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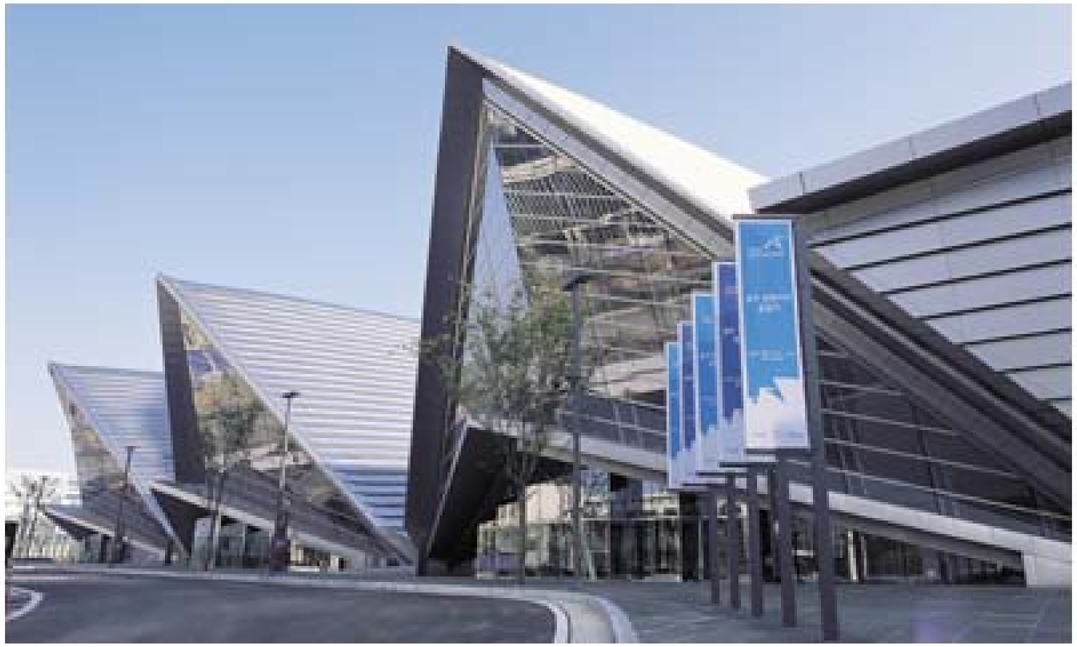

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Jung-Pyo Hong

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- Reduction Eddy Current Loss Design and Analysis of In-Wheel Type Vehicle Traction Motor

Reduction Eddy Current Loss Design and Analysis of In-Wheel type Vehicle Traction Motor

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Abstract — This paper deals with a method for reduction of eddy current loss in permanent magnet for high power in-wheel type motor applicable to electric vehicle traction. The In-Wheel type motor was built before this paper written. However, it has a problem of eddy current loss in permanent magnet. Therefore, this paper presented the eddy current loss reduction design in permanent magnet and analysis of in-wheel type vehicle traction motor. Rotor shape design for eddy current reduction and eddy current loss according to segmentation of permanent magnet are presented. Presented design approaches, dramatic reduction of eddy current in permanent magnet is achieved. 2D-FEM is used for rotor shape design and 3D –FEM is used for eddy current loss analysis.

I. Introduction

These days, a great interest is focused on more efficient and reliable propulsion systems of electric vehicles because of an exhaustion of petroleum resources and environmental problems. In-Wheel motor receives a lot of favorable attention as a new structure which satisfies this environment-friendly technology. If an In-Wheel motor system is applied as the power system of electric vehicles, the transmission composed of many components can be eliminated. Thus, the transmission losses are minimized, and the operation efficiency and reliability is improved[1].

The Model of In-Wheel type motor was designed before. Interior Permanent Magnet (IPM) type motor which has high efficiency and high durability was selected[2]. But it has problem that eddy current is occur as shown in Fig. 1. The eddy current is induced in the permanent magnets of machines is often neglected. However, this assumption may not always be justified. The eddy current in traction motor having a large output power make the eddy current loss a non negligible. And the eddy current causes demagnetization, because it is irreversible heat dissipation in the motor system. So, this paper deals with design and analysis of the eddy current loss reduction for In-Wheel type vehicle traction motor. Rotor design is optimized for reducing eddy current loss. Characteristic analysis, response surface methodology and 3D finite element method in consideration of eddy current loss reduction is used for designing In-Wheel motor.

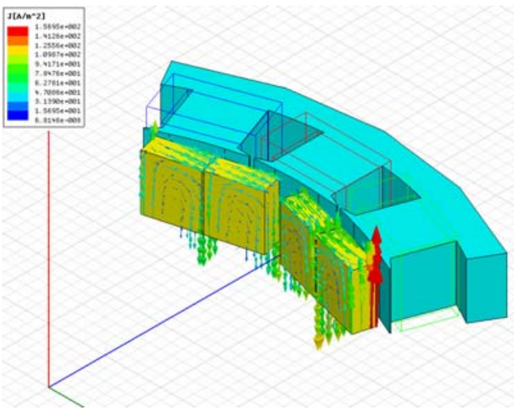

Fig. 1. Eddy Current Vectors in Permanent magnet at 1250rpm

TABLE I
PARAMETERS OF IN-WHEEL TYPE VEHICLE TRACTION MOTOR

Parameter	
Pole number	12
Slot number	18
Stack length	50 *mm*
DC link voltage	300 V_{DC}
Max./rated output power	25/10 *kW*
max./base speed	5000/1250 *rpm*
Current limit	212.1 A_{rms} (300 A_{peak})
Operating temperature	100 ℃
Eddy current loss	2.3 *kW @5000rpm*

II. Design Model

A. Analysis model

The prototype model is IPMSM which applied in In-Wheel type vehicle traction motor. Table I shows the motor parameters of prototype In-Wheel type vehicle traction motor. It has a maximum output power about 25kW. In high speed range, maximum 5000rpm, the eddy current loss is 2.3kW. As show in Fig. 3(a), there is the prototype of rotor shape.

B. d-q axis equivalent circuit analysis

In order to calculate characteristics of IPMSM, d-q equivalent circuit analysis is employed. Equivalent circuit frame including iron loss are presented Fig 2. The mathematical model of the equivalent circuits is given as follow equations. Iron loss is considered by equivalent resistance R_c, and the d- and q-axis voltages and effective torque equations are given by (1), (2) and (3), respectively. Where i_d and i_q are d- and q-axis component of armature current, i_{cd} and i_{cq} are d-and q-axis component of terminal

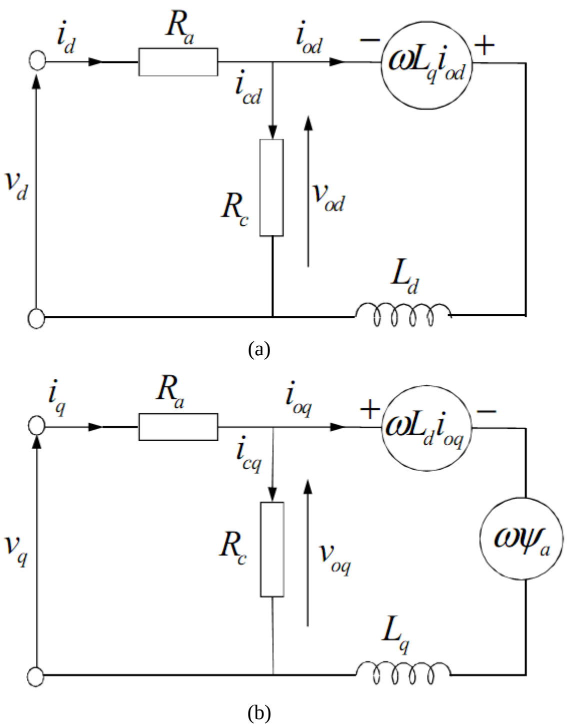

Fig 2. Equivalent circuits of IPMSM. (a) d-axis equivalent circuits. (b) q-axis equivalent circuits.

voltage, R_a is armature winding resistance per phase, R_c is iron loss resistance, Ψ_a is flux linkage of permanent magnet per phase (rms value), L_d and L_q are d-and q-axis armature self inductance, and P_n is pole pair [3].

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1+\frac{R_a}{R_c}\right)\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \quad (2)$$

$$T = P_n\left\{\psi_a i_{oq} + (L_d - L_q) i_{od} i_{oq}\right\} \quad (3)$$

III. RELATIONSHIP BETWEEN EDDY CURRENT LOSS AND FLUX VARIATION IN PERMANENT MAGNET.

Eddy current is generated by variation of magnetic flux in the conductor. It has problem that eddy current is occur as shown in Fig. 1. Actually, 10% of output power is dissipated while operating motor as shown in Table I. It causes a rise in temperature and the eddy current loss which does not satisfy output power and environment-friendly technology. Eddy current loss is proportional to the square of frequency and peak-peak quantity of flux variation. The frequency of the flux variation per pole is determined by the combination of pole and slot number. However, peak-peak value of flux variation can be minimized by the change of geometry of the motor.

In order to verify the relationship between eddy current loss and flux variation in Permanent Magnet, specific model is analyzed. Fig. 3(b) shows the shape of rotor core which is designed for reduction of eddy current loss in Permanent Magnet. The V-shape of rotor core between poles helps the reduction of flux variation in Permanent Magnet. Angle (A) and depth (B) of V-shape are selected as design variable[3]. It shows that eddy current loss and flux variation in PM according to design variable is changed almost same direction. Therefore, linear correlation exists between eddy current loss and squire of flux variation in Permanent Magnet[4][5].

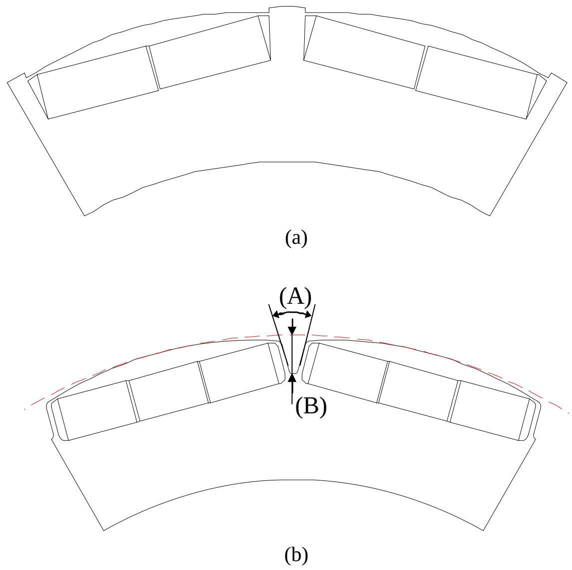

Fig 3. The rotor shape of In-wheel traction motor. (a) prototype of rotor. (b) rotor designed for reduction of eddy current loss in PM.

Therefore, we analyze and redesign the rotor shape optimized, reducing this eddy current loss. In Fig. 2, there are methods used reducing eddy current. There are three methods reducing it. First, V-shape rotor core optimization using RSM(Response surface method). V-shape in rotor core between one pole to opposite pole reduced eddy current loss, because RSM is used to find optimum value of each parameter which are selected to have influence on loss[3]. Optimum design is validated by comparison of eddy current loss with initial model using 3D transient analysis.

IV. RELATIONSHIP BETWEEN EDDY CURRENT LOSS AND PARTITION OF PERMANENT MAGNET

In large motors, the permanent magnet in the motor is segmented into parts in order to reduce the eddy current loss in permanent magnet. In this paper, the effects of number of segments of magnet, exciting frequency and contact resistance between magnets on the eddy current loss of the magnet are investigated. Eddy voltage induced by variation of magnetic field is proportional to variation of flux passed the cross section of loop[6].

$$E_d \propto f \cdot B_{\max} \quad (4)$$

The eddy current loss is irreversible heat dissipation in the

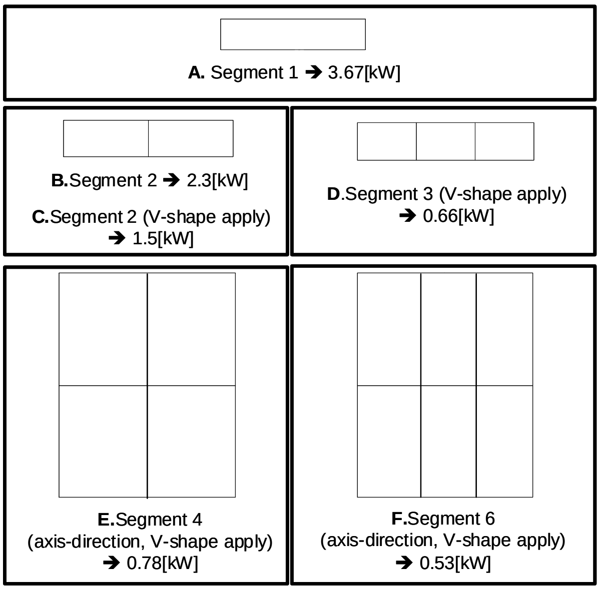

Fig 4. The segment of PM and V-shape rotor core design for reduction of eddy current loss(Segment 'B' is prototype model and six models are considered).

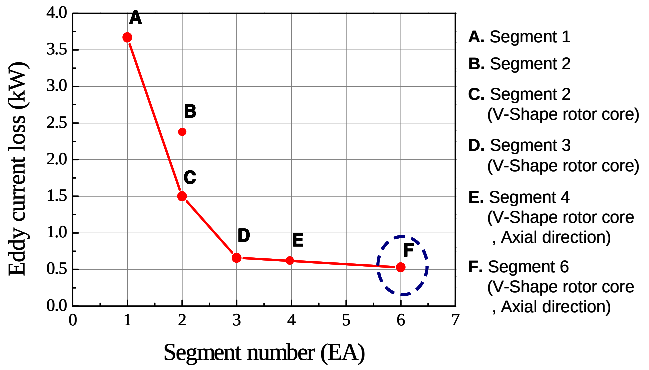

Fig. 5. Eddy current losses in permanent magnet according to combination of rotor design

resistance of current loop, it is proportional to square eddy voltage.

$$P_e \propto E_e^{\ 2} \tag{5}$$

Substitute (4) into (5) and rearrange to find,

$$P_e = k_e f^2 B_{max}^{\ \ 2} \tag{6}$$

Where, P_e is eddy current loss(*W/unit mass*), f is frequency of flux(*Hz*), B_{max} is maximum value of flux density(*T*), k_e is constant. The Constant k_e is changing value according to thickness of PM, electrical resistivity of Permanent Magnet, density and mass of Permanent Magnet.

We considered the segment of Permanent Magnet and V-shape rotor core design for reduction eddy current loss, as shown in Fig 4. The segment 'B' is the Permanent Magnet type of prototype model, and six models are considered. It is expected that 'F' model in Fig 4 is most reduced eddy current loss in Permanent Magnet, as shown in Fig 3(b) rotor design shape.

V. Results

A. Comparison of eddy current loss in 3-D analysis

In order to prevent irreversible demagnetization and heat dissipation, the reduction of eddy current loss in Permanent Magnet is dealt with optimum design process. The result of 3-D FEA about the prototype and optimum model is compared in Fig 5. The eddy current loss of optimum model calculated by 3-D FEA is decreased about 80% compared with prototype model as shown in Fig 5. The 3-D model of optimum design and the vector and distribution of eddy current is shown in Fig 1. This result shows the design method which is proposed in this paper is expected. Reduction of eddy current loss in PM means that the temperature of Permanent Magnet is decreased and improves the characteristic of irreversible demagnetization. In order to calculate exact prediction of irreversible demagnetization, thermal and demagnetizing analysis is required in the further study.

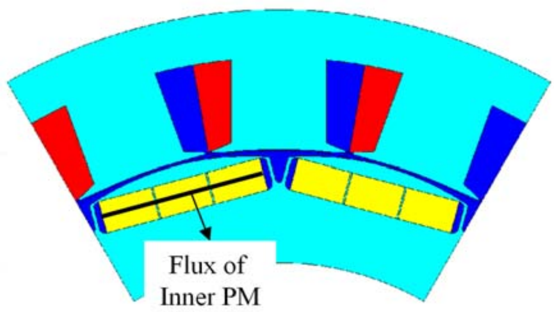

Fig 6. Measurement line of flux variation in Permanent Magnet

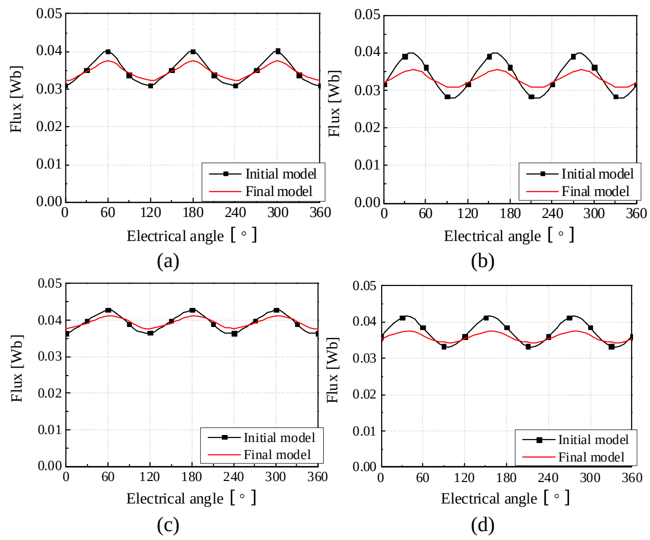

Fig 7. Comparison of flux variation in Permanent magnet according to rotor position. (a) Maximum output power at 1250 rpm. (b) Maximum output power at 5000 rpm. (c) rated output power at 1250 rpm. (d) rated output power at 5000 rpm

B. Comparison with flux density variation in PM

The flux variation of optimum model is calculated using by FEM. The flux variation between prototype and optimum model is shown in Table II. Reduction ratio of eddy current loss in Permanent Magnet can be estimated using the result. Based on the fact that eddy current loss is proportional to squire of flux density, eddy current loss of the optimum model is expected 80% reduced compared with prototype. The peak-peak value and THD of flux density variation is reduced as shown in II and Fig 7. This result means that the eddy current loss in Permanent Magnet is quite reduced.

TABLE II

The flux variation(peak-peak) between prototype and optimum model

	Prototype	Optimum model
Max. output power@*1250rpm*	0.00916 (*Wb*)	0.00515 (*Wb*)
Max. output power@*5000rpm*	0.01212 (*Wb*)	0.00480 (*Wb*)
Rated output power@*1250rpm*	0.00645 (*Wb*)	0.00341 (*Wb*)
Rated output power@*5000rpm*	0.00854 (*Wb*)	0.00329 (*Wb*)

VI. CONCLUSION

The irreversible demagnetization of Permanent Magnet is main issue in the design of IPMSM for the In-Wheel type traction motor. In order to prevent irreversible demagnetization in Permanent Magnet, the reduction of eddy current loss in Permanent Magnet is dealt with optimum design process. For the time saving to optimum design, relation between flux variation and eddy current loss in Permanent Magnet are analyzed and optimum design is conducted with flux variation in Permanent. The eddy current loss of optimum model calculated by 3D FEM is decreased about 80% compared with prototype. It is considered that the error is occurred by harmonics of flux variation. Reduction of eddy current loss in Permanent Magnet means that the temperature of Permanent Magnet is decreased and improves the characteristic of irreversible demagnetization. In order to calculate exact prediction of irreversible demagnetization, thermal and demagnetizing analysis is required in the further study.

REFERENCES

[1] Y. P. Yang and D. S. Chuang, “Optimal design and control of a wheel motor for electric passenger cars,” *IEEE Trans. on Magn*., Vol. 43, No. 1, pp. 51-61, Jan. 2007.

[2] B. H. Lee, “Design considerations of IPMSM for In-Wheel type electric vehicle”, *KIEE*, Jul.2009.

[3] J. W. Jung, “Reduction Design of Eddy Current Loss In Permanent Magnet”, *INTERMAG,* May. 2008.

[4] Jae-Woo Jung, Sang-Ho Lee, Jung-Pyo Hong, Senior Member, IEEE, Ki-Nam Kim, Hyoung-Jun Cho, Sang-Hoon Moon, “Optimum Design for Eddy Current Reduction in Permanent Magnet to Prevent Irreversible Demagnetization”, *ICEMS,* Oct. 2007.

[5] Jae-Woo Jung, Soon-O Kwon, Ji-Hyung Ban and Jung Pyo Hong, “Optimum Design for Eddy Current Reduction in IPMSM by Response Surface Methodology”, *Compumag*, June. 2007.

[6] Wan-Ying Huang, Adel Bettayeb, Robert Kaczmarek, and Jean-Claude Vannier, “Optimization of Magnet Segmentation for Reduction of Eddy-Current Losses in Permanent Magnet Synchronous Machine.”*, IEEE Transactions on energy conversion*, VOL.25, NO.2, JUNE 2010.