BLDC 전동기 고정자 코어의 비정현적인 자속밀도 분포특성를 고려하기 위한 철손 모델링에 대한 연구

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Novel Iron Loss Modeling of the BLDC Motor for Fuel Pump by Considering Non Sinusoidal Distributed Magnetic Flux Density Effect in Stator Core

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Abstract - In the design and analysis of electric machines the precise calculation of iron loss has incredible significance. It is tough to foresee iron losses precisely in machines due to distribution of non sinusoidal flux density. It is necessary to approximate the iron losses for the precise computation of efficiency. This paper presents a novel approach for the prediction of iron losses of the brushless dc (BLDC) motors by considering the effects of minor hysteresis loops in the simplified model. The novel iron loss model results are compared with the simplified model and with finite element method (FEM).

1. Introduction

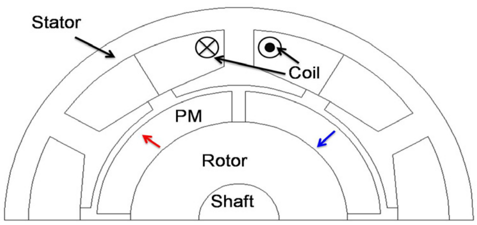
The current technological growth in manufacturing of permanent magnet (PM) having high energy product has led to remarkable performance improvement of PM machines. A PM machine has many advantages over other machines like higher efficiency, and smaller size [1]. Accurate prediction of iron losses is required for the higher efficiency.

In PM motors iron losses make a large proportion of the total losses than induction motors due to elimination of rotor copper losses. An earlier paper [2] presented a comprehensive model for iron losses but it not included minor hysteresis loops. The prediction of iron losses in [3, 4] were made by considering the minor hysteresis loops but in these papers rise and fall time of tooth flux density was assumed to be the time interval in which the magnet edge transverses one tooth width.

The novel iron loss model is proposed in this paper. The proposed model includes the minor hysteresis loops and it considers the rise and fall time of the flux density in the tooth as the time interval in which the magnet edge transverses one sloth pitch. The results obtained by the novel model are compared with finite element method (FEM) and also with the simplified model which is reference [2]. The results shows that the proposed model can calculate iron losses accurately.

2. Proposed Iron loss Modeling

In the proposed iron loss model hysteresis loss is calculated by considering the effects of minor hysteresis loops. The eddy current loss in tooth is calculated by considering the fact that the flux density reaches its maximum value in the time interval in which a magnet edge transverses one slot pitch. The effects of circumferential component of flux density in tooth and radial component of flux density in yoke are considered for eddy current loss calculation. The model also considers the effects of motor geometry for the eddy current losses. Fig. 1 shows the brushless dc (BLDC) motor model that is used in this paper.



<Fig. 1> Fuel type BLDC motor model

2.1 Total Iron Loss Model

In the magnetic materials the iron losses are measured for the sinusoidal flux density B of varying magnitude and frequency. The total iron losses P_{iron} can be expressed for sinusoidal flux density with angular frequency ω_s as

$$P_{iron} = P_h + P_e = K_h B^{\beta} \omega_s + K_e B^2 \omega_s^2 \quad (1)$$

Where P_h, P_e are hysteresis and eddy current loss densities and K_h, K_e are hysteresis and eddy current loss coefficients respectively.

2.2 Eddy Current Loss Model [2]

The convenient form to represent eddy current loss density for any arbitrary flux density waveform of the time period T can be written as

$$P_e = \frac{2K_e}{T} \int_0^T \left(\frac{dB}{dt} \right)^2 dt \quad (2)$$

It is stated that time required for the flux density to change from zero to maximum value was found to be the same as required for the magnet edge to transverse one slot pitch. Time required by the magnet edge to transverse one slot pitch is used for the calculation of eddy current loss instead of time required for the magnet to transverse one tooth width time as it was used in earlier assumption [5]. For m-phase machine with q slots per pole per phase time required by the magnet to transverse one slot pitch can be written as

$$\Delta t = \frac{T}{2} \frac{1}{mq} \quad (3)$$

It is stated that flux density in the tooth B_{th} changes from zero to peak value four times in one time period. By considering this effect and substituting Eq. 3 into Eq. 2, we can write as

$$P_{et} = \frac{4m}{\pi^2} q K_e (\omega_s B_{th})^2 \quad (4)$$

The eddy current loss in tooth when we consider the effects of motor geometry and longitudinal component of flux density can be written as

$$P_{et} = \frac{4m}{\pi^2} q K_e K_q K_c (\omega_s B_{th})^2 \quad (5)$$

Where K_q and K_c are the correction factor for motor geometry and longitudinal component of flux density respectively. The time required by the magnet of width w_m to pass a point on the stator yoke can be written as

$$\Delta t = \frac{p\omega_m}{2r\omega_s} = \frac{\alpha\pi}{\omega_s} \quad (6)$$

Where α is the magnet coverage, r is the inner radius of the stator, and p is the number of poles of the machine. It is stated that circumferential component of flux density B_c at any point in the yoke changes two times from $-B_{peak}$ to $+B_{peak}$ in each time period. By considering this effect and substituting Eq. 6 into Eq. 2, the eddy current loss in the yoke of BLDC motor can be written as

$$P_{eyc} = \frac{1}{\alpha}\frac{8}{\pi^2}K_e\omega_s^2B_c^2 \tag{7}$$

The complete form of eddy current loss in yoke by considering the effect of normal component of flux density can be written as

$$P_{ey} = \frac{1}{\alpha}\frac{8}{\pi^2}K_eK_r\omega_s^2B_c^2 \tag{8}$$

Where K_r is the eddy current loss due to normal component of flux density in the yoke and is related to motor geometry

$$K_r = 1 + \frac{8K_q d_y^2}{27\alpha q\lambda_2^2} \tag{9}$$

2.3. Hysteresis Loss Model [3, 4]

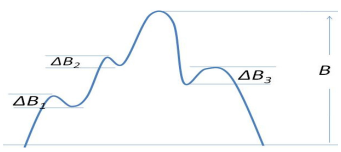
The above model can calculate eddy current loss very accurately but the hysteresis loss calculated from Eq. 1 do not consider minor hysteresis loops. To consider minor hysteresis loops following equation that had been used for hysteresis loss calculation is used in the proposed model for hysteresis loss calculation.

$$P_h = K_hK_{ch}B^{\beta}\omega_s^2 \tag{10}$$

Here K_{ch} is the minor hysteresis loops loss coefficient and is given as [6]

$$K_{ch} = 1.0 + k\frac{1}{B}\sum_{i=1}^{N}\triangle B_i \tag{11}$$

Here k is a constant with value in the range 0.6 to 0.7, B is the maximum value of flux density and $\triangle B_i$ is the variation in flux density as shown in Fig. 2.



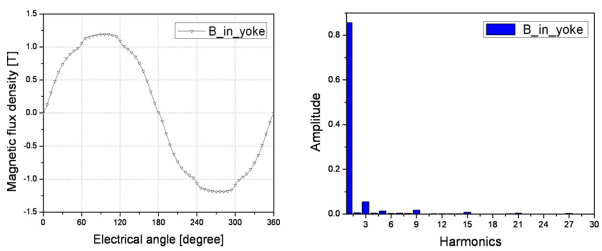
<Fig. 2> Variations in flux density

Hysteresis loss density in the tooth and yoke that is used in the proposed model can be written as

$$P_{ht} = K_hK_{cht}B_{th}^{\beta} \tag{12}$$

$$P_{hy} = K_hK_{chy}B_{yk}^{\beta} \tag{13}$$

Where K_{cht}, K_{chy} are the minor hysteresis loops loss coefficients for the teeth and for yoke respectively, B_{th}, B_{yk} are the tooth and yoke flux density respectively. The BLDC motor designed for the fuel pump has sinusoidal flux density in the tooth whereas yoke has non sinusoidal flux density waveform as shown in Fig. 3(a). The harmonics present in the flux density waveform of yoke are as shown in Fig. 3(b).

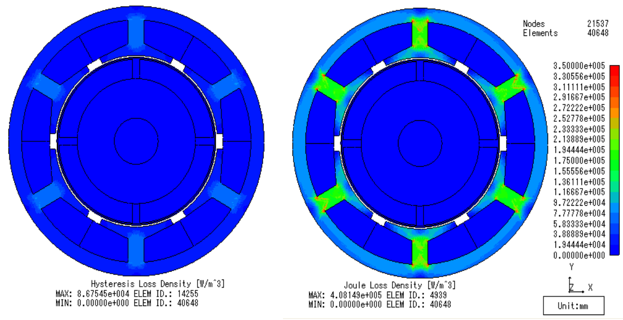


(a) B_c of yoke (b) Components of harmonics

<Fig. 3> Harmonics in B_c of yoke

3. Analysis Results

The various parameters of the experimental motor are shown in Table I. The values of the other parameters taken for this model are k_h=44, β=2.2, k_e=0.04, λ_2=22, k_q=1.14, k_c=1.35, k_{cht}=1.0, k_{chy}=1.44. Fig. 4 shows the hysteresis and eddy current loss densities for fuel type BLDC motor model. Table II shows the comparison of the novel iron loss model with FEM. It shows good consistency between predicted iron losses of novel model and FEM.



(a) Hysteresis loss density (b) Eddy current loss density

<Fig. 4> Distribution of hysteresis and eddy current loss densities by FEM

<Table I> Parameters of the BLDC Motor

Name	Value	Name	Value
outer radius of stator	17.5	tooth width	9.3
thickness of magnet	2.5	yoke width	1.8
yoke flux density	1.2	tooth height	4.6
tooth flux density	1.5	magnet coverage	0.944
tooth volume	0.000000515	inner radius of stator	11.1
yoke volume	0.000005068	air gap length	0.5

<Table II> Results

speed (RPM)	6500	7000	7500	8000	8500
By simplified model(W)	1.03	1.15	1.28	1.42	1.56
By FEM (W)	1.15	1.29	1.44	1.60	1.77
By Novel Model(W)	1.21	1.35	1.49	1.64	1.79

4. Conclusion

A novel iron loss model of BLDC motor was demonstrated in this paper. The novel iron model considered the effects of minor hysteresis loops due to non sinusoidal flux density. The results of the iron loss calculated by novel model in stator teeth and yoke were compared with simplified iron loss model and with FEM. The results showed a good consistency between the novel model and FEM.

[References]

[1] W. Roshen, "Iron loss model for permanent magnet synchronous motors," *IEEE Trans. on Magn.*, vol. 43, no. 52, August 2007.

[2] C. Mi, G. R. Slemon and R. Bonert, "Modelling of iron losses of permanent magnet synchronous motor," *IEEE Trans. Ind. Appl.*, vol. 39, no. 3, May/June 2003.

[3] F. Deng, "An improved iron loss estimation for permanent brushless machines," *IEEE Trans. on Energy Convers.*, vol. 14, no. 4, December 1999.

[4] M. K. Jamil and N. A. Demerdash, "Harmonics and core losses of permanent magnet dc motors controlled by chopper circuits," *IEEE Trans. on Energy Convers.*, vol. 5, no. 2, June 1990.

[5] G. R. Slemon and L.Xian, "Core losses in permanent magnet motors," *IEEE Trans. on Magn.*, vol. 26, pp. 1653-1655, September 1990.

[6] J. D. Lavers, P. P. Biringer and H. Hollitscher, "A simple method of estimating the minor hysteresis loss in thin laminations," *IEEE Trans. on Magn.*, vol. 13, pp. 386-388, September 1978.