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GW-09. Modeling of effect of plastic deformation on Barkhausen noise and magnetoacoustic emission in iron with 2% silicon. *M.J. Sablik*[1], B. Augustyniak[2] and F.J. Landgraf[3] *1. Mechanical and Materials Engineering Div., Bldg. 139,, Southwest Res. Inst., San Antonio, TX; 2. Physics, Gdansk Institute of Technology, Gdansk, Poland; 3. Metallurgical Engineering, University of Sao Paulo, Sao Paulo, Brazil*

GW-10. Fluxmetric and Magnetometric Demagnetizing Factors in Cylindrical and Rectangular Geometries. *A. Vashghani Farahani*[1] and A. Konrad[1] *1. Electrical and computer engineering, University of Toronto, Toronto, ON, Canada*

GW-11. Transmutation of momentum into position in magnetic vortices. *S. Komineas*[1] and N. Papanicolaou[2] *1. Max-Planck Institute, Dresden, Germany; 2. Department of Physics, University of Crete, Heraklion, Greece*

GW-12. Reduction Design of Eddy Current Loss in Permanent Magnet. *J. Jung*[1], S. Lee[1] and J. Hong[1] *1. Department of Mechanical Engineering, Hanyang University, Seoul, South Korea*

Reduction Design of Eddy Current Loss In Permanent Magnet

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Interior permanent magnet synchronous motor (IPMSM) is used for traction motor and air compressors. In order to improve the power density of IPMSM, Nd-Fe-B permanent magnet (PM) is usually inserted in the rotor core. However, characteristic of Nd-Fe-B magnet is seriously affected by temperature. Residual flux density is reduced and possibility of irreversible demagnetization in PM is highly raised according to increase the temperature of PM. Temperature of the motor is increased by the loss such as copper loss, core loss and eddy current loss in PM. Especially, temperature of PM is affected by eddy current loss in PM particularly driven by flux weakening control. In order to exactly calculate the eddy current loss in PM, transient analysis with 3-dimensional finite element method (3D FEM) is necessary. However, it requires huge computation time. This paper presents the method that can analogize eddy current loss in PM quickly more than 3D FEA based on the fact that eddy current loss is proportional to the square of frequency and peak-peak quantity of flux variation in PM. The optimum design is performed with proposed method and eddy current loss of optimum model is verified by 3D FEM.

***Index Terms*—Eddy current loss in PM, Flux variation in PM, Irreversible demagnetization**

I. Introduction

INTERIOR PERMANENT magnet synchronous motor (IPMSM) is used for traction motor and compressors because it can use both magnetic and reluctance torque. In the other side, it is suitable for flux weakening control which realizes high power and wide speed range. In addition, by using the Nd-Fe-B permanent magnet (PM) in IPMSM, the maximization of the torque per unit rotor volume (TRV) and minimization of the total size are possible [1].

The factors which affect the demagnetization in PM are divided into thermal, permeance coefficient and variation of external magneto motive force (MMF) [2]. Especially, demagnetization by the thermal effect is dominant because the rotor of traction motor for hybrid electric vehicle (HEV) is directly connected with the engine shaft. Except the thermal source form engine, temperature of motor is increased by the loss such as copper loss, core loss and eddy current loss in PM. Especially, temperature of PM is affected by eddy current loss in PM particularly driven by flux weakening control. Therefore, the eddy current loss in PM should be considered to design IPMSM for traction motor for HEV. However, calculation of eddy current loss in PM needs transient analysis with 3-dimensional finite element method (3D FEM) which requires huge computation time.

Since the flux variation usually affects the eddy current loss in PM, the flux variation should be minimized. Therefore, the variation of flux quantity per pole according to the change of the rotor position through 2D FEM is calculated and it is designated by the objective function for response surface methodology (RSM) which is combination of mathematical and statistical techniques. In order to verify the validity of suggested method, optimum model is analyzed by transient analysis with 3D FEM.

II. Design model

The prototype is IPMSM which is applied in traction motor.

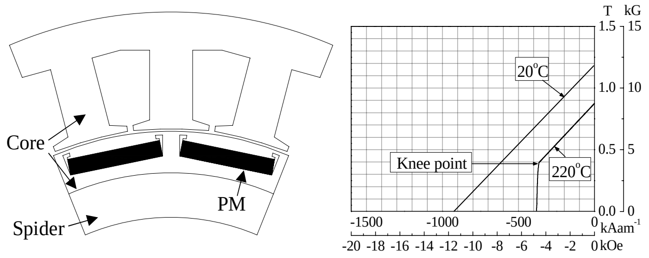

Fig. 1. Prototype of optimum design. (a) Configuration of prototype. (b) Demagnetization curve of Nd-Fe-B PM.

TABLE I
THE SPECIFICATION OF IPMSM

Items	Value	Unit	Remark
Input Voltage	155	V	DC link
Output Power	15	kW	Maximum
Speed	6000	rpm	Maximum
Pole / Slot	16 / 24	-	Concentrated winding
Br	1.18	T	20℃
Conductive	694000	Ω^{-1}/m	PM

The configuration of prototype is shown in Fig. 1(a). The Nd-Fe-B PM is inserted rotor core and its demagnetization curve is expressed in Fig. 4(b). There is not having a knee point at 20°C but knee point its value is 0.4T is appeared at 220°C. Table I shows detail specification of design model.

III. Relationship between eddy current loss and flux variation in permanent magnet

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 PM, specific model is analyzed. Fig. 2 shows the shape of rotor core which is designed for reduction of eddy current loss in PM. The V-shape of rotor core between poles helps the reduction of flux variation in PM. In order to find the relation between eddy current loss and flux variation in PM, full factorial design (FFD) which is one of the statistical methods is conducted. Angle (A) and depth (B) of V-shape are selected as design variables as shown in Fig. 3. The main effect plot expressing the relation between design variable and objective function is shown in Fig. 3. It shows that eddy current loss and flux variation in PM according to design variable is changed almost same direction. The slop of eddy current loss and flux variation is similar according to change of angle (A) and depth (B) respectively. Therefore, linear correlation exists between eddy current loss and squire of flux variation in PM.

IV. Optimum Design

A. *Objective function*

Eddy current is generated by variation of magnetic flux in the conductor and it causes temperature rising. In the case of IPMSM, field weakening control is essential to achieve high speed operation but at the same time the flux variation occurs in the PM due to the d-axis current as shown in Fig. 4 [3].

Eddy current loss is proportional to square of frequency and amplitude of magnetic flux density. The frequency variation of magnetic flux density in PM is determined by pole and slot combination. Therefore, the frequency cannot be changed unless pole and slot combination is changed. However, flux variation which can be considered variation of flux density can be minimized by change the geometry of rotor and stator core. In this paper, flux variation in PM is selected objective function and is given by equation (1). Current source is $140A_{rms}$ with current angle, 90° and speed is 6000rpm.

$$Y_{flux\ variation\ in\ PM} = (A_1 - A_2)\times stack\ length \tag{1}$$

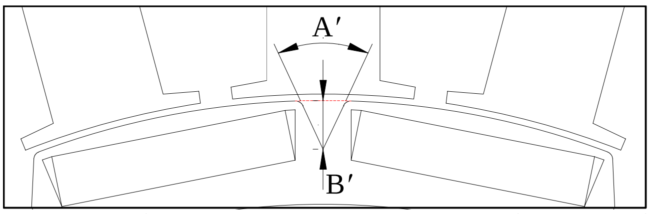

Fig. 2. Shape of rotor core and design variables; designed for reduction of eddy current loss in PM.

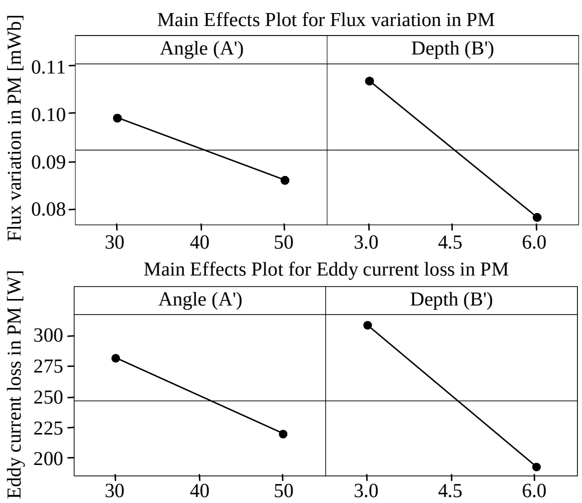

Fig. 3. Main effect plot for eddy current loss and flux variation.

B. *Full factorial design*

Generally, the range of design variable for optimization is determined by past experimental data or designer's experience. However, that is apt to make design very restrictive and subjective. Moreover, if the space is established after investigating responses according to the variation of each parameter, a lot of modeling and analysis time is required, and it is difficult to predict the interaction between the parameters and objective function. The FFD is applied to obtain more reasonable and objective design range for response surface methodology RSM [5]. Design variables are shown in Fig. 5. The ranges of each design variable are determined and listed in Table II.

Based on result of FFD, design variables and corresponding ranges of RSM are determined. Main effect of design variable is shown in Fig. 6. The objective function is decreased as large as chamfer and PM depth. This trend is considered that design variable, chamfer and PM depth can decrease armature reaction. Other design variables are not sensitive to the objective function. Therefore, these two variables are fixed in the optimum design.

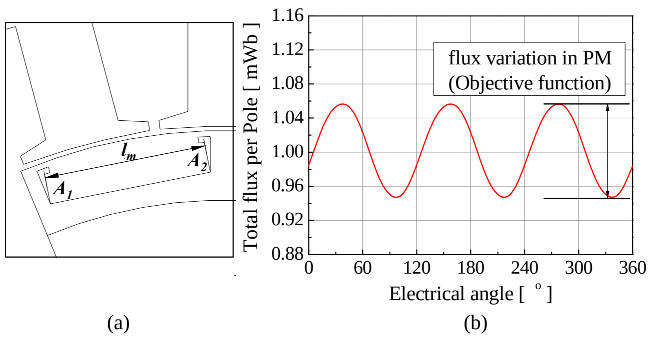

Fig. 4. Flux variation in PM according to rotor position in flux weakening control. (a) Magnetic vector potential and length between A_1 and A_2 for calculation of total flux from PM. (b) Flux variation in PM.

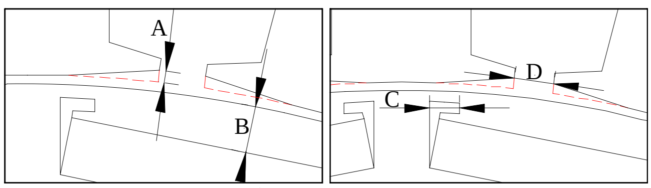

Fig. 5. The design variables of FFD.

TABLE II
The Range of Design Variable for the FFD

Symbol	Variables	Range	Unit
A	Chamfer	0.2 – 1.0	mm
B	PM depth	4.0 – 5.8	mm
C	Barrier width	1.0 – 3.0	mm
D	Slot opening	2.0 – 4.0	mm

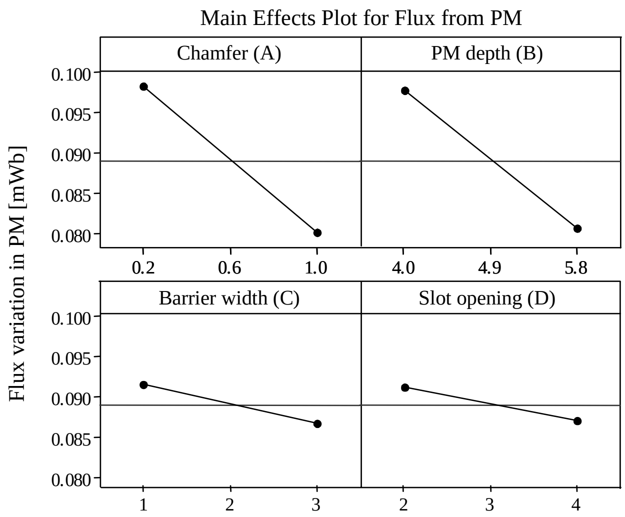

Fig. 6. Main effect plots for objective function.

C. Response surface methodology

RSM is applied to make appropriate response models of the objective function. In this paper, central composite design (CCD) is employed as the experimental design method to estimate the proper model of each response. The CCD is utilized as follow problems.

1. Find of effect about objective function in varying variables.
2. Find variables which satisfy the goal
3. Establish the variables to optimization

Regressive function with k independent variable is expressed as equation (2).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i \neq j}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

where β is regression coefficients for design variables, and ε is random error treated statistical error.

The fitted coefficients and the fitted response model by using least square method which is used to estimate unknown coefficients can be written as follow.

$$\hat{\boldsymbol{\beta}} = (\boldsymbol{X'Y})^{-1} \boldsymbol{X'Y} \qquad (3)$$

$$\hat{\boldsymbol{Y}} = \boldsymbol{X}\hat{\boldsymbol{\beta}} \qquad (4)$$

where $\boldsymbol{X}$ is the matrix notation of the levels of the independent variables, $\boldsymbol{X'}$ is the transpose of the matrix $\boldsymbol{X}$, $\hat{\boldsymbol{\beta}}$ is the matrix of fitted coefficients, and $\hat{\boldsymbol{Y}}$ is the vector of the observations [4][5].

Design variable and range is determined to conduct CCD based on result of FFD as shown in Table III. The polynomial model of the responses is given by equation (5) which is obtained by CCD. Now, the optimum model can be found without extra analysis.

$$Y_{peak-peak\ of\ flux} = 0.194 - 0.030A - 0.021B + 0.001AA + 0.001BB + 0.002AB \qquad (2)$$

TABLE III
THE RANGE OF DESIGN VARIABLES FOR THE RSM

Symbol	Variable	Range	Unit
A	Chamfer	0.6 – 1.0	mm
B	PM depth	4.9 – 5.8	mm
C	Barrier width	2.0 (Fixed)	mm
D	Slot opening	3.0 (Fixed)	mm

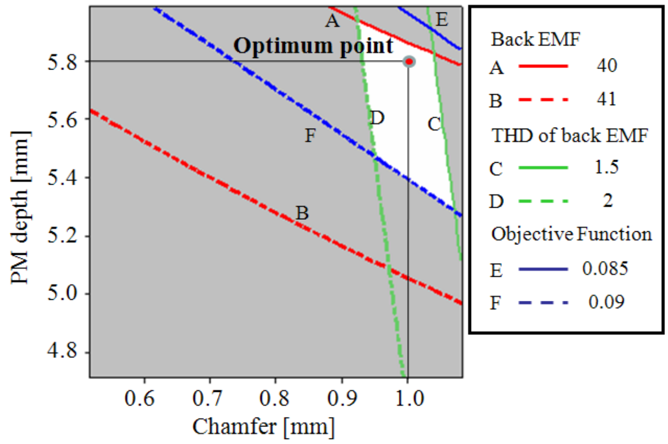

Fig. 7. Main effect plots for objective function.

TABLE IV
COMPARISON OF DESIGN VARIABLES

Variables	Prototype	Optimum model	Unit
Chamfer	0.2	1.0	mm
PM depth	4.0	5.8	mm
Barrier width	1.0	2.0	mm
Slot opening	2.0	3.0	mm

Generally, back EMF which has large harmonics increases current harmonics and it raises eddy current loss in PM and core loss in magnetic core. Therefore, total harmonic distortion of back EMF its range is 1.5-2.0% is determined as a constraint condition to find optimum model. In the other side, amplitude of back EMF its range is limited its value is 40-41V_{rms} because back EMF drop brings current rising in the constant torque region. The optimum point considering constraint condition is shown in Fig. 7 and the optimum point means that flux variation in PM is minimized. The comparison of value of design variable between prototype and optimum model is shown in Table IV. In conclusion, the armature reaction is minimized as big as design variables, chamfer and PM depth.

V. OPTIMUM MODEL

A. Comparison of flux variation in PM

The flux variation of optimum model is calculated using by FEM. Comparison of flux variations in PM according to calculation method, polynomial model and FEM is shown in Table V. It shows that there is good agreement between two results.

Comparison of objective function between prototype and optimum model is shown in Table VI. Reduction ratio of eddy current loss in PM 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 40% reduced compared with prototype

B. Comparison of eddy current loss in PM

In order to verify the design method deals in this paper, 3D FEA is conducted to calculate eddy current loss in PM. Fig. 8(a) shows the 3D model of optimum design. The vector and distribution of eddy current is shown in Fig. 8(b). The result of 3D FEM about the prototype and optimum model is compared in Fig. 9. Eddy current loss of optimum model is decreased about 50% compared with the prototype. This result shows the design method which is proposed in this paper is expected.

TABLE V
COMPARISON OF FLUX VARIATION ACCORDING TO CALCULATION METHOD

Calculation method	Objective function [mWb]
Polynomial model	0.0864
FEM	0.0863

TABLE VI
COMPARISON OF FLUX VARIATION ACCORDING TO CALCULATION METHOD

Calculation method	Objective function [mWb]
Optimum model	0.0864
Prototype	0.1100

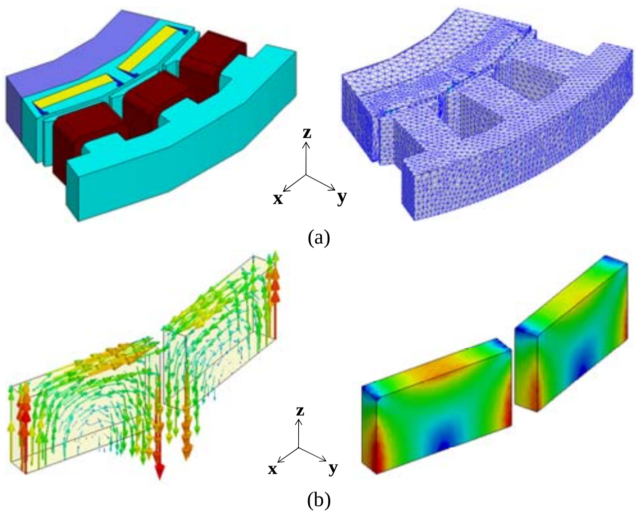

Fig. 8. 3D model for analysis and eddy current distribution. (a) Optimum model for 3D FEM. (b) Eddy current distribution.

VI. CONCLUSION

The irreversible demagnetization of PM is main issue in the design of IPMSM for the HEV traction motor. In order to prevent irreversible demagnetization in PM, the reduction of eddy current loss in PM is dealt with optimum design process. For the time saving to optimum design, relation between flux variation and eddy current loss in PM are analyzed and optimum design is conducted with flux variation in PM as an objective function. The eddy current loss of optimum model calculated by 3D FEM is decreased about 50% compared with prototype. Reduction ratio calculated by 3D FEM is 10% bigger than estimated value. It is considered that the error is occurred by harmonics of flux variation. Reduction of eddy current loss in PM means that the temperature of PM 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

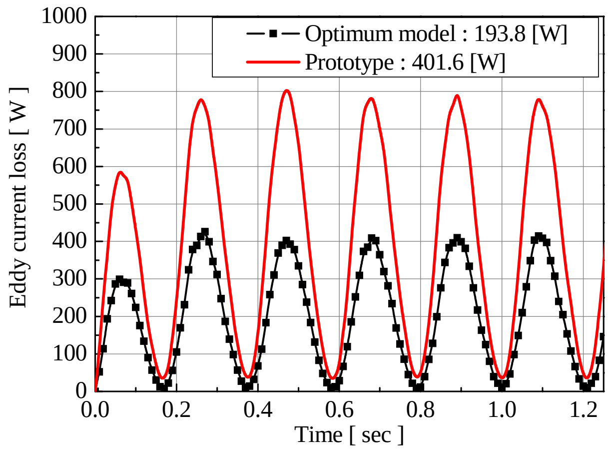

Fig. 9. Comparison of eddy current loss in PM.

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