Design for Total Harmonic Distortion Reduction of Concentric Winding type Interior Permanent Magnet Synchronous Motor for Integrated Starter and Generator

Jung Jae-Woo*, Peng Zhang*, Jung-Pyo Hong*, Ji-Young Lee**

* Changwon National University, #9 Sarim-dong, Changwon, Kyeongnam, Korea

** Korea Electrotechnology Institute, Transverse Flux Machine Research Group, Changwon, Kyeongnam, Korea

***Abstract*-- This paper provides design process of concentric winding type interior permanent magnet synchronous motor (IPMSM) for integrated starter and generator (ISG). ISG is operated as generator in driving region. In order to increase efficiency in generating mode, back EMF shape should be sinusoidal. Therefore in the optimal design, total harmonic distortion (THD) is considered as object function. In the design process, response surface method (RSM) coupled with design of experiment (DOE) is used for optimal design, and the effects of design variables on the object function are investigated. Result of THD is compared with optimal designed model.**

***Index Terms*--back EMF, ISG, IPMSM, THD.**

I. Introduction

With the increasing interest on Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV), the development of integrated starter and generator (ISG) is becoming one of the highly concerned matters. The ISG, which could operate as a motor and a generator when the vehicle is in the starting and driving condition respectively, should have a sinusoidal back electromagnetic force (EMF) to reduce the torque ripple in motoring region and to increase generating efficiency in generating region. This paper provides a design of interior permanent magnet synchronous motor (IPMSM) in order to reduce total harmonic distortion (THD) of back EMF using space harmonic analysis and design of experiment (DOE) combined with response surface method (RSM) [1].

In the design process, the required range of parameters, d-q axes inductance and back EMF that satisfy speed range and output power are researched and the space harmonic analysis is applied to determine the initial dimension. Parameters of the IPMSM such as amplitude of the back EMF, number of turns per phase could satisfy the object power and pole pitch that minimize the THD of the back EMF. The design factors are decided and their combinations are generated and analyzed by full factorial design (FFD) to confirm the effects of these parameters. At the same time the ranges of all the parameters are considered to conduct RSM, which is performed on the basis of FFD results. Finite element analysis (FEA) is used to analyze all the experiment combinations in order to obtain the optimized parameters. And then d-q axes equivalent circuit analysis is conducted in order to confirm the characteristics of the optimal model.

II. Motor Design

A. Process

The out line of design process is described before the optimal design. Fig. 1 shows total process of motor design including optimization.

First of all the specification of IPMSM for ISG is considered. Then the range of parameters such as back EMF and d-axis inductance are researched using d-q axes equivalent circuit equations [2]. The rotor dimension is decided considering cooling condition and torque per rotor volume (TRV). Rough dimensions, permanent magnet (PM), turn per phase of the base model that satisfy the back EMF range, are determined using space harmonic analysis. The Back EMF and d-axis inductance are calculated by FEA. In case of parameters of base model which satisfy range, the optimal design which consists of DOE and RSM is conducted to obtain the optimal model. The parameters, such as back EMF, d-q axis inductance, phase and core loss resistance of optimal model, are calculated for characteristics analysis. D-q equivalent circuit analysis, based on the parameters calculated above, is applied to get all characteristics, including torque, power, input current and voltage.

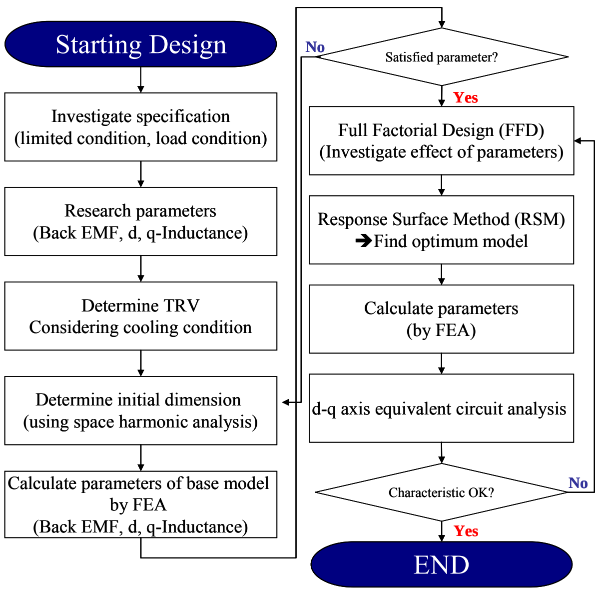


Fig. 1. Design process of IPMSM.

B. *Specification*

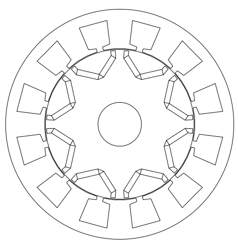
The object model of this study is the design of IPMSM for the ISG which can be applied to commercial bus. Because of battery in the bus and cost of switch device, input voltage and current are limited. The optimal model should satisfy the specification as shown in table 1. Especially the power has to satisfy 12kW in the whole speed range.

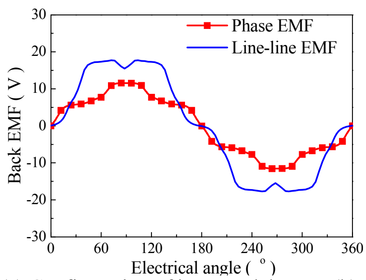
C. *Initial design*

The base model is decided through the design process as shown in Fig.1. The object ranges of parameters are determined considering efficiency and output power of the entire speed region according to variation of back EMF and d-axis inductance. The rough shape and dimensions, grade of PM, number of turns per phase of the base model are determined using space harmonic analysis assuming that the TRV is 160kNm/m^2. The ISG is cooled by liquid material. The base model that has 8pole and 12slot is decided as shown in Fig. 2 (a). The space harmonic analysis is also applied to find pole arc of the PM that minimize THD of back EMF. Table II is the result. Fig. 2 (b) shows a back EMF shape of base model. Table III shows the object parameters range and parameters of base model [3].

TABLE I
SPECIFICATION OF IPMSM FOR ISG

Section	Contents	Unit	Value	Remark
Motoring Mode	Input voltage	[V]	42	DC link
	Output Power	[kW]	12.6	Max value
	Current limit	[A]	600	
	Maximum torque	[Nm]	300	0-400 rpm
	Base speed	[rpm]	400	
	Maximum speed	[rpm]	2500	
Generating Mode	Output power	[kW]	12	
	Generating region	[rpm]	2500-7200	
	Main generation region	[rpm]	4500-6500	Max Efficiency control





(a) Configuration of base model (b) Back EMF(@400rpm)

Fig. 2. Base model of IPMSM

TABLE II
THD VARIATION ACCORDING TO THE CHANGE OF POLE ARC (UNIT: %)

Pole arc / Coil span	29°/ 45°	30°/ 45°	31°/ 45°	33°/ 45°	35°/ 45°
1	21.3	20.6	19.0	17.1	10.3

TABLE III
RANGE OF TARGET PRARMETER

List	Line-line EMF	d-axis inductance
Unit	[Vrms]	[mH]
Object range	12.1 - 13.9	0.12 – 0.16
Base model	13.11	0.125

D. *Full factorial design (FFD)*

The Optimal design is performed based on the result of initial design. The object of the optimal design is to insure that power is 12 kW at 400rpm at motoring mode and reduce THD of back EMF to improve efficiency at generating mode. Fig. 3 shows design variables that are used in FFD and Table IV describes design variables and their ranges. The PM angle is selected in order to ensure the output power and reduce THD of back EMF. Several simulations using FEA are performed to make main effect plots of design variables.

Fig. 4 shows the main effect plot produced by the result of FFD. The PM thickness (C) has most significant effect on the response which is torque in this design, because the flux variation highly affects magnetic torque. On the other side, chamfer at the stator teeth has highly effect on THD of back EMF because the chamfer can make the air-gap length increased and air-gap irregular.

Based on the result of FFD, the ranges of the design variables are determined for RSM

E. *Response surface method (RSM)*

The design variables and ranges are decided through FFD mentioned above as shown in Table V. Several experiments are conducted for RSM through FEA.

In this paper, central composite design (CCD) is employed as the experimental design to estimate the fitted model of each response. By adding center point and axial point to 2^k factorial design, the relationship between design variables and output can be considered. After implement of CCD, polynomial models of the response which are torque and THD are shown in (1) and (2) respectively. Fig. 5 and Table VI show the optimal value of each variable that satisfies maximum torque and minimum THD of back EMF [4].

$$\hat{y}_{Torque} = 300 - 0.676A - 1.077B + 6.292C - 0.170A^2 - 0.251B^2 - 1.379C^2 - 0.105AB - 0.402AC - 0.014CA \quad (1)$$

$$\hat{y}_{THD} = 3.935 - 0.008A + 0.022B + 0.060C + 0.015A^2 + 0.741B^2 + 0.003C^2 - 0.231AB - 0.024AC + 0.310CA \quad (2)$$

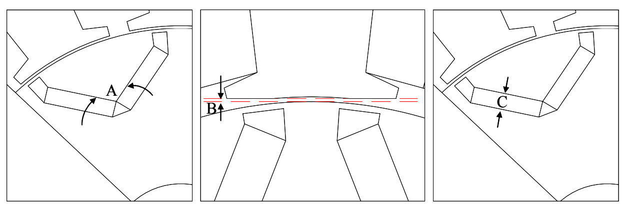
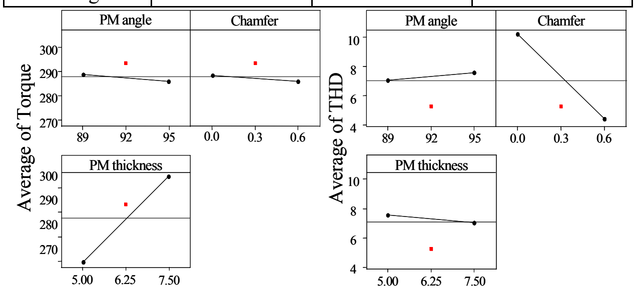


Fig. 3. Design variables of FFD

TABLE IV
NAME AND RANGE OF DESIGN VARIABLES FOR FFD

Symbol	A	B	C
Name	PM angle	Chamfer	PM thickness
unit	[°]	[mm]	[mm]
Range	89-95	0-0.6	5-7.5



(a) Torque (b) THD
Fig. 4. Main effect plot

TABLE V
NAME AND RANGE OF DESIGN VARIABLES FOR RSM

Symbol	A	B	C
Name	PM angle	Chamfer	PM thickness
unit	[°]	[mm]	[mm]
Range	89-92	0.3-0.6	6.25-7.5

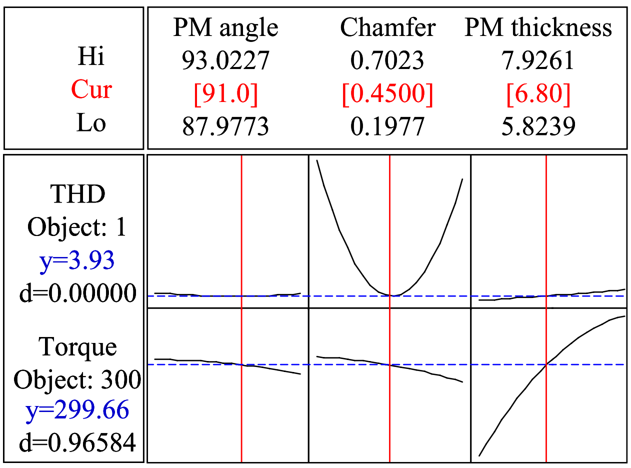


Fig. 5. Optimal point of each variable

TABLE VI
OPTIMAL POINT OF EACK VARIABLE

Symbol	A	B	C
Name	PM angle	Chamfer	PM thickness
unit	[°]	[mm]	[mm]
Value	91	0.45	6.8
THD	3.93 %		
Torque	299.6 Nm		

F. *Optimal model*

The back EMF of optimal model, designed using DOE combined with RSM, is calculated by FEA. Fig.6 shows configuration of optimal model which has 130mm stack length and 0.8mm air-gap. Back EMF of the optimal model and base model is calculated by FEA and compared as shown Fig. 7 (a), and Fig. 7 (b) is harmonic distribution of back EMF in the optimal model. Table VII describes the comparison of the amplitude and THD of back EMF between base model and optimal model. The THD of back EMF of the optimal model is …% less than that of the base model. However the amplitude of two models has similar value.

The optimal model is determined using DOE combined with RSM and parameters are calculated.

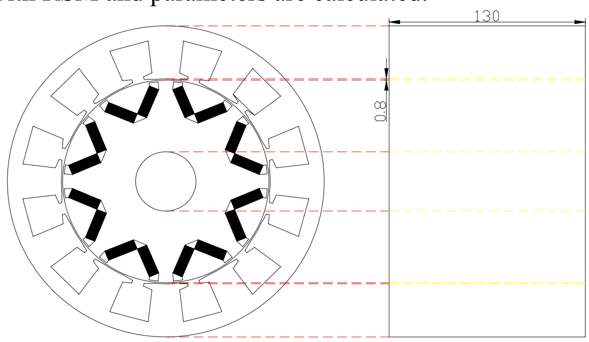
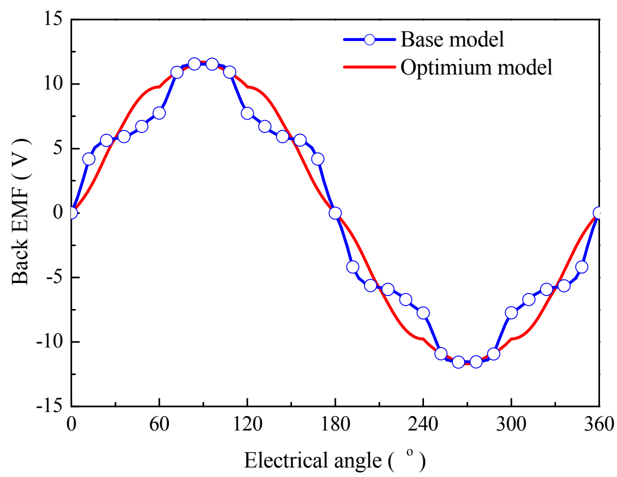
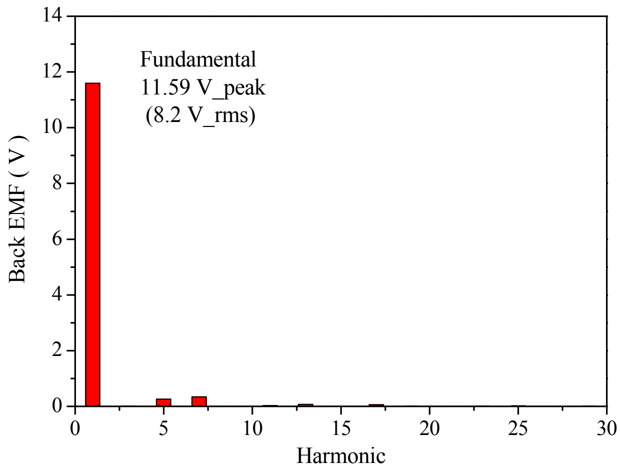


Fig. 6. Configuration of optimal model



(a) Comparison of back EMF shape (@400rpm)



(b) Harmonic distribution of back EMF(Optimal model)
Fig. 7 Analysis of back EMF

TABLE VII
OPTIMAL POINT OF EACK VARIABLE

	Line-Line EMF (@400rpm)	THD
unit	[Vrms]	[%]
Base model	13.8	23.7
Optimal model	14.2	3.7

III. CHARACTERISTICS

A. *Calculate parameters*

Before the d-q axes equivalent circuit analysis, parameters such as back EMF, d-q axes inductance, phase resistance and core loss resistance are calculated. The back EMF is estimated above as shown in Fig.7 and Table VII. In order to calculate d-q axes inductance profile, several equations induced by vector diagram, which have relationship with no-load flux linkage and load flux linkage, are applied and calculated. The core loss resistance is also computed by the relation between back EMF and core loss which is calculated using FEA at specified speed.

B. *D-q equivalent circuit analysis*

In order to calculate the characteristics of optimal model, parameters which are back EMF, d-q axes inductance, phase resistance and core loss resistance are computed. Using the parameters, d-q axes equivalent circuit analysis is performed to obtain the characteristics. The equations derived from equivalent circuits are shown in (3)-(5).

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_a}{R_c}\right) \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \tag{4}$$

$$T = P_n \left\{ \psi_a i_{oq} + \left(L_d - L_q\right) i_{od} i_{oq} \right\} \tag{5}$$

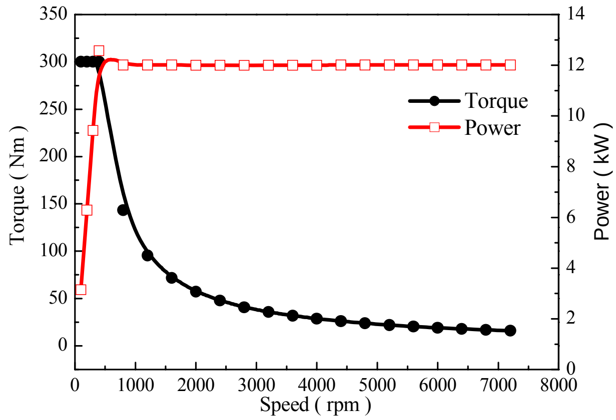
where P_n is number of pole pairs, ω is electrical angular velocity [2].

The characteristics of ISG, especially output power should be satisfied not only in motoring region but also in generating region. The analysis that uses d-q axes equivalent circuit is performed only in motoring mode due to the reversibility of motor and generator. Assume that output power is satisfied in the whole speed range of motoring mode, the power of generator is also satisfied.

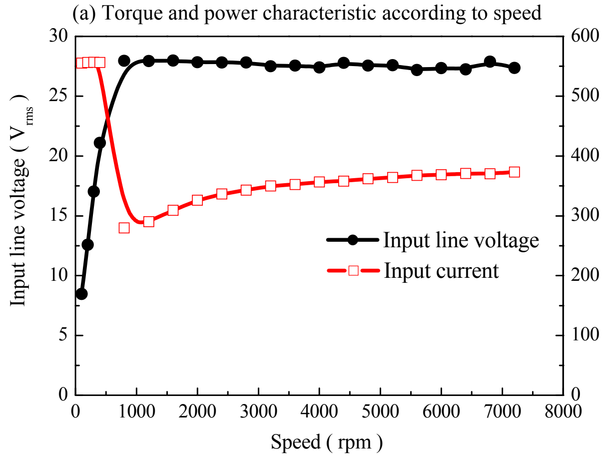
The result of d-q equivalent circuit analysis satisfies output power and torque in all the speed range as shown in Fig. 10 (a). Fig. 10 (b) shows the voltage and current mentioned above which must satisfy the limited conditions, which satisfy the specification.

IV. CONCLUSION

This paper deals with the optimal design of the IPMSM for ISG that is utilized in the mild type of HEV bus. The ISG can operate as not only motor but also generator. Therefore the output power of ISG should be satisfied in the whole speed range. In order to increase efficiency of generating mode, the back EMF should be as sinusoidal as possible. In this paper, an IPMSM which has both sinusoidal back EMF and object output power in all speed range is designed using DOE combined with RSM. Consequently the THD of back EMF is 3.7% and output power is 12kW in the whole generating speed range.



(a) Torque and power characteristic according to speed



(a) Input voltage and current characteristic according to speed

Fig. 10 Characteristics of IPMSM

ACKNOWLEDGMENT

This work was supported by grant no. RTI04-01-03 from the regional technology innovation program of ministry of commerce, industry and energy (MOCIE).

REFERENCES

[1] Ji Young Lee, Soon O Lee, Jae Woo Jung, Jung Pyo Hong, Yang Su Lee, Yoon Hur, "The comparison study of distributed and concentrated winding types in interior permanent magnet motor for integrated starter generator", Conference on electromagnetic field computation, pp.491, 2006.

[2] Yoji Takeda, Nobuyuki Matsui, Shigeo Morimoto, Yukio Honda, "Design and control of interior permanent magnet synchronous reluctance motor", Ohmsa, 2001

[3] Akira Nishio, Masahiro Hirano, Yoshiki Kato, Takayuki Irie, Tsutomu Bara, "Development of small size, light weight and high power IPM motor for electric vehicle", Mitsubishi heavy industries, LTD. Technical review, Vol. 40, No. 5. Oct. 2003.

[4] Sung-Il Kim, Ji-Young Lee, Young-Kyoun Kim, Jung-Pyo Hong, Yoon Hur, and Yeon-Hwan Jung, "Optimization for Reduction of Torque Ripple in Interior Permanent Magnet Magnet Motor by Using the Taguchi Method", *IEEE Transaction on Magnetics*, Vol. 41, No. 5, pp. 1796-1799, May. 2005.

ICEMS 2006

The 2006 International Conference on Electrical Machines and Systems

November 20-23, 2006, Nagasaki, Japan

Welcome Message

Dear Colleagues,

It is a real pleasure and an honor for us to announce the 9th International Conference on Electrical Machines and Systems (ICEMS 2006) organized by the IEEJ Industry Applications Society (IAS).

ICEMS is the only major international conference devoted entirely to electrical machines and systems in Asia and provides an excellent opportunity for scientists and experts from all parts of the world to present recent developments and to exchange useful information and experiences from their research. In this conference, four outstanding professors are scheduled to offer presentations.

ICEMS 2006 concludes the first technical co-sponsorship with IEEE IAS. Each committee has been making every effort in the careful preparation of ICEMS 2006. We sincerely hope that ICEMS 2006 shall conclude successfully and ICEMS will go on to develop further as an important conference in this field.

On behalf of all the Committees of ICEMS 2006, I would like to say that we welcome you to the 9th International Conference on Electrical Machines and Systems (ICEMS 2006).

Sincerely,

Prof. Ichiro Miki
ICEMS 2006 Conference Chairman
October 23, 2006

Session LS2A
PM Machines and Drives (4)
Date: Wednesday, 22 November 2006
Time: 11:05-12:25
Venue: Room A

LS2A-1 PDF	Comparing Coupled Analysis with Experimental Results for an Interior PM Machine K. Akatsu [1], R. D. Lorenz [2] [1]Tokyo University of Agriculture Technology, Japan, [2]University of Wisconsin, USA
LS2A-2 PDF	Design for Total Harmonic Distortion Reduction of Concentric Winding Type Interior Permanent Magnet Synchronous Motor for Integrated Starter and Generator Jung Jae-Woo [1], Peng Zhang [1]Jung-Pyo Hong [1], Ji-Young Lee [2] [1]Changwon National University, Korea, [2]Korea Electrotechnology Institute, Korea
LS2A-3 PDF	Loss Investigation of Interior Permanent Magnet Motors Considering Carrier Harmonics and Magnet Eddy Currents Katsumi Yamazaki, Atsushi Abe Chiba Institute of Technology, Japan
LS2A-4 PDF	3-D Lumped Magnetic Circuit Model for Analyzing High-Speed Single-Phase Flux-Switching Permanent Magnet Motor Y. Chen, Z.Q. Zhu, D. Howe University of Sheffield, UK

TOP

Session LS2B
Induction Machines, Doubly Fed Machines, and Their Drives (3)
Date: Wednesday, 22 November 2006
Time: 11:05-12:25
Venue: Room B

LS2B-1 PDF	Sensor-Less Induction Motor Drives with Stator Resistance Adaptation Using Estimation Error Index Tetsuya Sasao, Hisao Kubota Meiji University, Japan
LS2B-2 PDF	AC Induction Machine Simplified Model for Sensorless Control Design and its Observability Analysis P. Vaclavek, P. Blaha Brno University of Technology, Czech Republic
LS2B-3 PDF	A Simple Robust Control of an Induction Motor for High Torque without a Speed Sensor Koichiro Nagata [1], Toshiaki Okuyama [1], Haruo Nemoto [2], Toshio Katayama [2]