

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

Jae-Woo Jung<sup>1</sup>, Soon-O Kwon<sup>1</sup>, Ji-Hyung Ban<sup>1</sup> and Jung Pyo Hong<sup>2</sup>

<sup>1</sup>ECAD Lab., Dept. of Electrical Engineering, Changwon National University

Changwon, 641-773, Korea

[saltacello@hotmail.com](mailto:saltacello@hotmail.com)

<sup>2</sup>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°C to 80°C but at 130°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

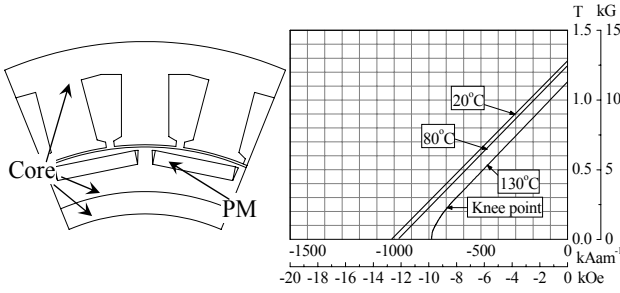
Section	Value	Unit	Remark
Input Voltage	155	V	DC link
Output Power	17.6	kW	Maximum
Pole / slot	16 / 24		Concentrated winding
Permanent magnet Br	1.28	T	20°C

## 12. ELECTRICAL MACHINES AND DIVICE

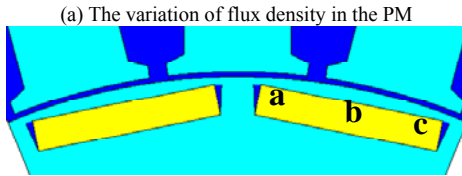
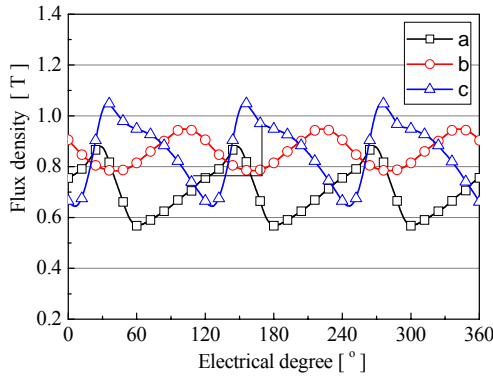
$$f_{range} = \frac{\sum_{k=1}^n (B_{pk-pk(fundamental)})_k}{n} \quad (1)$$

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

$n$  = 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

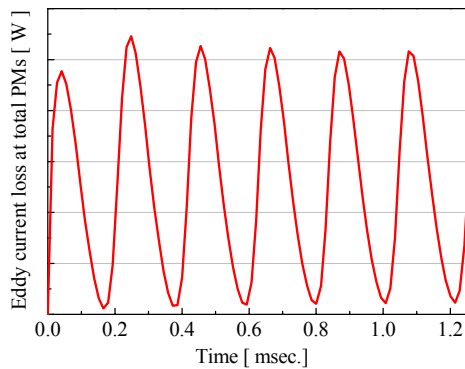


Fig. 3. Eddy current loss in the PM

### 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", Mitsubishi 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
$\theta_1$	Barrier angle
$\theta_2$	Magnet angle
A	PM depth
B	Flux link thickness

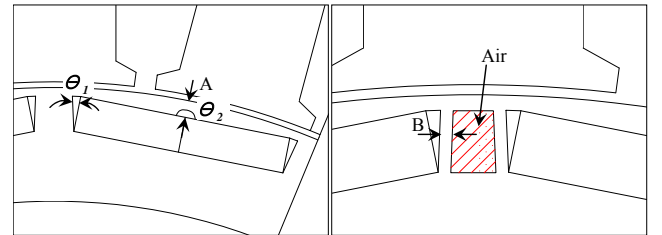


Fig. 4. The design variables of DOE



**Proceedings  
of the**

**16<sup>th</sup> Conference on the Computation of  
Electromagnetic Fields**

# **COMPUMAG 2007**

**June 24<sup>th</sup> - 28<sup>th</sup>**

**Aachen, Germany**

## Wednesday, June 27<sup>th</sup>

### OC1 – Optimisation - Software Methodology

EUROPA SAAL

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

<b>IPC-1</b>	<i>Parallel Computers Everywhere</i> Prof. Dr. Christian Bischof, GERMANY	693
<b>*OC1-1</b>	<i>A New Strategy for Reducing Communication Latency in Parallel 3-D Finite Element Tetrahedral Mesh Refinement</i> Da Qi Ren, Steve Mcfee, Dennis Giannacopoulos, CANADA	701
<b>*OC1-2</b>	<i>Analysis of the Computational Cost of Approximation-based Hybrid Evolutionary Algorithms in Electromagnetic Design</i> Frederico Gadelha Guimaraes, David Alister Lowther, Jaime Arturo Ramirez, BRAZIL	703
<b>OC1-3</b>	<i>Dynamic Multiobjective Optimization: a Way to the Shape Design with Transient Fields</i> Paolo Di Barba, ITALY	705

### PC1 – Electrical Machines and Drives

BALUSTRADE

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

<b>PC1-1</b>	<i>An Improved Design for Steady-Static Characteristic of Permanent Magnet Type Step Motor with Claw Poles by 3D FEM</i> Dae-Sung Jung, Seung-Bin Lim, Ju Lee, SOUTH KOREA	707
<b>PC1-2</b>	<i>Holding Torque Characteristics Analysis of Permanent magnet Spherical Motor</i> Sung Hong Won, Tae Heoung Kim and Ju Lee, SOUTH KOREA	709
<b>PC1-3</b>	<i>Characteristic Analysis of Claw-pole Generator using Equivalent Magnetic Circuits</i> Sang-Ho Lee, Soon-O Kwon, Jung-Pyo Hong, Yang-Soo Lim, Yoon Hur, SOUTH KOREA	711
<b>PC1-4</b>	<i>Design and Analysis of Switched Reluctance Motor Working at Optimum Operating Point</i> Jian Li, In-Jae Lee, Yunhyun Cho, SOUTH KOREA	713

<b>PC1-5</b>	<i>Analysis of PWM Vector Controlled Squirrel Cage Induction Motor during Eccentricity Rotor Motion Using FEM</i> Mi Jung Kim, Byung-Kuk Kim, Ji-Woo Moon, Yun-Hyun Cho, Don-Ha Hwang, Dong-Sik Kang, SOUTH KOREA	715
<b>PC1-6</b>	<i>Influence of Load Fluctuations upon Diagnosis of Mixed Eccentricity Fault In Induction Motors using Time Stepping Finite Element Method</i> Jawad Faiz, B.M. Ebrahimi, IRAN	717
<b>PC1-7</b>	<i>Synthetic Flux Linkage Identification for Interior Buried Permanent Magnet Synchronous Motor considering Cross-Magnetization</i> Sang-Yong Jung, Cheol-Gyun Lee, Sung-Chin Hahn, Sang-Yeop Kwak, Hyun-Kyo Jung, SOUTH KOREA	719
<b>PC1-8</b>	<i>Determination of Parameters Considering Magnetic Nonlinearity in Solid Core Transverse Flux Linear Motors for Dynamic Simulation</i> Ji-Young Lee, Ji-Won Kim, Jung-Hwan Chang, Do-Hyun Kang, and Jung-Pyo Hong, SOUTH KOREA	721
<b>PC1-9</b>	<i>Analysis Strategy Considering Magnetic Saturation of Interior Permanent Magnet Synchronous Motors</i> Young-Kyoun Kim, Jung-Pyo Hong, SOUTH KOREA	723
<b>PC1-10</b>	<i>Performance Computation of Claw-Pole Type Alternator based 3 Dimension Finite Element Method and Fourier Series</i> Seung-Bin Lim, Ki-Chan Kim, Go Sung Chul, Sang-Hwan Ham, SOUTH KOREA	725
<b>PC1-11</b>	<i>Flux-Weakening Performance and Output Power Capability of Permanent Magnet Synchronous Motors with Different Permanent Magnet Arrangement</i> Bojan Stumberger, Gorazd Stumberger, Miralem Hadziselimovic, Marko Jesenik, Anton Hamler, Mladen Trlep, SLOVENIA	727
<b>PC1-12</b>	<i>Arc models for simulation of brush motor commutations</i> Jerome Cros, Geraldo Sincero, Philippe Viarouge, CANADA	729
<b>PC1-13</b>	<i>Torque Ripple Reduction of Interior Permanent Magnet Synchronous Motor Using Harmonic Injected Current</i> Ji-Hyung Bahn, Sung-Il Kim, Geun-Ho Lee, Jung-Pyo Hong, SOUTH KOREA	731
<b>PC1-14</b>	<i>Investigation of Parameters Variation and Radial Magnetic Forces by Pole-Slot Combinations in Interior Permanent Magnet Synchronous Motor with Concentrated Winding</i> Seung-Hyoung Ha, Sang-Ho Lee, Soon-O Kwon, Jung-Pyo Hong, SOUTH KOREA	733

<b>PC1-15</b>	<i>Accurate induction motor estimator based on magnetic field analysis</i> Dimitrios S. Raptis, Antonios G. Kladas and John A. Tegopoulos, GREECE	735
<b>PC1-16</b>	<i>Power Generation Optimization from Sea Waves by using a Permanent Magnet Linear Generator Drive</i> N. M. Kimoulakis, A. G. Kladas and J. A. Tegopoulos, GREECE	737
<b>PC1-17</b>	<i>Study on the Characteristics for A Novel Segmental Switched Reluctance Motor</i> Tao Sun, Ji-Young Lee, Jung-Pyo Hong, SOUTH KOREA	739
<b>PC1-18</b>	<i>Determination of Parameters of Motor Simulation Module Employed in ADVISOR</i> Tao Sun, Suk-Hee Lee, Soon-O Kwon Jung-Pyo Hong, SOUTH KOREA	741
<b>PC1-19</b>	<i>Analysis of Transient Short Circuit Electromagnetic Forces in Isolated Phase Buses</i> Arash Hassanpour Isfahani, Sadegh Vaez-Zadeh, IRAN	743
<b>PC1-20</b>	<i>Coupling Boundary Element and Permeances Network Methods for Modeling Permanent Magnet Motors in automotive applications</i> Said Touati, J. A. Farooq, A. Djerdir, R. Ibtouen, A. Miraoui, O. Touhami, ALGERIA	745
<b>PC1-21</b>	<i>Optimum Design for Eddy Current Reduction in IPMSM</i> Jaewoo Jung, Soon-O Kwon, Ji-Hyung Ban, Jung Pyo Hong, SOUTH KOREA	747
<b>PC1-22</b>	<i>Design of a Permanent Magnet Assisted Synchronous Reluctance Motor for Integrated Starter and Generator in 42 Volt System of Vehicles</i> Yang-Su Lim, Dong-Hun Lee, Yoon Hur, Jae-Woo Jung, Jung-Pyo Hong, SOUTH KOREA	749

## PC2 – Numerical Techniques

BALUSTRADE

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

<b>PC2-1</b>	<i>An Adaptive Remeshing Technique Insuring High Quality Meshes</i> Marcel Ebene-Ebene, Y. Marechal, D. Armand, D. Ladas, FRANCE	751
--------------	-------------------------------------------------------------------------------------------------------------------------------------	-----