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The Iron loss Estimation of IPMSM According to Current Phase Angle

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Abstract – Variable iron loss as function of current phase angle of Interior Permanent Magnet Synchronous Motor(IPMSM) was calculated through Curve Fitting Method(CFM). Also, a magnetic flux density distribution of iron core according to current phase angle was analyzed, and an iron loss calculation was performed including harmonic distortion. The experiment was performed by production of non-magnetizing model for the separation of mechanical loss, and the iron loss was calculated by the measurement of input using power analyzer and output power using dynamometer. Some error was generated between experimental results and calculation value, but an iron loss diminution according to current phase angle followed a same pattern. So, errors were generated by measurement, vibration, noise, harmonic distortion loss, etc.

Keywords: Iron loss, Current phase angle, Curve Fitting Method, Torque, Total error losses

1. Introduction

Generally, iron loss is usually known as the no-load loss in electrical machine. But, iron loss was changed due to control strategy as id=0, Maximum Torque Per Ampere (MTPA), maximum efficiency control and maximum power factor according to the current phase angle [1, 2]. The formula of iron loss depends on magnetic flux density, and d-axis current has an effect on magnetic flux density distribution in iron core [3, 4]. The iron loss current was increased by increasing iron loss, but total torque decreased. Therefore, the iron loss variation should be considered in d, q-axis equivalent circuit of IPMSM.

In this paper, the iron loss was closely calculated from Finite Elements Method(FEM) according to current phase angle by magnetic flux density. And, the direct measurement of iron loss was very difficult. At measurement of input and output powers, a very small amount of loss was always presented. Therefore, in this paper, the input was measured by power analyzer, and output was measured by dynamometer. And then, output power, copper loss and mechanical loss were left out of the input power. On the assumption that the remaining losses were composited by the iron loss and total error losses. The total error losses were measured error, vibration, noise, harmonic distortion of current and voltage losses, etc.

2. Iron Loss

The iron loss is calculated from iron loss coefficients by Curve Fitting Method(CFM). The estimation on the iron loss coefficients were performed by FEM and magnetic field variation of iron core [5, 6].

Fig. 1 shows comparison of analyzed value and experimental value. The numerical formula of iron loss can be obtained by (1).

$$W_i = k_h \cdot f \cdot B_m^2 + k_e \cdot f^2 \cdot B_m^2 + k_a \cdot f^{1.5} \cdot B_m^{1.5} \quad (1)$$

where k_h is the hysteresis loss coefficient, k_e is eddy-current coefficient, k_a is abnormal eddy-current loss, f is operating frequency, B_m is maximum value of magnetic flux density.

Fig. 2 shows the result of linkage flux by FEM and iron loss at rated current and rated speed.

The iron loss by current phase angle was slowly decreased from current phase angle 0°. The d-axis current was affected on total linkage flux on the direction of shrinkage. If current phase angle increased, d-axis current

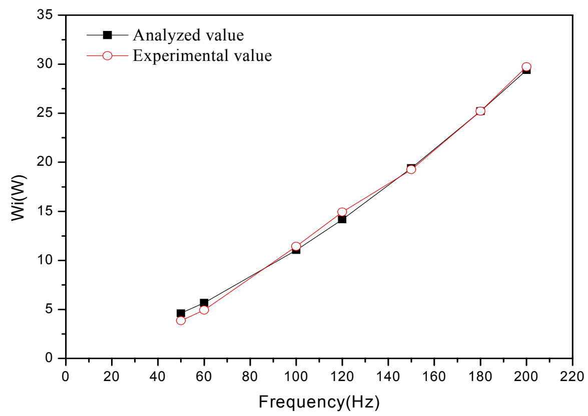

Fig. 1. The comparison of analyzed value and experimental value at no-load

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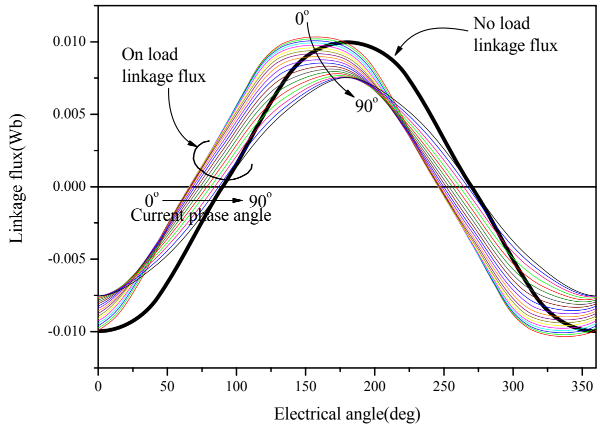
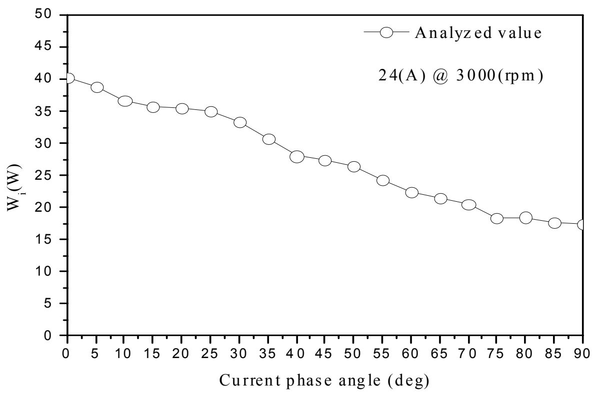


(a) Linkage flux



(b) Iron loss by current phase angle

Fig. 2. The variable linkage flux and calculation of iron loss

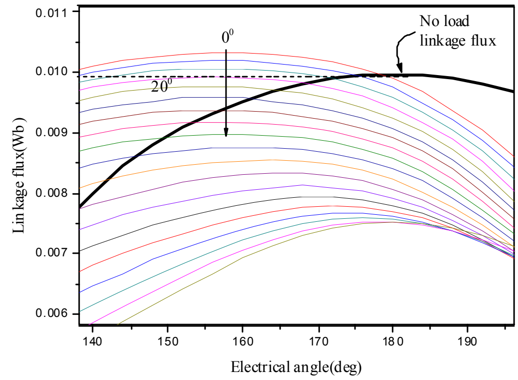
also increased. So, an iron loss was decreased by reduction of magnetic flux density of iron core.

3. Iron Loss According to Current Phase Angle

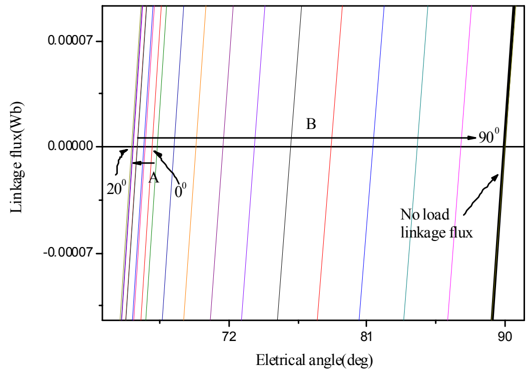
Generally, an iron loss is usually known as the no-load loss in electrical machine. But the iron loss can be change by current in IPMSM. Because, the magnetic flux density of iron core was increased by composition of a permanent magnet flux and a flux by current.

Fig. 3 shows the increased linkage flux at a flow of current. The linkage flux at current phase angle 0° was larger than no-load linkage flux like as Fig. 3(a). The linkage flux and iron loss have the same magnitude as no-load linkage flux at current phase angle 20°. Fig. 3(b) shows linkage flux according to current phase angle. The gap between no-load linkage flux and total linkage flux were increased in 0° to 20° like as A, but it slowly decreased after current phase angle 20° like as B.

Fig. 4 shows separation of teeth by 55 elements for an iron loss calculation. The source of increasing iron loss was analyzed by comprising the magnetic flux density at no-load and current flow on circle marks [6].



(a) linkage flux



(b) phase angle of linkage flux

Fig. 3. Magnitude and phase of linkage flux

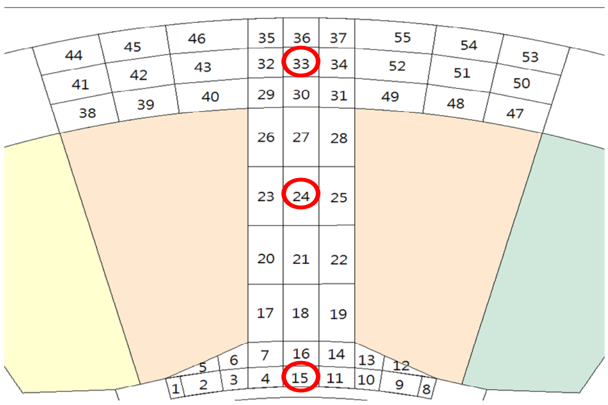
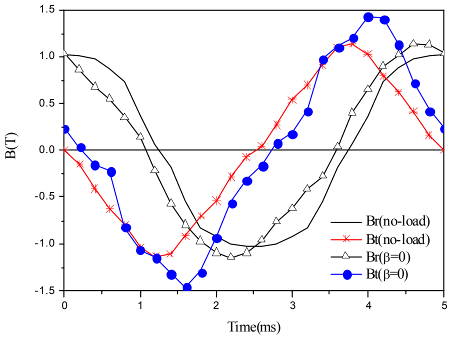
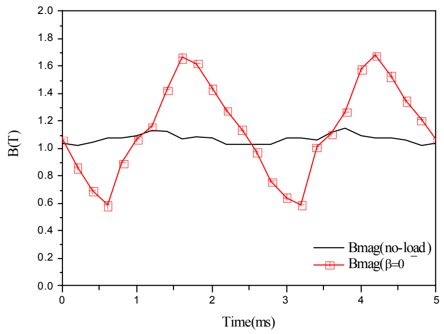


Fig. 4. Separations of stator teeth

Figs. 5-7 shows magnetic flux density of radial direction and tangential direction. The radial and tangential magnetic flux density was increased in point 15 and 33. These points are the rotating magnetic field. Here, β is current phase angle. So, magnitude of magnetic flux density was largely increased than no-load case, because magnitude of magnetic flux density was calculated from summation of square of radial and tangential magnetic flux density [7, 8]. The point 24 is an alternating field. The phase of magnetic flux density was changed due to current, and it magnitude

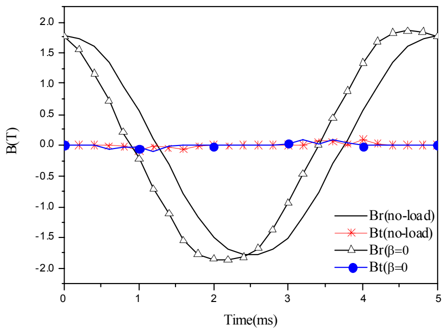


(a)

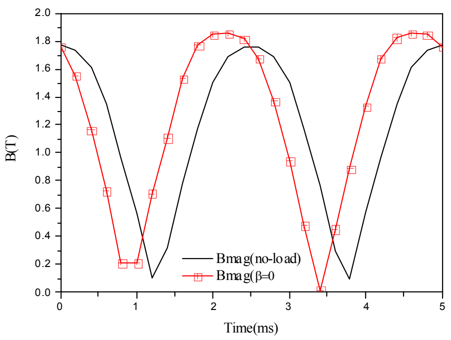


(b)

Fig. 5. Flux density pattern of point 15: (a) comparison of flux density components; (b) comparison of flux density magnitude

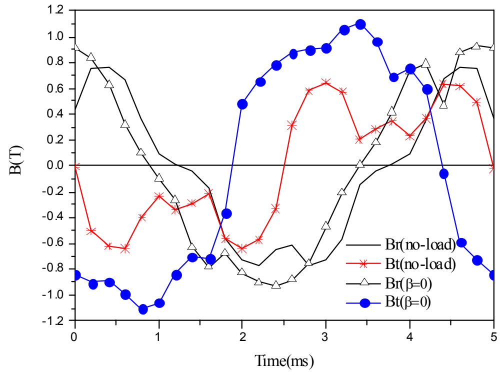


(a)

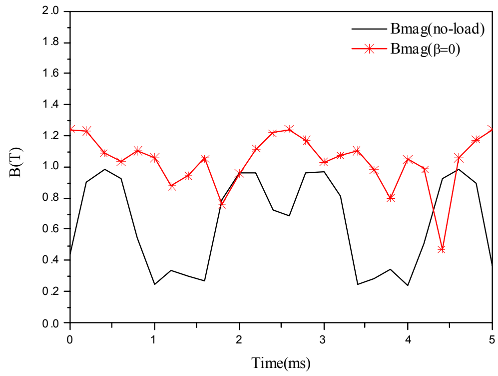


(b)

Fig. 6. Flux density pattern of point 24: (a) comparison of flux density components; (b) comparison of flux density magnitude



(a)



(b)

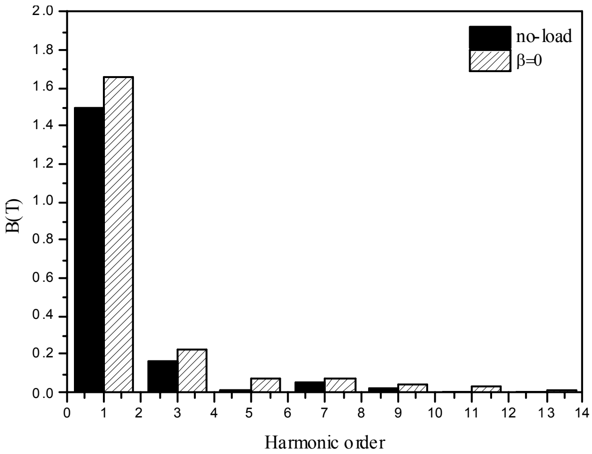
Fig. 7. Flux density pattern of point 33: (a) comparison of flux density components; (b) comparison of flux density magnitude

was increased. As a result, the iron loss was increased, because the iron core magnetic flux density of current phase angle 0° was larger than no-load magnetic flux density [9].

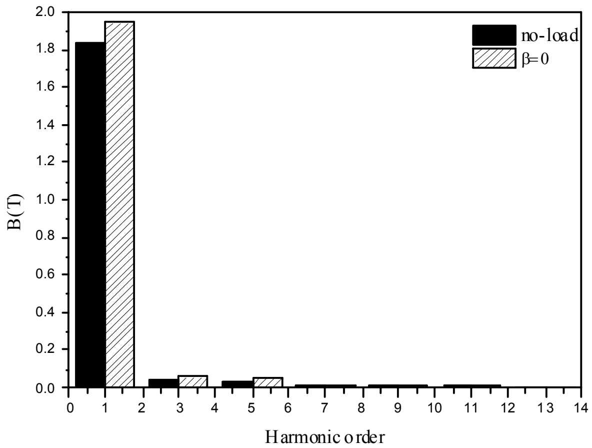
Fig. 8 shows Fast Fourier Transform(FFT) of magnetic flux density in each point. The fundamental component was increased, and the iron loss was calculated from (2) considering of harmonic distortion.

$$
\begin{aligned}
W_h &= \int_{iron} \sum_{n}^{M} k_h \cdot (nf) \cdot \left\{ \sqrt{B_{r,n}^2 + B_{t,n}^2} \right\} dv \\
W_e &= \int_{iron} \sum_{n}^{M} k_e \cdot (nf)^2 \cdot \left\{ \sqrt{B_{r,n}^2 + B_{t,n}^2} \right\} dv \\
W_a &= \int_{iron} \sum_{n}^{M} k_a \cdot (nf)^{1.5} \cdot \left\{ \sqrt{B_{r,n}^{1.5} + B_{t,n}^{1.5}} \right\} dv \\
W_i &= W_h + W_e + W_a
\end{aligned}
\tag{2}
$$

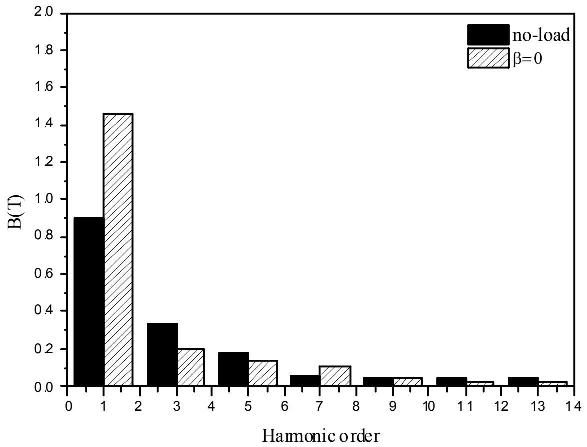
The iron loss was increased, 34.4% in P15, 12.9% in P24 and 30.3% in P33. Obviously, iron loss was changed by magnetic flux density in 55 elements at a flow of current.



(a) point 15



(b) point 24



(c) point 33

Fig. 8. FFT of magnetic flux density

4. Experimental Verification

The iron loss is measured in Fig. 1, which does not magnetize the permanent magnet, and the mechanical loss is measured at the rated speed. In no-load input of the test motor at the same speed, the iron loss was measured by excluding the mechanical loss.

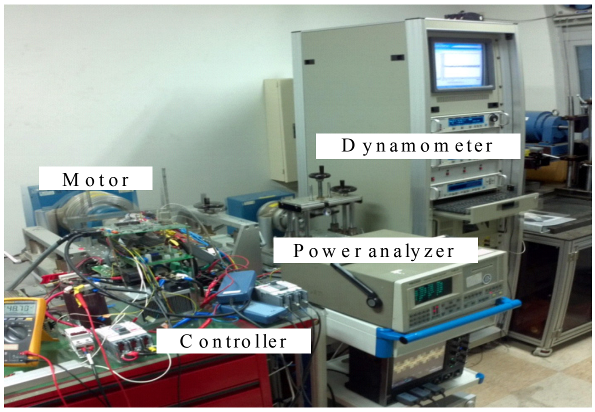


Fig. 9. Experimental equipment

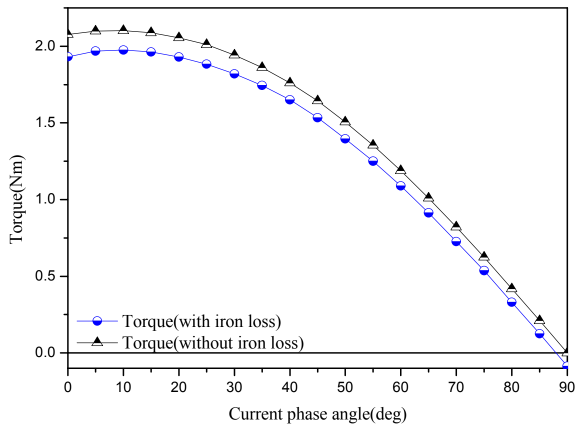


Fig. 10. Generated torque in consider of iron loss

Fig. 9 shows torque experimental equipment. The torque and speed were measured by dynamometer. The torque was measured at current phase angle 7°, 27°, 47° and 67°.

Fig. 10 shows variation of total torque. The torque was decreased by a rising iron loss. Because, q-axis current was decreased by an iron loss current. So, precise estimation of iron loss is very important in torque calculation.

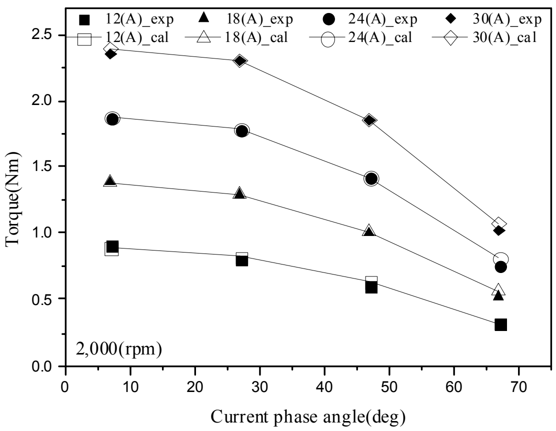
Fig. 11 shows experimental result of torque. The torque calculation was performed by voltage equation of IPMSM [10]. The iron loss was calculated by CFM of magnetic flux density in the iron core. The iron loss analysis in the previous study was carried out in advance paper [11].

The torque was changed. Because the q-axis current was decreased by the variation of iron loss. So, the torque estimation was affected by the iron loss calculation. The maximum error was generated 4.5% at current phase angle 67°. The vibration and noise according to rising current phase angle were a cause of error. But, another current phase angle does not have error nearly.

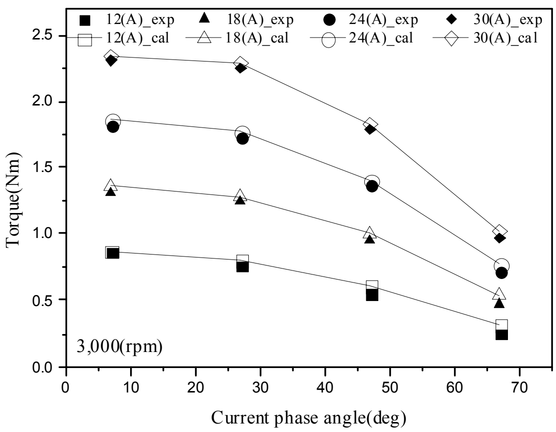
The direct measurement of iron loss was very difficult. At measurement of input and output powers, a very small amount of loss was always presented. Therefore, in this paper, the input was measured by power analyzer, and output was measured by dynamometer. And then, output power, copper loss and mechanical loss were left out of the input power. So, the remaining losses were composited by the iron loss and total error losses [12, 13]. The total error losses were measured error, vibration, noise, harmonic component loss, etc. The numerical formula of loss composition can be obtained by (3).

$$W_i + W_{er} = W_{In} - W_{out} - W_c - W_m \qquad (3)$$

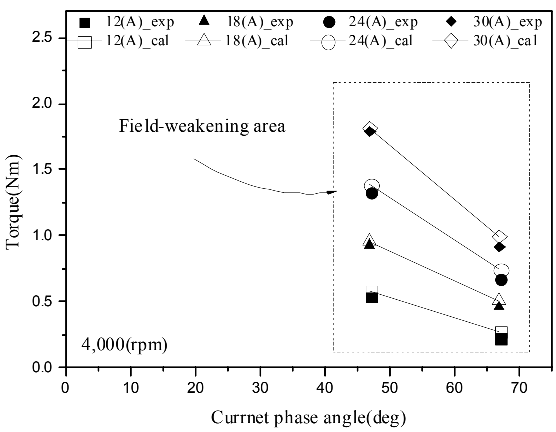
here, W_{In} is input power, W_{out} is output power, W_c is the



(a) 2,000(rpm)

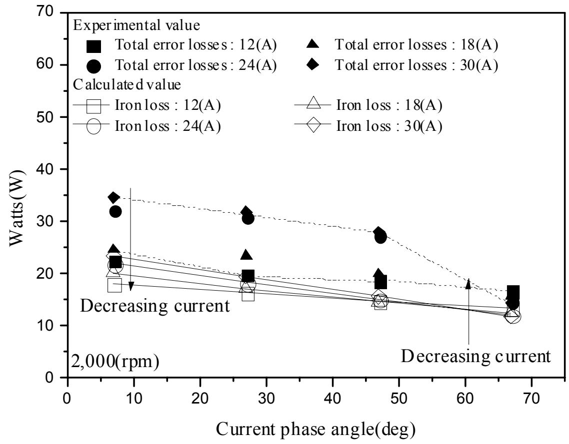


(b) 3,000(rpm)

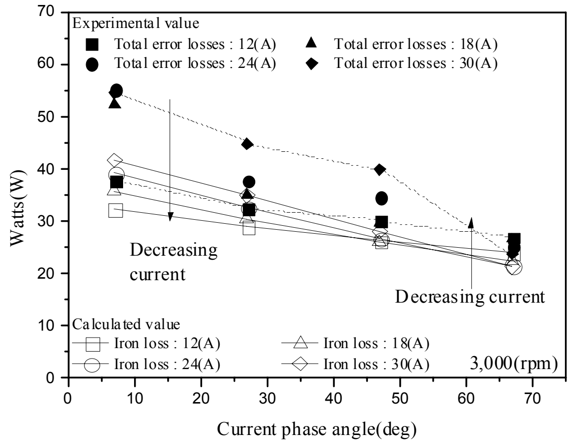


(c) 4,000(rpm)

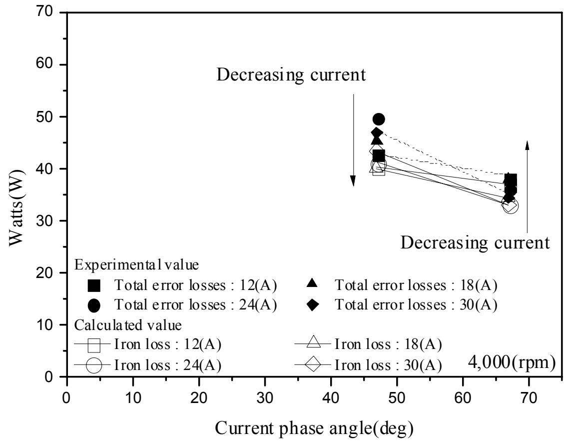
Fig. 11. Comparison of torque



(a) 2,000(rpm)



(b) 3,000(rpm)



(c) 4,000(rpm)

Fig. 12. Measured total error losses and calculated iron loss

copper loss, W_m is the mechanical loss, W_i is the iron loss, W_{er} is total error losses.

Fig. 12 shows the measured total error losses and the calculated iron loss. The maximum error was 15(W) between measured total error losses and the calculated iron loss. However it has almost no effect on torque like as torque experimental result.

Most importantly, the maximum and minimum values of the calculated iron loss were reversed at specific current phase angle. Also, the measured total error losses were showed the same pattern. So, measured total error losses include the iron loss.

So, in this paper, the aspect of iron loss variation according to current phase angle was measured by the total error losses.

5. Conclusion

Generally, an iron loss is usually better known as the no-load loss in electrical machine. But an iron loss was changed by current phase angle variation, because a linkage flux was changed by magnetic flux density of iron core.

In iron loss calculation, the iron loss coefficients were calculated by CFM, and magnetic flux density of iron core was calculated by FEM. The iron loss was stepwise decreased according to a rise of d-axis current.

In this paper, the torque including the iron loss was calculated and experimented. So, the torque does not have error nearly. And, the direct measurement of iron loss was very difficult. Therefore, the total error was measured for estimation of the iron loss. As a result, the maximum error was 15(W) between measured total error losses and the calculated iron loss. However it has almost no effect on torque like as torque experimental result.

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