2[T]) (a) Non_segmented magnet (b) 3segmented magnet (c) 7segmented magnet

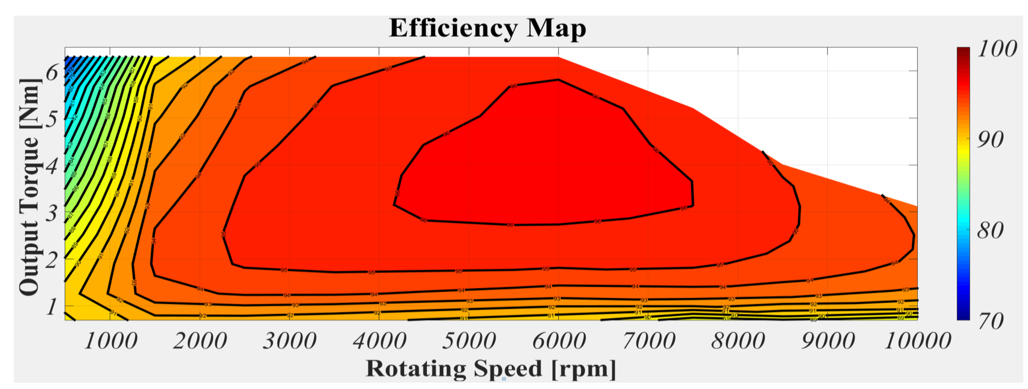
- The simulation was performed by applying a current seven times the maximum current (Irms = 168 A). The current phase angle was set to 92 deg represent-ing the maximum reduction rate. Fig. 5. show the Magnet flux density according to segmented reference permanent magnet and GBD permanent magnet. It shows the magnetic flux density after receiving the effect of the armature reaction. The more blue, the lower the magnetic flux density



Demagnetization Ratio[%], 100℃	Non segmented	3 segmented	7 segmented
Ref.Magnet	-21.71	-19.32	-12.04
GBD Magnet	-5.30	-4.47	-2.68
Demagnetization Ratio[%], 140℃			
Ref.Magnet	-48.41	-52.39	-48.33
GBD Magnet	-45.99	-50.56	-45.85

Fig. 7. Demagnetization ratio according to Ref.magnet and GBD magnet

Fig. 8. Model shape and experiment setting



	Prototype Model	Simulation Model
Speed[RPM]	6000	6000
Output Power[kW]	3.98	4.08
Output Torque [Nm]	6.31	6.5
Induced Voltage[V]	15.3	15.36
Efficiency[%]	91.4	96.2

Fig. 9. Efficiency mag(GBD) comparison of Simulation data and experiment Data

- shows the test environment. The data was analyzed by conducting experiments by connecting control inverter and analysis equipment. GBD permanent magnet is currently in production and will be tested later

Conclusion

- In this paper, we analyzed the characteristics of the perma-nent magnet synchronous motor (IPMSM) using reference per-manent magnets and rare earth grain boundary diffusion (GBD) permanent magnet. This magnet has less rare earth (Dy, Tb) and higher coercive force (Hc). A permanent magnet with the same performance can be used at a lower cost. In addition, the de-magnetization characteristics of the permanent magnets were compared. Because of the high coercivity, the grain boundary diffusion (GBD) has a high resistance to hot demagntization. GBD main-tains higher magnetic flux density than reference permanent magnet at the same temperature. When the segmented permanent magnet were used, the demagnetization characteristics of the permanent magnet were improved, but no significant difference was ob-served at high temperature. Data analysis was conducted by simulation, and motor output was verified by test