



# WELCOME TO INTERMAG EUROPE 2008 CD

The INTERMAG Europe 2008 Conference is to be held in the *Palacio Municipal de Congresos de Madrid*, from **May 4 to May 8, 2008**.

Information related to the location, conference registration, publications, presentations, posters, etc can be found in the introductory sections of the Advance Program Book. For more information please check the conference web-site at http://www.intermagconference.com/intermag2008.

To view the digests of the papers to be presented at the conference you will need to have Adobe Acrobat Reader installed on your computer. If you do not have this available Click here to install the software on your laptop.

**EL-08. Thrust Ripple Minimization of Permanent Magnet Linear Synchronous Motor by the Notch and the Auxiliary-teeth.** *D. Lee*[1], K. Jang[1] and G. Kim[1] *1. Electrical Engineering, Changwon National University, Changwon, Gyeongsangnam-do, South Korea*

**EL-09. A Study on the Vibration Characteristic According to PM Arrangement in PMLSM.** *D. Lee*[1], S. Lee[1], K. Jang[1] and G. Kim[1] *1. Electrical Engineering, Changwon National University, Changwon, Gyeongsangnam-do, South Korea*

**EL-10. Flux Barrier Design to Improve Torque Characteristics of Double-layer Interior Permanent Magnet Synchronous Motor.** *S. Kim*[1], J. Jung[1], J. Hong[1] and S. Lee[2] *1. Department of Mechanical Engineering, Hanyang University, Seoul, South Korea; 2. Research Center, Korea Institute of Industrial Technology, Gwangju, South Korea*

**EL-11. Study on High Efficiency Performance in Interior Permanent Magnet Synchronous Motor with Double-layer PM Design.** *L. Fang*[1], J. Jung[1], B. Lee[1] and J. Hong[1] *1. Department of Mechanical Engineering, Hanyang University, Seoul, South Korea*

**EL-12. A new PMLSM having 9 pole 10 slot structure and its shape optimal design for detent force reduction.** *C. Koh*[1], I. Hwang[1] and H. Yoon[1] *1. School of Electrical & Computer Engineering, Chungbuk National University, Cheongju, Chungbuk, South Korea*

# Study on High Efficiency Performance in Interior Permanent Magnet Synchronous Motor with Double-layer PM Design

Liang Fang, Jae-woo Jung, Byeong-Hwa Lee and Jung-Pyo Hong, *Member, IEEE*

School of Mechanical Engineering, Hanyang University, Seoul, South Korea

**This paper presents a study on the high efficiency performance of an interior permanent magnet synchronous motor(IPMSM). A prototype model of single-layer IPMSM is developed into double-layer design for improving motor efficiency performance furthermore. On the other hand, the optimal approaches that design of experiment(DOE) combined with response surface methodology (RSM) based on simulation technique is applied to build an optimum IPMSM model having double-layer PM structure. The main emphasis is placed on revealing the merits of double-layer rotor design benefit to the motor efficiency improvement in this study. In the optimal design, all the machine parameters and performances are calculated by using the equivalent circuit method(ECM) and finite element method(FEM).**

***Index Terms*— Interior permanent magnet synchronous motor(IPMSM), efficiency performance, double-layer rotor design, DOE, RSM, optimal design, ECM, FEM.**

## I. Introduction

THE INTERIOR permanent magnet synchronous motors (IPMSM) have wide applications to household goods, industrial use, and electric and hybrid vehicle propulsion[1]. The IPMSM have superior performance characteristics, that including high efficiency, high torque density, and wide constant power operating range[2]，which make the IPMSM attractive for vehicle propulsion.

In this study, a high efficiency IPMSM used as a traction motor in vehicle propulsion system is introduced as analysis model for motor efficiency performance investigation.

In permanent magnet machines, the PMs buried insider the rotor core, which is benefit for avoiding the separation of PM caused by the centrifugal force at high speed. On the other hand, the IPMSM generates hybrid torque production that including magnet torque and reluctance torque. The magnet torque is produced by the buried magnets, and another additional reluctance torque is generated from the unique rotor structure. As Fig. 1 shows, the axis directly along the $d$-axis exhibits high reluctance due to the low permeability of PM, while along the $q$-axis that between the flux-barriers inside the IPM rotor, there exists no magnetic barrier, that having low reluctivity to magnetic flux. This variation of the reluctance around rotor creates saliency in the rotor structure, by which the reluctance torque in generated.

It can be found that a single-layer PM with one flux-barrier rotor design can also be split into several layers creating a multi-layer PM design. As some investigators reports, the multi-layer PM design can reduce flux leakage and improve the rotor saliency. Therefore, the IPMSM having multi-layer rotor design have numerous performance advantages over the single-layer rotor design, such as enhancing overall efficiency, extending high speed constant power operating range, and improving power factor[3].

In this study, a double-layer rotor design is adopted in the optimal design for practical consideration, that as simplicity for manufacturing, the easiness of inserting PM into the rotor core and the mechanical robustness. Howbeit, the double-layer rotor design can still reveal the peculiarity of multi-layer rotor design, which owning the beneficial attributes of both the synchronous reluctance motors(SynRM) and the PM motors from the rotor structure point.

Therefore, in the case of generating specific hybrid torque produce, the increasing of reluctance torque production due to high rotor saliency can compensate the reducing magnet torque production. In general, the higher the rotor saliency creates, the lower the dependency on magnet torque. Correspondingly, the copper loss in the armature windings can decrease with the reducing of armature current.

In the paper, the optimal design of double-layer rotor structure is presented. In order to quickly determine the optimal structure of double-layer PMs buried in the rotor, the simulation approaches of design of experiment(DOE) combined with response surface methodology (RSM) is performed. In the simulation procedure, the machine parameters and performances are calculated by using finite element method(FEM) and equivalent circuit method(ECM). Finally, the machines characteristics between the prototype single-layer IPMSM model and the optimal designed double-layer IPMSM model are compared to verified the improvement of motor efficiency performance.

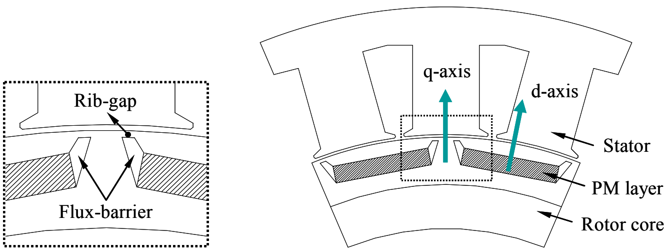



Fig. 1 Configuration of an typical IPMSM model

## II. Analysis Model Description

### A. Analysis IPMSM Model

The analysis IPMSM model used as a traction motor in electrical vehicle propulsion system is given, as Fig. 2 shows. It has 16-pole and 24-slot, with concentrated windings arranged in stator part. In each pole region, a single-layer PM is inserted into radial cavity, and the single-layer PM is designed as “V” shape.

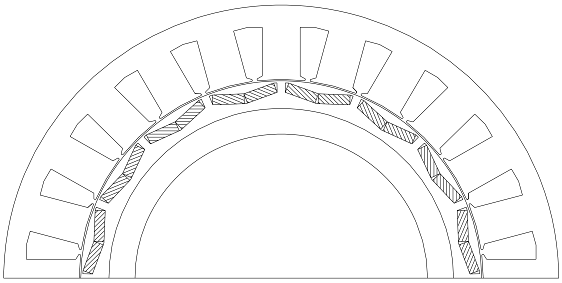
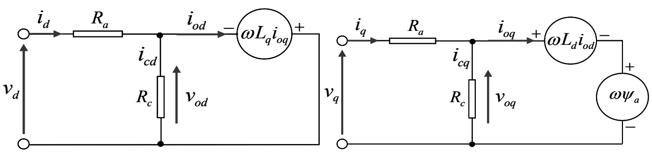


Fig. 2 Prototype analysis IPMSM model

### B. Equivalent Circuits Method

Equivalent circuits for IPMSM based on a synchronous *d-q* reference frame including iron losses, are presented in Fig. 3. The mathematical model of the equivalent circuit is given as following equations. Iron loss is considered by equivalent resistance $R_c$, and *d*- and *q*-axis voltages and hybrid torque equations are given by (1), (2) and (3), respectively [5], [6].



(a) *d*-axis equivalent circuit (b) *q*-axis equivalent circuit

Fig. 3 Equivalent circuit of IPMSM model

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

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

$$\begin{aligned} T &= P_n \{\psi_a i_{od} + (L_d - L_q) i_{od} i_{oq}\} \\ &= P_n \left\{\psi_a I_a \cos\beta + \frac{1}{2}(L_q - L_d) I_a^2 \sin 2\beta \right\} \end{aligned} \quad (3)$$

Where $i_d$ and $i_q$ are *d*- and *q*-axis component of armature current, $i_{cs}$ and $i_{cq}$ are *d*- and *q*-axis component of iron loss current, $v_d$ and $v_q$ are *d*- and *q*-axis component of terminal voltage, $R_a$ is armature winding resistance per phase, $R_c$ is iron loss resistance, $\psi_a$ is flux linkage of PM per phase(rms), $L_d$ and $L_q$ are *d*- and *q*-axis armature self inductance, $P_n$ is number of pole pairs, $\beta$ is the lead angle of phase current (=$\tan^{-1}(-i_d/i_q)$), and the saliency ratio is defined as $\rho(=L_q/L_d)$, $T$ is the hybrid torque production in IPMSM.

## III. Optimal Design Of Double-layer IPMSM

In order to determine an optimum structure of double-layer PM design, the simulation approach that design of experiment (DOE) coupling with response surface methodology (RSM) is performed in the following optimal design. According to the above discussion, the rotor saliency under phase current (@100[A], current angle=40$^o$) and the line-to-line Back-EMF under 2000[rpm] are chosen as object functions because the object functions are closely relates to efficiency performance and are able to calculate easily by FEM.

### A. Design of Experiment

The approach of double-layer IPM rotor provides much more flexible variables for optimum structure design. Therefore, for investigating which design variables affect the object functions critically and determining the optimal rotor structure quickly, the simulation DOE is performed firstly. The design variables in the double-layer rotor structure are given as the Fig. 4 shows. TABLE I lists all the design variables and corresponding experiment ranges, respectively.

By performing the simulation DOE, the full factorial combination of all the design variables that ($2^N$+1) models are built that the four design variables [LPM_1, LPM_2, α, β] makes ($2^4$+1=)17 models. Then, all models are analyzed under the object functions of saliency ratio and Back_EMF. From main effect and interaction effect analyzing, the significant design variables and reasonable design ranges are decided.

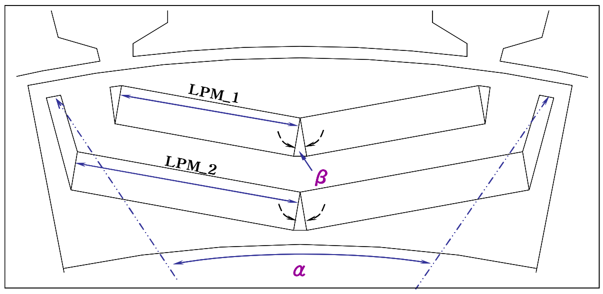
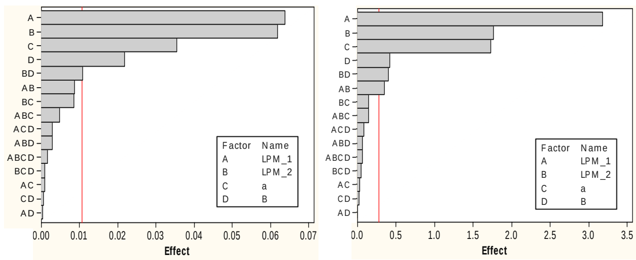



Fig. 4 Design variables of double-layer IPM rotor structure

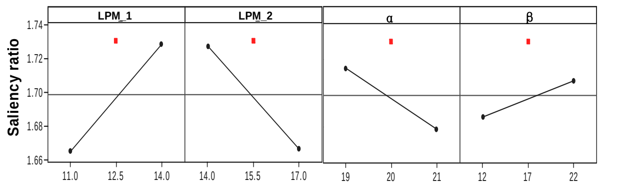
TABLE I
DESIGN VARIABLES AND EXPERIMENT RANGES FOR DOE

| Design variable | Items of design variable | Experiment range | Unit |
|---|---|---|---|
| LPM_1 | Length of 1st PM layer | [11 ~ 14] | mm |
| LPM_2 | Length of 2nd PM layer | [14 ~ 17] | mm |
| α | Mechanical Angle of pole-arc | [18 ~ 22] | degree |
| β | Angle of gap of PM segments | [10 ~ 22] | degree |

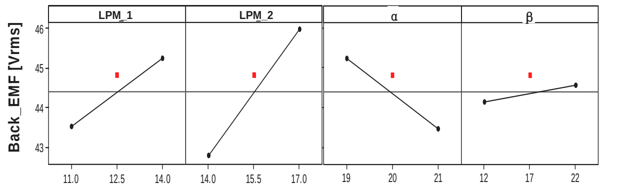



(a) Rotor saliency, (b) Back_EMF

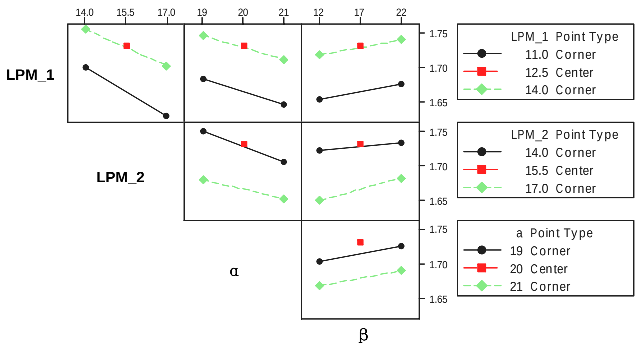
Fig. 5 Pareto Chart of standardized effect of all design variables



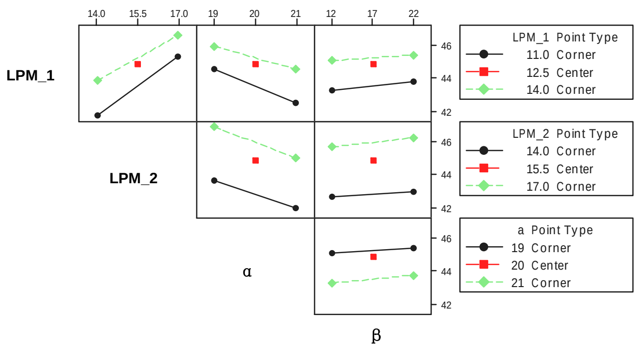
(a) Main effect analysis for saliency ratio [@100[A], current angle=40°]



(b) Main effect analysis for Back_EMF [line-to-line@2000[rpm]]



(c) Interaction effect analysis for saliency ratio[@100[A], current angle=40°]



(d) Interaction effect analysis for Back_EMF [line-to-line@2000[rpm]]

Fig. 6 Main effect and interaction effect analysis of all design variables

The effect of the design variables upon the object functions can be concluded from the above plots analysis. The design variables [LPM_1, LPM_2, α] shows significant effect on both object functions, as Fig. 5(a) and (b) show. It is also found that the length of PM layers [LPM_1, LPM_2] has significant effect on rotor saliency oppositely. And, the design variables [LPM_1, LPM_2] are associated by using the same amount of PM. Therefore, the main design variables [LPM_2, α] are determined for the next RSM optimizing analysis.

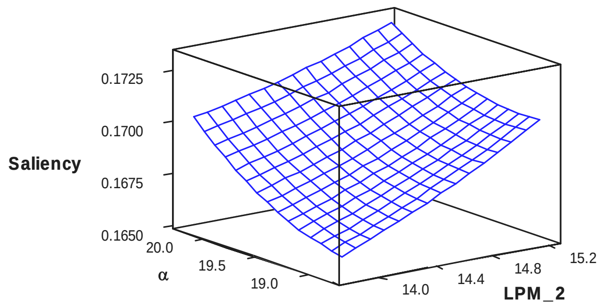
## *B. Response Surface Methodology*

RSM is a collection of statistical and mathematical techniques used for developing, improving and optimizing process[4]. With the main design variables [LPM_2, α], the analysis models are built in more reasonable experiment ranges by using similar approach of simulation DOE. TABLE Π gives the design variables and their experiment ranges that investigated in RSM. The design variable [LPM_1] changes with [LPM_2] for simplicity consideration, and the design variable [β=17°] is constant.

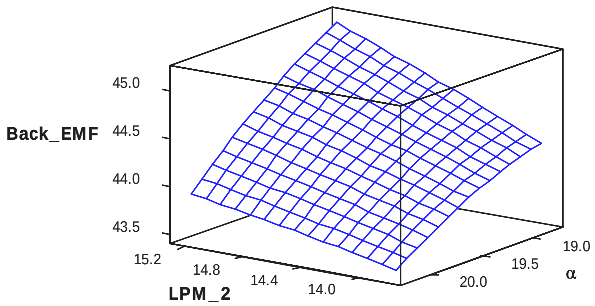
The response surface of each object function is obtained with design variables of [LPM_2, α] by performing RSM. According to the response surfaces of object function, as shown in Fig. 7(a) and (b), the maximum of saliency ratio with desired Back_EMF is achieved with the design variables [LPM_2=14.5mm, α=19.5°]. Therefore, the optimal double-layer rotor structure is determined with [LPM_1=13.5mm, LPM_2=14.5mm, α=19.5°, β=17°].

TABLE Π
DESIGN VARIABLES AND EXPERIMENT RANGES FOR RSM

| Design variable | Items of design variable | Experiment range | Unit |
|---|---|---|---|
| LPM_1 | Length of 1st PM layer | 28-LPM_1 | mm |
| LPM_2 | Length of 2nd PM layer | [14 ~ 15] | mm |
| α | Mechanical Angle of pole-arc | [19 ~ 20] | degree |
| β | Angle of gap of PM segments | 17 | degree |

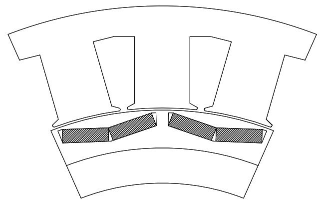


(a) Object function of saliency ratio[@100[A], current angle=40°]



(b) Object function of Back_EMF [line-to-line@2000[rpm]]

Fig. 7 Response surfaces of object functions by RSM


(a) Prototype single-layer model

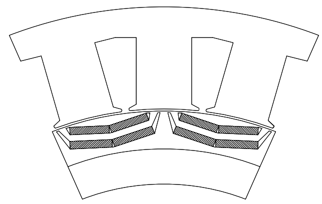

(b) Optimal double-layer model

Fig. 8 Configuration of IPMSM models

## IV. Result and Analysis

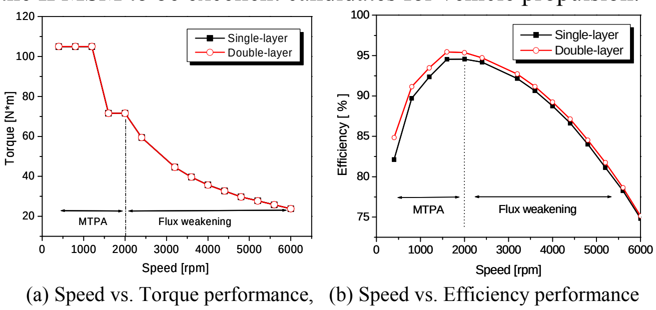
The optimal designed IPMSM model with double-layer rotor structure is built with the determined design variables. The configurations of both the prototype single-layer model and optimal double-layer design model are shown in Fig. 8. Then, the characteristics are analyzed and compared.

Both of the prototype and optimal designed IPMSM models are required to satisfy the same torque performance along all the speed range in the analysis. As the Fig. 9(a) shows, the maximum torque per ampere (MTPA) control strategy is adopted at low speed range, while the flux weakening control strategy is applied to high speed operation[7],[8]. And then, the improvement of efficiency performance all over operation range is verified, as Fig. 9(b) shows.

The inductance along *d*- and *q*-axis are calculated by FEM under the phase current $I_a$=100[A]. It is found that the double-layer IPMSM model has higher rotor saliency, with larger q-inductance while smaller d-axis inductance, as the Fig. 10(b) shows. Therefore, the higher reluctance torque production is generated, and the reducing of magnet torque production is realized under the same hybrid torque production. Both of the two kinds of torque production are calculated and compared separately in Fig 11 (a) and (b).

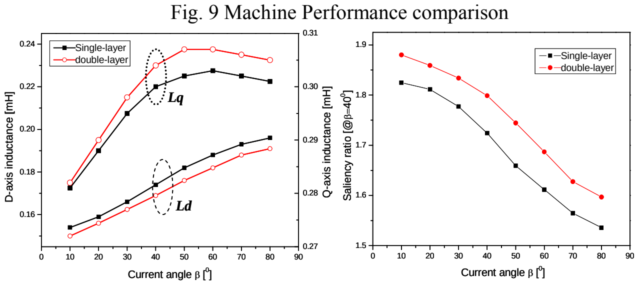
The decrease of magnet torque production helps to alleviate the copper loss caused by the current following in armature windings. On the other hand, the iron loss exists in both stator core and rotor core decreased since the flux leakage reduction, as Fig. 12 shows. These are the essential reasons of efficiency performance improving.

In general, the presented approach of double-layer rotor design in IPMSM realizes the improvement of motor efficiency performance. Although the design process of increasing layer is different, and the cost of manufacture of rotor will increases, the double-layer rotor design can promote the IPMSM to be excellent candidates for vehicle propulsion.



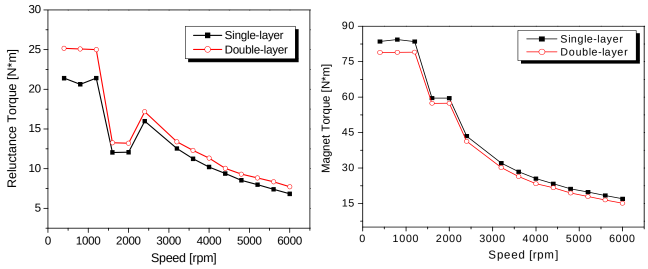
(a) Speed vs. Torque performance, (b) Speed vs. Efficiency performance

Fig. 9 Machine Performance comparison



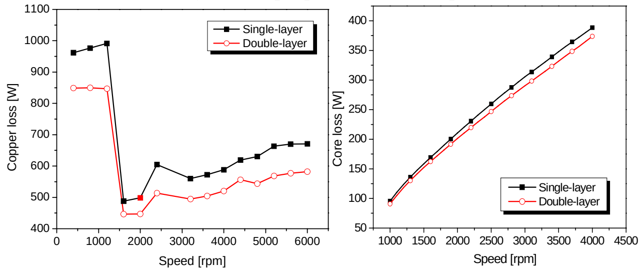
(a) *d*- and *q*- axis inductances (b) Saliency ratio

Fig. 10 Inductance characteristic comparison ($I_a$=100[A])



(a) Speed vs. Reluctance torque (b) Speed vs. magnet torque

Fig. 11 Torque performance comparison



(a) Speed vs. copper loss, (b) Speed vs. core loss@ No-load

Fig. 12 Energy loss characteristic comparison.

## V. Conclusion

This paper has presented the optimal design of double-layer IPMSM for improving efficiency performance. From the above analyzing based on characteristic comparisons between the prototype single-layer IPMSM model and the optimal design double-layer IPMSM model, the efficiency performance improving through multi-layer rotor design is well verified in theory and instantiation. In conclusion to this study, the multi-layer rotor design, as compared to single-layer design, can generate higher rotor saliency that is helpful to improve machine performances without increasing PM usage.

## References


[1] John M Miller. "Propulsion System for Hybrid Vehicles", *IEE Power and Energy Seies 45*.

[2] Nicole Bianchi, Thomas M. Jahns, "Design, Analysis, and Control of Interior PM synchronous Machines", IEEE-IAS Electrical Machines Committee.

[3] T. Ohnishi, Takahashi "Optimal Design of Efficiency IPM motor Using Finite Element Method," *IEEE Transaction on Magnetics, vol. 36, no. 5, SEPTEMBER 2000*

[4] Raymond H. Myers, Douglas C. Montgomery, "Response Surface Methodology: Process and Product Optimization Using Designed Experiment", A Wiley-Interscience Publication John Wiley & Sons, INC.

[5] Ji-Yong Lee, Sang-Ho Lee, Geun-Ho Lee, Jung-Pyo Hong, Jin Hur, "Determination of Parameters Considering Magnetic Nonlinearity in an Interior Permanent Magnet Synchronous Motor," *IEEE Transaction on Magnetics, vol. 402, no. 4, APPRIL 2006*

[6] Khwaja M. Rahman, Silva Hiti, "Identification of Machine Parameters of a Synchronous Motor," *IEEE Transaction on Inducstry Applications, vol. 41, no. 2, MARCH/APPRIL 2005.*

[7] Shigen Morimoto, Masayuki Sanada, and Yoji Takeda, "Performance of PM-Assisted Synchronous Reluctance Motor for High-Efficiency and Wide Constant-Power Operation," *IEEE Transaction on Inducstry Applications, vol. 37, no. 5, SEPTEMBER/OCTOBER 2001*

[8] SHIGEO MORIMOTO, YOJI TAKEDA. "Machine Parameters and Performance of Interior Permanent Magnet Synchronous Motors with Different Permanent Magnet Volume," *Electrical Engineering in Japan, vol. 131, No. 4,2000.*