Optimum Design for Eddy Current Reduction in IPMSM by Response Surface Methodology

Jae-Woo Jung[1], Soon-O Kwon[1], Ji-Hyung Ban[1] and Jung Pyo Hong[2]
[1]ECAD Lab., Dept. of Electrical Engineering, Changwon National University
Changwon, 641-773, Korea
saltacello@hotmail.com
[2]Dept. of Automotive Engineering, Hanyang University
Seoul, 133-791, Korea

Abstract — This paper deals with the optimum design to reduce eddy current loss in permanent magnet (PM). Instead of direct calculation of eddy current loss using 3D transient magnetic field analysis, indirect method is used. To estimate eddy current loss indirectly, magneto-static field analysis is conducted and flux density variation in PM is used for estimating eddy current loss based on the fact that eddy current loss is proportional to square of flux density and frequency. RSM coupled with DOE is used for optimum design with the object function of THD of flux density variation in PM. Motor design process ensuring minimum variation of flux density in PM is presented and transient analysis is used for verification of optimum design.

I. Introduction

Interior permanent magnet synchronous motor (IPMSM) has advantage of high power density compared with surface mounted permanent magnet motor by utilizing both magnetic and reluctance torque and also provides wide speed range by field weakening control. To maximize its high power density and size effectiveness, rare earth permanent magnet (PM) is generally used in IPMSM [1].

In designing IPMSM using rare earth magnet, sometimes eddy current loss in permanent magnet can be important design consideration, because excessive eddy current in PM seriously affect the motor performance by demagnetizing permanent magnet irreversibly. Considering relatively high conductivity of rare earth magnet, eddy current in permanent magnet becomes significant issue in terms of efficiency and irreversible demagnetization of permanent magnet [2]. Therefore, in the design stage, eddy current loss in permanent magnet should be considered in that case.

To calculate eddy current loss, transient analysis is required. However transient analysis requires huge computation, moreover eddy current analysis is 3-dimensional (3D) problem, and this becomes serious time consuming especially for the optimal design. Instead of direct calculation of eddy current loss for optimization, indirect quantity representing eddy current analysis is used in this paper. THD of flux density variation in permanent magnet is chosen as an object function for the RSM and DOE. Prototype of IPMSM is optimized for minimum eddy current loss and the design result is verified by 3D transient analysis.

II. Analysis Model

The prototype model is IPMSM which is applied in mild type HEV traction motor. The configuration of analysis is indicated in Fig. 1 (a) and Table I is the specification of the IPMSM. The PM, assembled in IPMSM is rare earth PM and its demagnetizing curve is indicated in Fig. 1 (b). There is no knee point from 20^{o}C to 80^{o}C but at 130^{o}C its knee point exists at 0.16[T] as shown in Fig.1 (b).

III. Design of Experiment

A. Objective function

Eddy current is generated by variation of magnetic flux in the conductor and it causes a rise in temperature. In case of IPMSM, field weakening control is essential to achieve high speed operation but at the same time flux density variation occurs in the PM due to the d-axis current as shown in Fig.2 [3]. Supposing that core and PM is insulated electrically, the result of eddy current analysis in the PM using transient analysis is shown in Fig. 3.

It is time consuming task conducting transient analysis for the all experiments. Since eddy current loss is proportional to square of flux density and frequency it can be predicted by indirect method. Frequency of flux density variation is determined by pole slot combination. Therefore, the frequency can not be changed unless pole slot combination changed. However, amplitude of variation and its total harmonic distortion (THD) can be minimized by changing shape of PM or barrier. In this study, average value of variation of flux density in the PM and its THD is selected as objective functions and those are given by equation (1), (2)

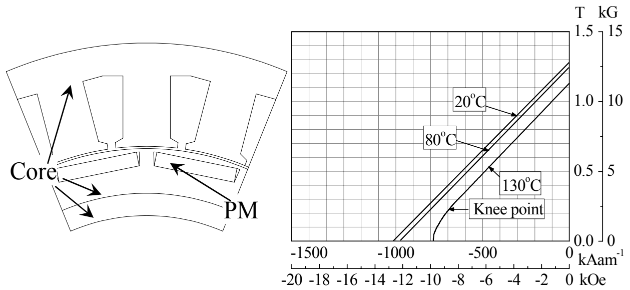
TABLE I
The specification of IPMSM

Section	Value	Unit	Remark
Input Voltage	155	V	DC link
Output Power	17.6	kW	Maximum
Pole / slot	16 / 24		Concentrated winding
Permanent magnet Br	1.28	T	20℃

$$f_{range} = \frac{\sum_{k=1}^{n} \left(B_{pk-pk(fundamental)}\right)_k}{n} \tag{1}$$

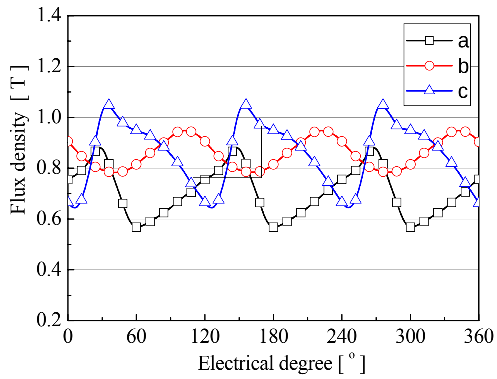
$$f_{THD} = \frac{\sum_{k=1}^{n} (THD)_k}{n} \tag{2}$$

$$n = total\ element\ number\ of\ PM$$

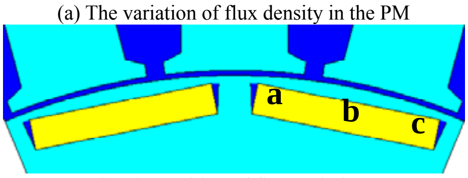


(a) Configuration of IPMSM (b) Demagnetization curve

Fig. 1. Prototype of optimum design



(a) The variation of flux density in the PM



(b) The position of flux variations

Fig. 2. The variation of flux density in the PM

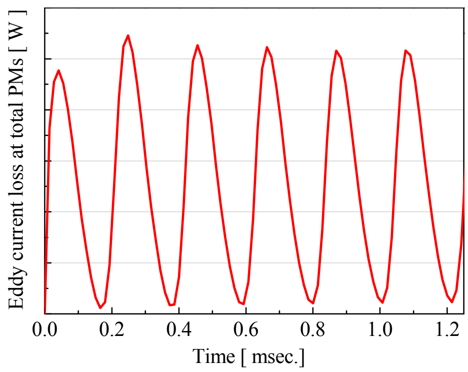


Fig. 3. Eddy current loss in the PM

B. Optimum design

Optimum design using RSM coupled with DOE is conducted to reduce THD and variation of flux density in PM [4]. Design parameters listed in Table II are determined as shown in Fig. 4 and the effect of each design parameter is analyzed by full factorial design. After analyzing effects of parameters on the object function; THD and variation of flux density in PM, RSM is used to find optimum value of each parameter. Optimum design is validated by comparison of eddy current loss with initial model using 3D transient analysis.

IV. CONCLUSION

Optimum design of IPMSM to reduce eddy current loss in PM is presented. In order to calculate eddy current loss, 3D transient magnetic field analysis is applied. In this paper, indirect method is applied to optimum design process. Using the magneto static field analysis eddy current loss is estimated by indirect way; eddy current loss is expected by flux density variation in the PM and THD of flux variation. Using the presented method design variables which mainly effect to the eddy current loss is investigated and design result is verified by comparing the eddy current loss of initial and optimized model calculated by 3D transient analysis.

V. REFERENCES

[1] Akira Nishio, Masahiro Hirano, Yoshiki Kato, Takayuki Irie, Tsutomu Baba, "Development of small size light weight and high power IPM motor for electric vehicle", Mitubishi Heavy Industries, Ltd. Technical Review, vol. 40, no. 5, 2003.

[2] Gyu-Hong Kang, Jin Hur, Hyuk Nam, Jung-Pyo Hong, Gyu-Tag Kim, "Analysis of irreversible magnet demagnetization in line-start motors based of the finite element method", *IEEE Trans. Magn.*, vol.39, no. 4, pp.1488-1491, May. 2003.

[3] Yoshida. K, Hita. Y, Kesamaru. K, "Eddy current loss analysis in PM of surface mounted PMSM for electric vehicles", *IEEE Trans. Magn.*, vol, 36, no.4, pp. 1941-1944, July. 2000.

[4] Sung-Il Kim, Jung-Pyo Hong, Young,-Kyoun Kim, Hyuk Nam, Han-Ik Cho, "Optimal design of slotless-type PMLSM considering multiple responses by response surface methodology", *IEEE Tran. Magn.*, vol. 42, no. 4, pp. 1219-1222, April 2006

TABLE II
The symbol and name of design variables

Symbol	Name
θ_1	Barrier angle
θ_2	Magnet angle
A	PM depth
B	Flux link thickness

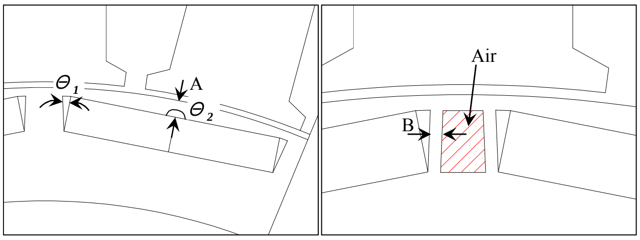


Fig. 4. The design variables of DOE

Compumag 2007
Aachen, Germany

INSTITUTE OF ELECTRICAL MACHINES
CHAIR OF ELECTROMAGNETIC ENERGY CONVERSION
RWTH AACHEN UNIVERSITY

Proceedings of the

16th Conference on the Computation of Electromagnetic Fields

COMPUMAG 2007

June 24th - 28th

Aachen, Germany

ITG INFORMATIONSTECHNISCHE GESELLSCHAFT IM VDE

IET
The Knowledge Network

Wednesday, June 27th

OC1 – Optimisation - Software Methodology EUROPA SAAL

08:30–10:10 Session chair: **Gabriela Ciuprina, Jan Sykulski**

PC1 – Electrical Machines and Drives BALUSTRADE

10:30–12:10 Session chair: **Erich Schmidt, Yoshihiro Kawase**

PC2 – Numerical Techniques BALUSTRADE

10:30–12:10 Session chair: **Igor Tsukerman, Georg Wimmer**