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Effect of Material Characteristics on PMDC Motors based on the Grade of Electrical Steel Sheet

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In this study, the effect of the material characteristics of electrical steel sheet on permanent magnet direct current (PMDC) motors is investigated using finite-element analysis. The motor design and test results are examined and verified through fabrication. The characterizations of brushless direct current (BLDC) motors according to the materials used in their cores have been actively studied. On the other hand, the effect of material characteristics on a PMDC motor consisting of brushes and commutators has not been studied as much. In the case of the PMDC motors, electrical steel sheets are infrequently used because this motor is relatively smaller than the BLDC motor. However, the iron loss characteristics, which are proportional to the frequency and the magnetic flux density, affect the efficiency even in small motors. Further, the output of the motor changes owing to saturation due to iron loss. The outcome presented in this study provides core materials selection guidelines to improve motor efficiency.

Keywords : electrical steel, hysteresis loss, iron loss, permanent magnet direct current motor (PMDCM)

1. Introduction

DC motors or direct current electric motors have almost linear speed and torque characteristics, which facilitate excellent linear voltage controllability. Windings can be wound around the field of a DC motor and used as an electromagnet or a permanent magnet. Recently, PMDC motors have become dominant components in 60 % of automobiles. Unlike BLDC motors, PMDC motors do not require separate control mechanism and are therefore affordable. However, owing to the combination of a brush and a commutator, PMDC motors require voltage input and mechanical maintenance. This has the disadvantage of low efficiency. The losses seen in the operation of the motor can be broadly classified into copper loss, iron loss, and mechanical loss, and the iron loss can be further classified into losses due to eddy currents and hysteresis. The copper loss has correlations with current and resistance, and the iron loss relates to magnetic flux and frequency. The mechanical losses may be due to various causes such as mechanical structure and rigidity. The efficiency of the motor can be optimized through the design of the stator and rotor shapes. However, if the figurative design is limited, high quality materials, for example aluminum wires and low loss steel plates, can be used to improve the properties. As the eddy current loss in iron loss is caused by heat due to the resistance of the core, an electrical steel plate with high resistivity should be used; thus, an electrical steel plate with a small hysteresis loss area and hysteresis loss should be used. As a result of this, as the silicon content increases, and the iron loss and magnetic flux density decrease. However, the use of low iron loss steel plates does not unconditionally reduce iron loss. In the case of the data of B-H and B-Loss, loss is increased if high quality materials are used, due to their nonlinear properties. Therefore, magnetic flux density and harmonic iron loss should be taken into consideration when applying low iron loss electrical steel plates.

In this study, the influence of the electrical steel characteristics on a PMDC motor was investigated. Generally, the PMDC motor is composed of the field coil, armature,

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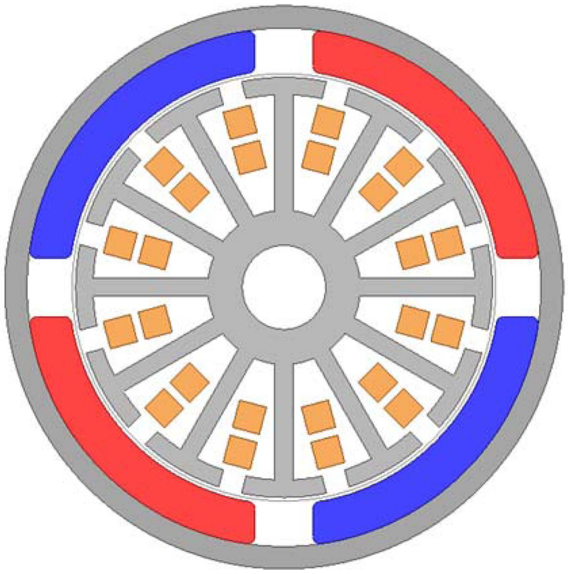


Fig. 1. (Color online) PMDCM model.

Table 1. Permanent magnet motor performance requirements.

Contents	Units	Value
Outer Dia. (Stator)	mm	40.2
Outer Dia (Rotor)	mm	30
Stack Length.	mm	40
DC link	Vdc	13.5
Branch Current	A	9.5
Rotor Resistance at 20ºC	Ω	0.18
Parallel	·	2
Wire size/Turns	mm/·	0.35/28
Output	W	55

and DC motor. The field coil can be made of electromagnets with copper wire windings. However, a permanent magnet may also be used. Owing to the electrical resistance being directly proportional to the silicon content of the steel sheet plates, eddy current losses can be reduced with an increase of the silicon content [1]. Fig. 1 shows the structure of a PMDC motor. This model has 4 poles and 12 slots, and the winding method used is lap-winding. Table 1 shows the specifications of the PMDC motor. This model is generally used in vehicles. The output power generated is up to 55W.

2. Material Properties and Motor Simulation

Iron loss is divided into eddy current and hysteresis losses. Iron loss data can be expressed by an equation to consider higher order harmonics in iron loss calculations. Under sinusoidal flux conditions, the iron loss is computed in the frequency domain as follows [2, 3].

$$P_i = P_e + P_h \tag{1}$$

$$P_h = k_h f B_m^n [W/m^3] \tag{2}$$

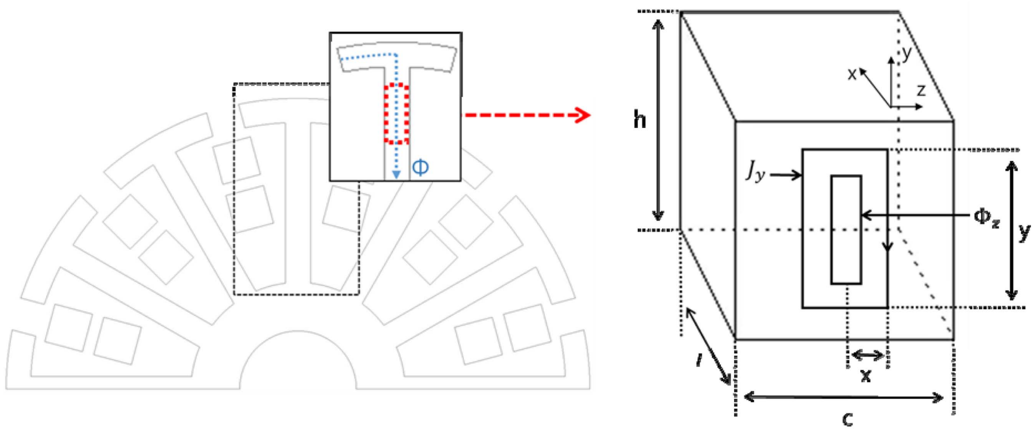
$$P_e = k_e f B_m^2 [W/m^3] \tag{3}$$

Where P_i is the iron loss, P_h is the Output, P_e is the hysteresis loss coefficient, k_e is the eddy current loss coefficient and B is the flux density. In particular, the order for n in magnetic flux density is a value of 1.5 to 2. The eddy current loss is very small for ferrite. Because of the high resistance of ferrite. But rapidly increases with frequency for steel laminations. So the iron loss of the ferrite material can be simplified to be [3].

$$P_{i(ferrite)} \cong k_{h(ferrite)} f B_m^2 \tag{4}$$

Where the iron loss of the steel laminations is

$$P_{i(steel)} = k_{e(steel)} f^2 B_m^2 t_n^2 + k_{h(steel)} f B_m^2 \tag{5}$$



(a) (b)

Fig. 2. (Color online) Flux and induced current of iron core: (a) flux in cross section, (b) induced current by magnetic flux.

Figure 2(a) shows the electromotive force induced in the winding. Also, electromotive force is induced in the iron core. Figure 2(b) shows that the induced current is blurred. This is because the conductivity of the iron core is included in a high range. This current is defined as eddy current.

The eddy current is the current flowing inside the iron core. It is also consumed as heat by the resistance of the iron core. This is called eddy current loss.

As shown in Fig. 2(b), the equation of the magnetic flux passing through the closed curved surface is as follows.

Equation (6) shows the nature of the eddy current loss.

$$\phi_z = 2xyB \tag{6}$$

The value of B in the equation represents the magnetic flux density.

Assuming $y > x$, The electromotive force in the x direction is neglected and the intensity of the electric field in the y direction is as shown in equations (7) and (8).

$$E_y \cdot 2y = \frac{d\phi_z}{dt} \tag{7}$$

$$E_y = x \cdot \frac{dB}{dt} \tag{8}$$

Therefore, the current density at a distance x from the cross-section of xy is equal to Equation (9).

$$J_y = \frac{E_y}{\rho} = \frac{x}{\rho} \cdot \frac{dB}{dt} \tag{9}$$

As shown in Fig. 2, the loss in the thickness c, the height h, and the length l is equal to the equation (10).

$$P = \int \rho J^2 dV = \int_{-\frac{c}{2}}^{\frac{c}{2}} \rho \left(\frac{x}{\rho} \cdot \frac{dB}{dt} \right) hldx = \frac{c^3 hl}{12\rho} \left(\frac{dB}{dt} \right)^2 \tag{10}$$

In equation (10), the eddy current loss per unit volume can be obtained as in equation (11) by dividing by volume to obtain the loss for the unit volume.

$$p = \frac{c^2}{12\rho} \left(\frac{dB}{dt} \right)^2 \tag{11}$$

The eddy current loss can be reduced by increasing the resistivity of the iron core.

Also, the lamination length (c) must be reduced and the magnetic flux density should be lowered in accordance with the design characteristics [8]. Most importantly, thin sheets of insulation coated steel should be laminated. The reason for this is that one eddy current is separately formed in the steel sheet, which can greatly reduce the eddy current loss [9].

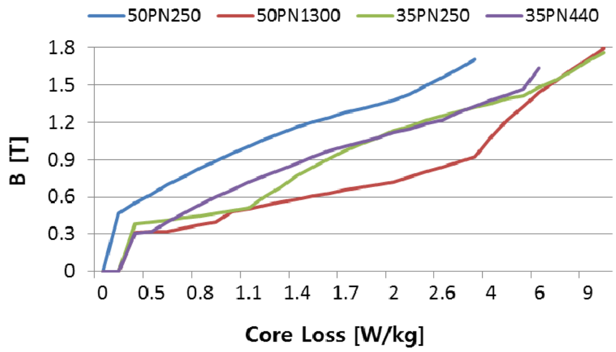


Fig. 3. (Color online) Saturation loss.

Figure 3 is the characteristic curve of the iron loss of the silicon steel plate at 50 [Hz]. The 50PN400 and 35PN440 materials show similar losses and magnetic flux densities. The 50PN1300 material has low resistance and high volume of loss. As the steel plate is thinner, it helps decrease loss. However, considering saturated magnetic flux density, 50PN1300 is advantageous. The 35PN250 material has high magnetic flux density in low saturation regions. Therefore, when 35PN250 is used in low saturation regions, the current and core losses can be diminished to achieve better efficiency. Table 2 shows the density, resistivity, weight loss, and saturation flux density at 50 Hz according to the material of the core. Furthermore, the silicon ratios in the steel sheet plates are inversely proportional to the numbers that come after the term PN in the "Materials" column. PN is a notation used in Korea and refers to a non-oriented silicon steel plate.

In Figure 4, (a) is 35PN250, (b) is 35PN440, (c) is 50PN250, and (d) is 50PN1300. In addition, there are several grades of electrical steel, but the 2D analysis is performed using the finite-element method for the largest loss and smallest grade material. The prefixed number in the material indicates the thickness of the electrical steel sheet. That is, 50 represents 0.5 mm. The postfixed digits indicate that the loss of the iron core increases as the number increases.

The transition steel sheet reduces eddy current loss via the added silicon to pure iron to increase the electrical resistance. However, the permeability decreases with the

Table 2. Typical electrical and magnetic property.

Material	Density [Kg/m^3]	Resistivity	W15/50 [W/Kg]	B50 [T]
35PN250	7600	55	2.25	1.66
35PN440	7700	42	3.08	1.71
50PN250	7600	59	2.37	1.67
50PN1300	7850	17	7.56	1.75

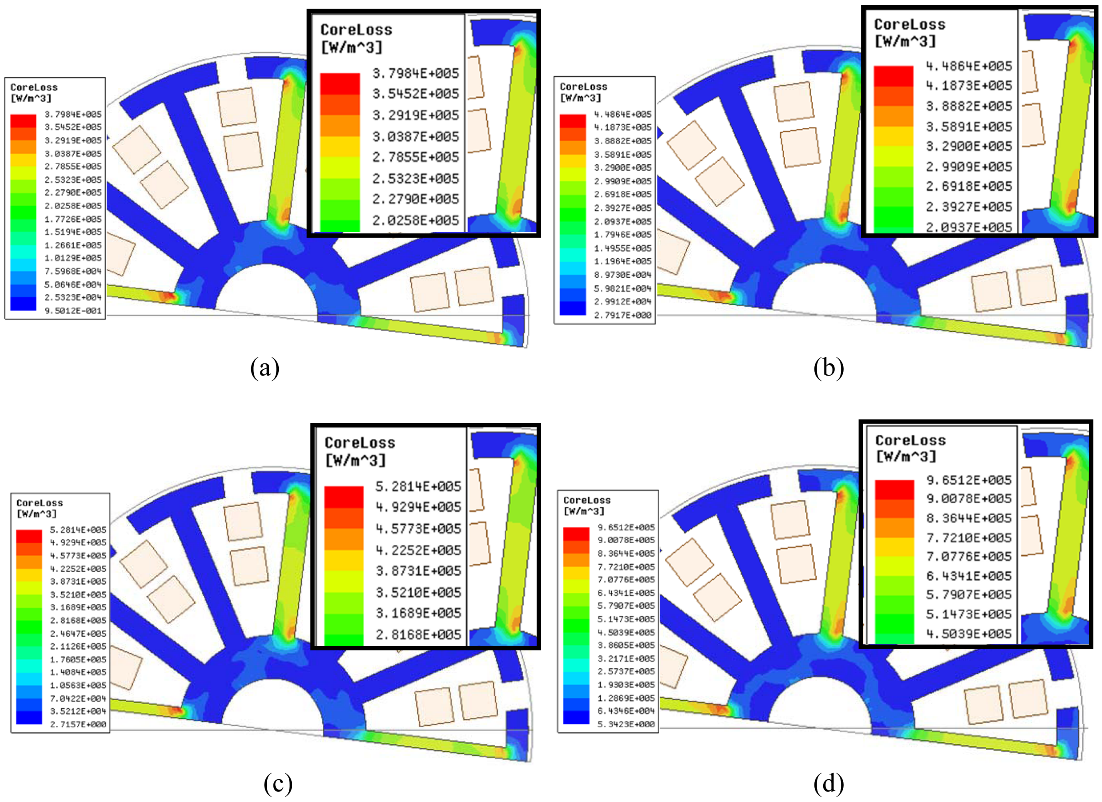


Fig. 4. (Color online) Distribution of iron loss by material of electrical steel sheet: (a) 35PN250, (b) 35PN440, (c) 50PN250, (d) 50PN1300.

content of silicon. Moreover, even if an electric steel sheet is made by overlapping thin steel sheets, the eddy current loss is reduced. The unit of the hysteresis loss density is watts per cubic meter. The positions where the maximum hysteresis loss densities are seen are the rotor teeth because both radial and tangential components of the flux density have large amplitudes and multiple local hysteresis loops [5].

Figure 4 (a) shows the iron loss distribution of 35PN250, which shows the lowest iron loss when compared to other materials. PMDC motors applied to vehicles are mostly small and have small core areas. In particular, there is a lot of loss in the rotor tooth, and the loss at both ends is larger than the tooth body part. Figure 4 (d) is the 50PN1300 material, and the result shows that the loss per volume is about three times that of 35PN250. It can be seen that the iron loss density in tooth tips is much higher than the loss density in the other parts [6]. Among them, the tooth shoe and slot opening have the largest iron losses. The losses result in radial and tangential magnetic flux densities higher than those of the parts [7]. Further, due to the increase of the saturation magnetic flux density due to the magnetomotive force of the stator, the upper part of the teeth abutting the air gap is vulnerable to saturation.

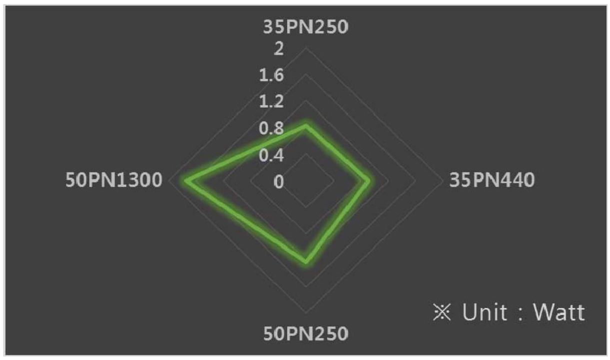


Fig. 5. (Color online) Core loss of materials at 50 Hz.

3. Experiment

Tests were conducted after changing only the material of the electric steel sheet at the same size condition of the PMDC motor. Figure 6 below shows the assembled product after changing the material of the rotor. Figures 6 (a) and 6 (b) are of the 35PN series, and (c) and (d) are of the 50PN series.

Figure 7 compares the characteristics of the analysis

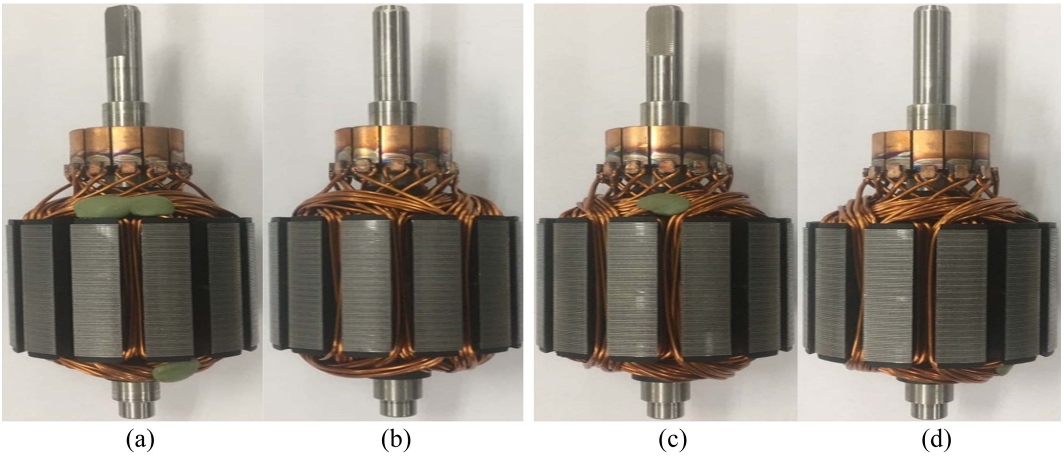


Fig. 6. (Color online) Products by material of electrical steel: (a) 35PN250, (b) 35PN440, (c) 50PN250, (d) 50PN1300

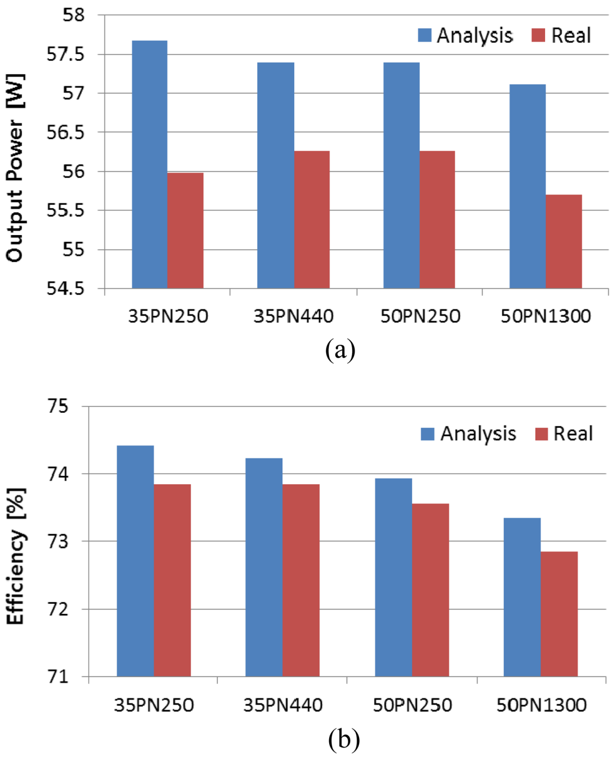


Fig. 7. (Color online) Comparison of analysis and real: (a) output power, (b) efficiency.

and the actual sample. Figure (a) shows the output and figure (b) shows the efficiency. Figure 7 (a) shows the output difference of the motor is less than 1 % when comparing 35PN250 and 50PN1300.

There is not a large difference of output. As a result, 35PN250 shows the highest efficiency at low load torque and in the high speed region. However, as the torque increases with decreasing the speed, there is no significant difference of efficiency between 35PN250 and 50PN1300. It can be said that the few improvements of efficiency can be achieved with the presented PMDC motor at a high torque region with high grade materials [2]. The difference between the analysis and actual motor characteristics is about 2 to 3 %. The reason is that the mechanical losses that occur when the motor is manufactured can't be accurately considered at the design stage. In addition, the manufacturing performance of the permanent magnet and the core is lower than the ideal value applied at the design stage. A dynamometer is used for measuring the performance, but it also includes the slight error of the torque sensor. In the case of efficiency, errors also occur due to the above described causes. The efficiency of the inverter also affects the efficiency of the motor and the voltage across the power supply. The inverter and the motor in the test environment should be minimized.

4. Conclusion

In this paper, we analyze the characteristics of PMDC motors according to their core materials. We chose PMDC instead of PMSM, which is widely used today, because PMDC has a significantly smaller core area than PMSM and its efficiency changes depending on core material. For the analysis, the correlation between the electrical steel sheet and the loss was confirmed through a mathematical approach. The amount and distribution of iron loss was confirmed by 2D finite element analysis. Based on this, the actual steel plate tests were conducted and the results were derived. As a result, it was proven that the 35PN250 material with thin steel sheet and low iron loss is the best material, and that it improves the efficiency even with low core motor usage.

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