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The Estimation Method Comparison of Iron Loss Coefficients through the Iron Loss Calculation

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Abstract – A new calculation method for iron loss coefficients is proposed by using the Steinmetz equation from Epstein data. The hysteresis loss must have linear characteristic according to the frequency. However, the existing iron loss coefficients are defined by formula of frequency. In this case, the hysteresis loss has non-linear characteristics by frequency. So, in this paper, the iron loss coefficients were defined by a function of the magnetic flux density, and the iron loss calculation is applied for Interior Permanent Magnet Synchronous Motor(IPMSM) of 600(W) and 200(W). The iron loss calculation results and the experimental results are compared according to the various materials.

Keywords: IPMSM, Steinmetz equation, New calculation method of iron loss coefficients, Curve fitting method

1. Introduction

The IPMSM can use a reluctance torque. As a result, the torque per unit volume is relatively large and IPMSM has high magnetic flux density. Therefore the iron loss is greater than the other motors. The formulation about iron loss is defined by Steinmetz. But, the research on iron loss is still being done [1]. The residual magnetic flux density of the Permanent Magnet(PM) has been increased and the iron core material has been improved too. Therefore, the previous iron loss coefficients are hard to be applied for recent ferromagnetic material. The existing calculation method of iron loss coefficients assumes that the Steinmetz constant n is unknown quantity. In this paper, it was fixed at 2 by considering enhanced magnetic flux density and iron core material. And, the other coefficients were calculated. So, the new calculation method of the iron loss coefficients is proposed by using the function of magnetic flux density. The coefficients calculation method was verified through experimental value of 600(W) and 200(W) class motor.

2. Application Model

As shown in Fig. 1, IPMSM of 600(W) and 200(W) class was used to calculate the iron loss. The specifications of the two models are described in Table 1. The 600(W) IPMSM used electrical steel 50PN1300 at iron core. In order to reduce the iron loss, 200(W) IPMSM used 50PN800 at iron core.

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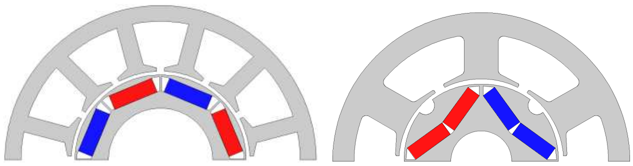


(a) 600(W) class (b) 200(W) class

Fig. 1. The shape of the applied model

Table 1. Specifications of the applied model

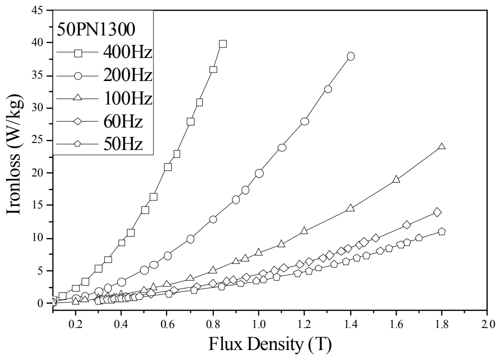
Item	Specification	
	600(W)	200(W)
Material	50PN1300	50PN800
Pole/Slot	8/12	4/6
Rated Speed(rpm)	3000	
Operating Frequency(Hz)	200	100
Br(T)	1.3	1.07
Stack Length(mm)	45	
Stator Diameter(mm)	83.6	83
Phase Resistance(Ω)	0.0235	0.15

3. The Existing Method of Iron Loss Coefficients Calculation

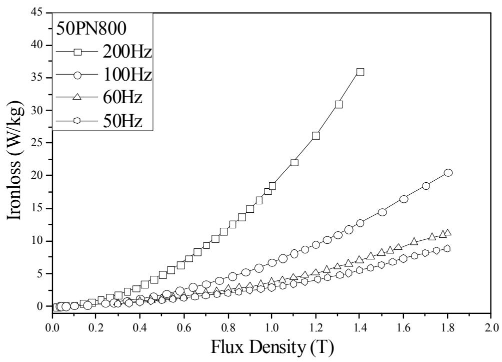
Generally, the Steinmetz equation of iron loss is given as in (1).

$$W_i = W_h + W_e + W_a = k_h f B_m^{\ n} + k_e f^2 B_m^{\ 2} + k_a f^{1.5} B_m^{\ 1.5} \quad (1)$$

where, f is the frequency of the external magnetic field, B_m is the maximum value of magnetic flux density, k_h is the hysteresis loss coefficient, k_e is the eddy current loss coefficient, k_a is the abnormal eddy current loss coefficient, and n is the Steinmetz constant [2].



(a) 50PN1300



(b) 50PN800

Fig. 2. Epstein data by the manufacturer

Eq. (1) responds rapidly to the eddy current loss term, but it does not correspond to hysteresis loss term by in the increased magnetic flux density in the core material and PM. Therefore, the Steinmetz constant is fixed to 2. Because, the magnetic flux density was increased by improvement of the PM and iron core material in electrical machine. Eventually, the other coefficients were estimated. In conclusion, the numerical formula of iron loss can be obtained by (2).

$$W_i = W_h + W_e + W_a = k_h f B_m{}^2 + k_e f^2 B_m{}^2 + k_a f^{1.5} B_m{}^{1.5} \quad (2)$$

The provided Epstein data from the manufacturer are shown in Fig. 2. It did not contain the required information by magnetic flux density and frequency. So, the iron loss must be recalculated from the desired frequency band by using the provided data. The Curve Fitting Method(CFM) and iron loss calculation of IPMSM were performed on the basis of the provided Epstein data. The estimated coefficients were satisfied at 50(Hz), 60(Hz), 100(Hz) and 200(Hz). Therefore, the iron loss coefficients were estimated up to the 20th harmonic of operating frequency. The calculation result was obtained by summation of harmonic components in iron loss. The Table 2 shows the iron loss coefficient fitting results according to frequency.

Table 2. Calculation results of iron loss coefficients according to the frequency

Function : $y=A\cdot f^B$				
Coefficients	50PN1300		50PN800	
	A	B	A	B
k_h	0.06253	-0.1155	0.05	-0.266
k_e	0.00051	-0.1134	0.001955	-0.3673
k_a	0.03414	-0.7477	0.000513	0.2127

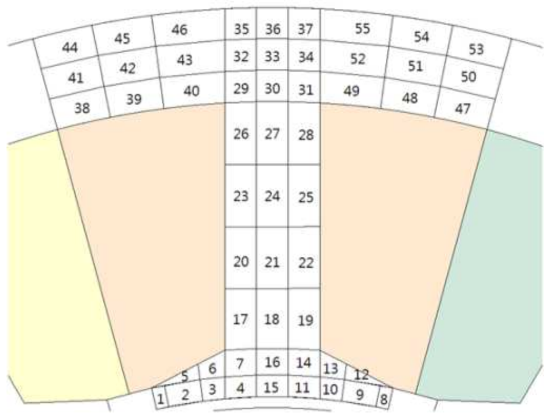


Fig. 3. Divided stator core shape

For the calculation of the iron loss, the flux density was calculated through the FEM by dividing one stator teeth into 55 areas, as shown in Fig. 3. In this paper, the driving frequency is 200 [Hz]; the magnetic flux density in the yoke and the teeth was calculated by using the finite element method from the iron loss data of 50PN1300 [3].

The estimated coefficients of Table 2 were inserted in (2). Thus, the calculated iron loss results and loss ratio were shown in Tables 3~6.

In operating frequency, hysteresis loss is 20%~30%,

Table 3. Iron loss calculation results in 600(W); CFM

(Hz)	W_h(W)	W_e(W)	W_a(W)	W_i(W)cal	W_i(W)exp
50	2.76	1.30	0.84	4.90	3.02
60	3.24	1.83	0.96	6.05	5.46
100	5.10	4.82	1.41	11.33	9.30
120	5.99	6.80	1.62	14.41	13.88
150	7.29	10.36	1.92	19.58	19.04
200	9.41	17.83	2.38	29.62	28.35

W_i(W)cal : calculation data, W_i(W)exp : experimental data

Table 4. Iron loss ratio calculation results in 600(W); CFM

(Hz)	W_h(%)	W_e(%)	W_a(%)
50	56.27	26.57	17.14
60	53.64	30.41	15.95
100	44.96	42.53	12.50
120	41.54	47.17	11.27
150	37.26	52.91	9.81
200	31.76	60.18	8.05

eddy current loss is 60%~70%, and abnormal eddy current losses is 10% in the total iron loss[4, 5]. As shown in (1), Steinmetz constant should be estimated and set as a variable. However, the proposed method of this paper, Steinmetz constant value was fixed, and other coefficients were estimated more accurately. Steinmetz constant was fixed, and the three coefficients were calculated. This result has a strong resemblance to an iron loss aspect of rotating

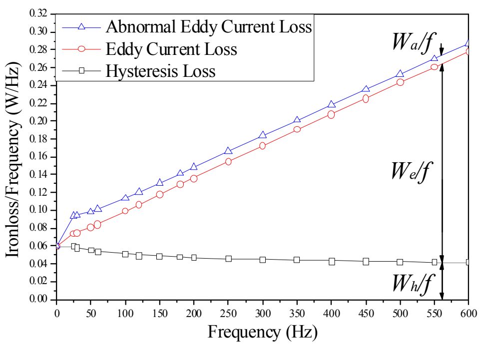
Table 5. Iron loss calculation results in 200(W); CFM

(Hz)	W_h(W)	W_e(W)	W_a(W)	W_i(W)cal	W_i(W)exp
50	1.44	2.17	1.09	4.69	4.82
60	1.65	2.92	1.48	6.05	5.78
70	1.85	3.75	1.93	7.53	6.58
80	2.04	4.66	2.43	9.13	7.51
90	2.22	5.65	2.97	10.85	9.01
100	2.40	6.71	3.56	12.67	10.58

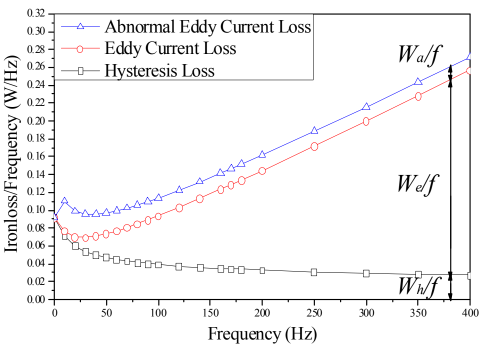
W_i(W)cal = calculation data, W_i(W)exp = experimental data

Table 6. Iron loss ratio calculation results in 200(W); CFM

(Hz)	W_h(%)	W_e(%)	W_a(%)
50	30.76	46.11	23.13
60	27.29	48.19	24.53
70	24.55	49.80	25.66
80	22.33	51.07	26.60
90	20.49	52.11	27.40
100	18.95	52.97	28.08



(a) 600(W) class



(b) 200(W) class

Fig. 4. The aspect of the iron loss divided by the frequency (CFM)

machinery. Table 4, 6 shows the calculation results of hysteresis loss and eddy current loss ratio.

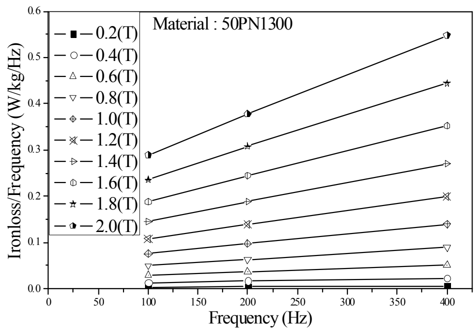
The calculation values were analyzed. As a result, the abnormal eddy current losses according to increasing frequency were reduced at 600(W) class motor, on the other hand, that was increased at 200(W) class motor. The difference between the calculation and experimental results is similar in Table 3, 5. But, the results are different with an aspect of abnormal eddy current loss of (2).

Fig. 4 shows results of iron loss divided by frequency [6]. In this case, the hysteresis loss should have a constant value according to the frequency. But, the hysteresis loss was reduced, because iron loss coefficients were defined as a function of frequency. To compensate the reduction of the loss, the iron loss coefficients were expressed by function of magnetic flux density in this paper.

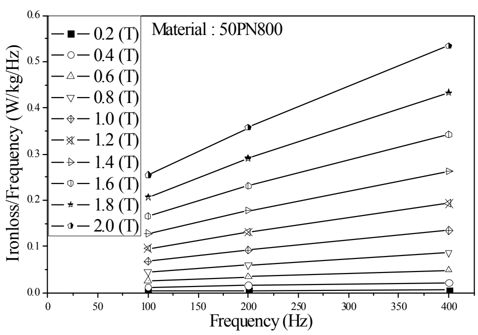
4. The Proposed Method of Iron Loss Coefficients Calculation

Fig. 5 shows Epstein data divided by frequency [1].

The iron loss coefficients were estimated for each magnetic flux density. That result was expressed for iron loss coefficients versus magnetic flux density. By using the calculated results of existing method of iron loss coefficients calculation, Each loss divided by frequency. As

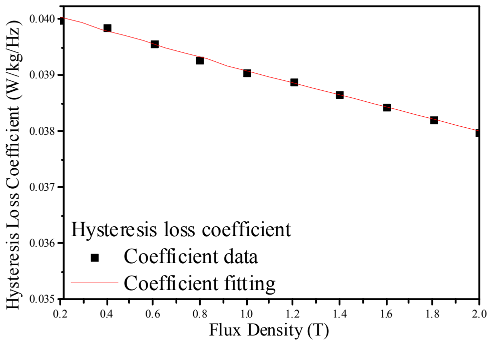


(a) 600(W) class

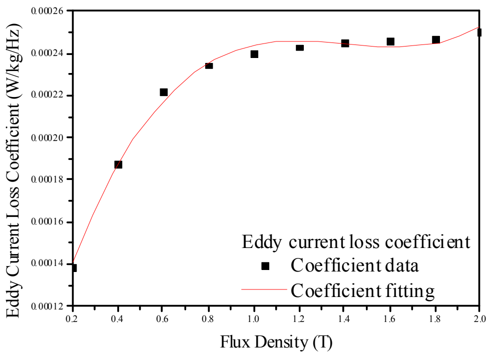


(b) 200(W) class

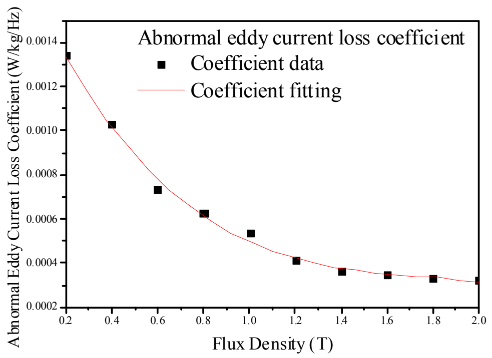
Fig. 5. The result of iron loss according to frequency at each magnetic flux density



(a) hysteresis Loss Coefficient



(b) eddy Current Loss Coefficient



(c) abnormal Eddy Current Loss Coefficient

Fig. 6. Iron loss coefficients calculation according toflux density(50PN1300)

a result, the hysteresis loss was reduced, as shown in Fig. 4, because iron loss coefficients were defined as a function of frequency. To solve the problem, the iron loss coefficients were expressed by function of magnetic flux density as shown in (3)~(5). Then, the results can be represented as Fig. 6 [1]. The same process was applied to IPMSM of 200(W) class motor.

$$k_h = k_{h_0} + k_{h_1} \cdot B_m + k_{h_2} \cdot B_m{}^2 + k_{h_3} \cdot B_m{}^3 \qquad (3)$$

$$k_e = k_{e_0} + k_{e_1} \cdot B_m + k_{e_2} \cdot B_m{}^2 + k_{e_3} \cdot B_m{}^3 \qquad (4)$$

$$k_a = k_{a_0} + k_{a_1} \cdot B_m + k_{a_2} \cdot B_m{}^2 + k_{a_3} \cdot B_m{}^3 \qquad (5)$$

5. The Iron Loss Comparison of Experimented and Calculated Results

The iron loss experiment was performed through the process outlined in Fig. 7. And Fig. 8 shows the iron loss experiment system. So, power analyzer is 99.5% accurate. Variation of copper loss was considered by measuring the input power and current from the inverter to the operating motor. A non-magnetized model was manufactured to measure the mechanical loss.

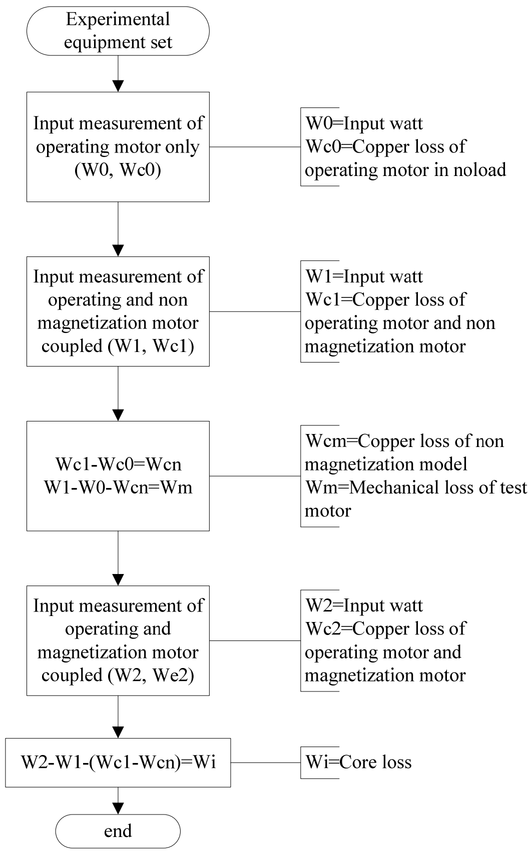


Fig. 7. Process for an iron loss experiment

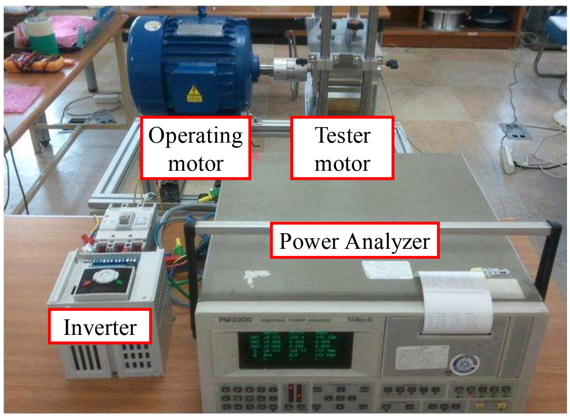


Fig.8. Iron loss experiment equipment

Table 7, 9 shows the results of calculation value and experimental value in 600(W) and 200(W). Experimental value and calculation value was compared. The error between experimental value and calculation value was 0.45(W) at operating frequency of 600(W) class motor. And the error of 200(W) class motor was 0.5(W) at the operating frequency.

The abnormal eddy current loss ratio was increased. However, it shows decreasing aspect at the specific frequency. Because, the iron loss was divided by frequency and the abnormal eddy current was a root function about frequency. Those results are shown in the Table 8, 10.

The iron loss of (2) was divided by frequency, and the hysteresis loss has a constant value about the frequency. Consequentially, the iron loss coefficients were defined by

Table 7. Iron loss calculation results in 600(W); cubic function

(Hz)	W_h(W)	W_e(W)	W_a(W)	W_i(W)cal	W_i(W)exp
50	2.69	0.90	0.44	4.04	3.02
60	3.23	1.30	0.58	5.12	5.46
100	5.39	3.62	1.26	10.26	9.30
120	6.47	5.21	1.65	13.33	13.88
150	8.08	8.14	2.31	18.53	19.04
200	10.78	14.47	3.55	28.80	28.35

W_i(W)cal : calculation data, W_i(W)exp : experimental data

Table 8. Iron loss ratio calculation results in 600(W); cubic function

(Hz)	W_h(%)	W_e(%)	W_a(%)
50	66.66	22.36	10.98
60	63.17	25.43	11.40
100	52.52	35.24	12.23
120	48.54	39.08	12.38
150	43.63	43.92	12.45
200	37.43	50.24	12.33

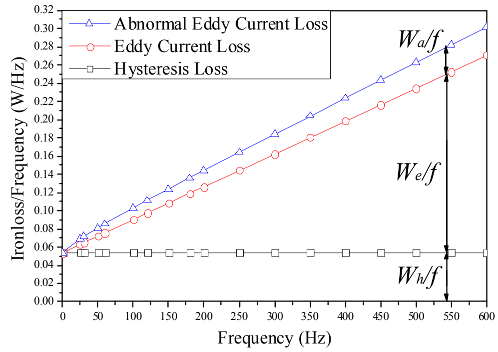
Table 9. Iron loss calculation results in 200(W); cubic function

(Hz)	W_h(W)	W_e(W)	W_a(W)	W_i(W)cal	W_i(W)exp
50	2.40	1.20	0.52	4.12	4.82
60	2.88	1.74	0.68	5.30	5.78
70	3.36	2.36	0.86	6.58	6.58
80	3.84	3.08	1.05	7.97	7.51
90	4.32	3.90	1.26	9.47	9.01
100	4.79	4.82	1.47	11.08	10.58

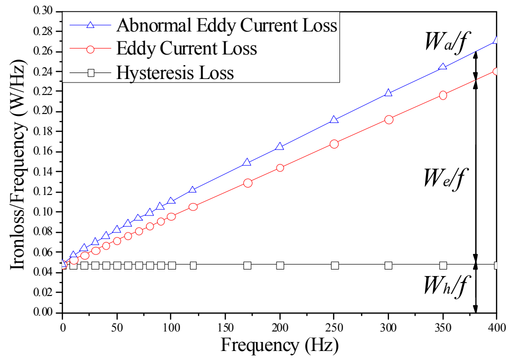
W_i(W)cal = calculation data, W_i(W)exp = experimental data

Table 10. Iron loss ratio calculation results in 200(W); cubic function

(Hz)	W_h(%)	W_e(%)	W_a(%)
50	58.16	29.23	12.61
60	54.33	32.77	12.90
70	51.01	35.90	13.09
80	48.11	38.69	13.19
90	45.55	41.21	13.25
100	43.25	43.48	13.26



(a) 600(W) class



(b) 200(W) class

Fig. 9. An aspect of the iron loss by the frequency (cubic function)

function of the magnetic flux density. As a result, iron loss analysis results were different from those of Fig. 4. The results are shown in Fig. 9.

6. Conclusion

In this paper, the new estimation method of iron loss coefficients were proposed and iron loss was calculated by using proposed method. So, calculation results of iron loss were verified from comparison of experimental and calculation value.

At the existing calculation method of iron loss coefficients, iron loss coefficients were defined as a function of frequency. As a result, the hysteresis loss $W_h$divided by frequency f and the results W_h/f was reduced about increasing frequency, as shown in Fig. 4. This is because the iron loss coefficients k was defined as a function of frequency. To solve the problem, the iron loss coefficients k were proposed by function of magnetic flux density. And the calculated results of the iron loss, the hysteresis loss W_h was divided by frequency f. As a result, W_h/f has a constant value about the frequency, as shown in Fig. 9.

And, the iron loss by using proposed method, 600(W) class motor has hysteresis loss components of 37.43%, eddy current loss components of 50.24% and abnormal eddy current loss components of 12.33%. 200(W) class motor has hysteresis loss components of 43.25%, eddy current loss components of 43.48%, abnormal eddy current loss components of 13.26%. In conclusion, computation results well agreed with classically loss components ratio as widely known in existing iron loss calculation method.

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