반응 표면법을 이용한 Multi-layer 매입형 영구자석 동기전동기의 효율 향상

방량, 권순오, 이상호, 장붕, 홍정표
창원대학교 전기공학과

Improvement of efficiency in Multi-layer IPMSM using Response Surface Methodology

LIANG FANG, SOON-O KWON, SANG-HO LEE, PENG ZHANG, JUNG-PYO HONG
Changwon National University

Abstract - This paper deals with the optimum rotor design approach about the multi-layer design of the buried magnets in an Interior Permanent Magnet Synchronous Motor (IPMSM), on the efficiency improvement by using Response Surface Methodology (RSM).

In the multi-layer design of the prototype 15kw IPMSM, the constant amount of buried PM is split from the single-layer into double-layer design for improving the efficiency characteristics. The optimum double-layer rotor structure is built with the help of RSM analysis. The improvement of IPMSM efficiency is verified by the Finite Element Method (FEM) results comparison with the prototype single-layer IPMSM.

1. INCTRODUCTION

In recent years, high-efficiency motors are required in the public welfare, industrial use, and hybrid and electric vehicle (HEV) propulsion. The interior permanent magnet (IPM) synchronous motors are of particular interests because of their several superior characteristics, such as high efficiency, high torque/power density, and wide constant-power speed range.

The IPM synchronous motor with the PM buried inside the rotor core, can utilize a hybrid torque production, magnet torque and reluctance torque. The reluctance torque is produced by the saliency effect of the IPM rotor structure, which is essentially created by the variation of the reluctance between d- and q-axis along the rotor surface. Therefore, the IPM rotors have reluctance torque in additional to the magnet torque generated by the buried PMs.

As we know, the synchronous reluctance motors (SRM) produce pure reluctance torque for output. The high rotor saliency can be achieved by increasing the flux-barriers in the SRM rotor part. Correspondingly, multi-layer flux-barrier design is introduced into the IPMSM rotor part design. In this paper, the single layer buried PM in the proto IPM model is split and embedded into the redesign flux-barriers creating a multi-layer design, by which the IPMSM having the beneficial attributes of both the SRM and IPM motor. Take the view of the advantages of motor performance, the multi-layer design have higher efficiency, extended high speed constant power operating range, and improved power factor.

In this paper, a 15kw single-layer IPMSM as the prototype model is redesigned into a V-shape double-layer IPMSM structure for improving the efficiency characteristic. With the help of response surface methodology (RSM) analysis, the optimum design parameters are obtained for rebuilding the double-layer IPMSM model. The improved efficiency of the new design is observed from the characteristic comparisons with the prototype model . All the characteristic results are calculated by Finite Element Method (FEM).

2. ANALYSIS AND MODELS

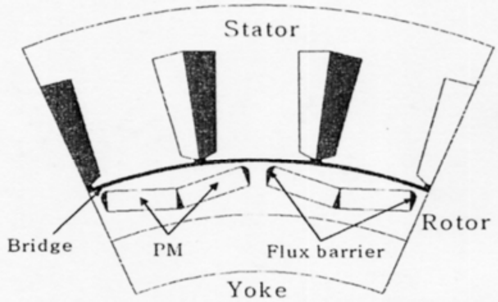
2.1 Prototype IPMSM Model

Fig. 1 shows the 1/8 prototype model, which is built from an IPMSM used in HEV. Table 1 lists the detailed informations of this model.

From the above introduction, the prototype IPMSM model has V-shape single layer PM buried in the rotor core, at has a relative high efficiency at speed 2000rpm, about 94.5%.

2.1.1 Design of Experiments (DOE)

In this paper, multi-layer IPM design method is adopted for further improving the efficiency of this IPMSM model. In the design process, double layer IPM is chosen because of the consideration of the simplicity for manufacturing, the easiness of inserting PM into the rotor core and the mechanical robustness.

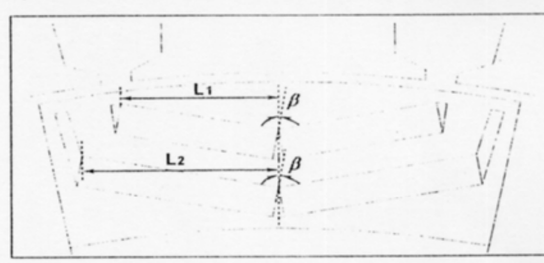


<Fig 1> Prototype single V-shape IPMSM model

Firstly, the design parameters should be determined. In the basic structure of the V-shape double-layer model (as Fig. 2 shows), the design variables are obtained primarily. The same amount of PM is split into two layers. The lengths of two layers and the included angle of the V-shape are interested.

In the design of experiment (DOE) part, the (2^3+1) models are built with all the combinations of design parameters, that are lengths (*L1, L2*), and the angle (β) among their respective ranges. Table 2 lists the array of the 2^3 designed models.

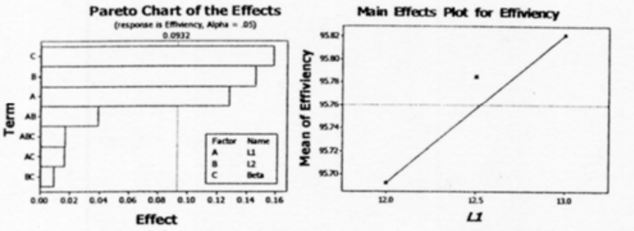
In the DOE analysis, the significant design parameters are selected from the investigation of main and interaction effect analysis. In this double-layer design, parameters (*L2 and* β) are determined for further detail optimal design in next RSM analysis. The parameter (*L1*) is token off from the DOE for its limitation in the design, who easily makes other design parameters more complicate. And from the parameter (*L1*) main effect plot, the longer of *L1* is benefit for the improvement of efficiency. Therefor, the maximum length of (*L1=13mm*) is fixed.



<Fig 2> Design parameters of V-shape double-layer IPMSM

<Table 1> The Array of the DOE Analysis Models

Experiment (2^3+1) No.	*L1* [12, 13]	*L2* [13, 15]	β [0, 9]	Efficiency %
1	12.0	13.0	0	95.50
2	12.0	15.0	9	95.86
3	13.0	13.0	9	95.84
4	13.0	13.0	0	95.7
5	13.0	15.0	0	95.8
6	12.0	15.0	0	95.71
7	12.5	14.0	4.5	95.79
8	12.0	13.0	9	95.7
9	13.0	15.0	9	95.95

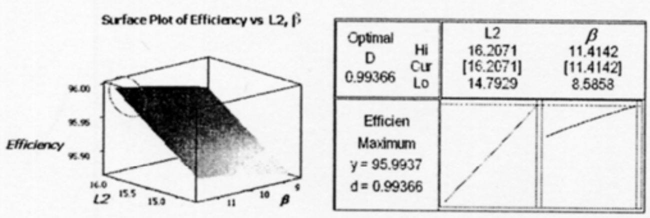


(a) (b)

<Fig 3> DOE analysis (a) Main effect and (b) L2 effect analysis

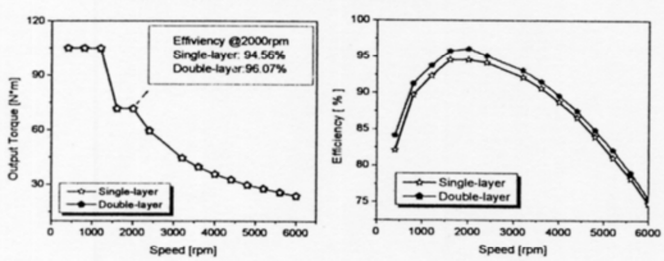
2.1.2 Response Surface Methodology (RSM)

RSM is applied to find the optimum combination of the significant design parameters more detail. From the DOE analysis, the maximum efficiency is predicted to exist near the design ($L1$=13, $L2$=15, and β=9^o). And, considering their trends of variation, the RSM is dealt with the range of (14.5mm<$L2$<16mm, and 9^o<β<11.5^o). The Fig. 4(a) displays the response surface of efficiency. And, the optimum analysis of parameters combination ($L2$, and β) is obtained from their related variation, as Fig. 4(b) shows.



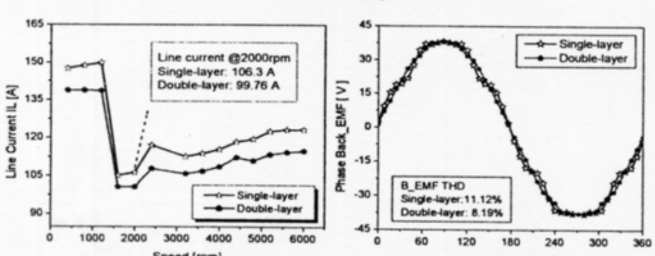
(a) (b)

<Fig 4> Efficiency response surface (a), and Response optimization analysis (b) in RSM



(a) (b)

<Fig 5> IPMSM models characteristics analysis #1 (the same MTPA output) (a) Efficiency@2000rpm comparison; (b) Efficiency comparison (all speed range)



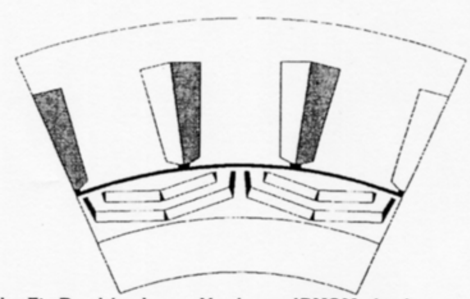
(a) (b)

<Fig 6> IPMSM models characteristics analysis #2 (the same MTPA output) (a) Stator windings current comparison; (b) Back_EMF characteristics comparison

2.2.1 Analysis of Efficiency Improvement

From the response surface methodology (RSM) analysis, the optimum design of the V-shape double-layer IPMSM model is determined. In the Fig. 7, the finally designed model is built with the optimum parameters, which are list in Table 1, comparing with the prototype model. Then, the characteristics of the new designed model is studied bu FEM.

Compare with the prototype single-layer model, the double-layer redesigned IPMSM model improves the efficiency characteristic. With the same performance of maximum torque per ampere (MTPA) characteristic plot as the Fig. 5(a) shows, the efficiency of all the speed range is enhanced. And, the rated operation point at 2000 rpm as the design point is investigated, where the efficiency is improved from 94.56% to 96.07%.



<Fig 7> Double-layer V-shape IPMSM design model

The improvement of the efficiency performance can be partly understood from the Fig. 6(a) and (b). In the Fig. 6(a), the line current in the stator windings is compared. According to the same MTPA output, the double-layer model is operated with the current 99.76 (Ampere), compare with the 106.34 (Ampere) in the prototype single-layer IPMSM model. The reduced windings current results in the decrease of the copper loss in the stator core directly. In addition, the back_EMF THD characteristic in stator windings also is improved, which is decreased from 11.12% to 8.19%. Therefore, the core loss is decreased correspondingly.

3. CONCLUSION

The multi-layer IPMSM design is presented in this paper. The prototype single-layer IPMSM model is redesigned with a double-layer V-shape rotor structure for improving the efficiency at the operation point speed=2000(rpm). The optimum double-layer model determined by the DOE and RSM analysis increases the efficiency from 94.56% to 96.07%, saves 226 (Watta) electric loss. It is well proved that multi-layer design can well improve the performance of the IPMSM.

[REFERENCE]

[1] Shigo Morimoto, Masayuki Sanada, Yoji Takeda, "Performance of PM Assisted Synchronous Reluctance Motor for Hign Efficiency and Wide Constant Power Operation," *IEEE Transactions On Industry Applications, Vol. 37, No. 5, Sepetember/Octorber 2001*

[2] Erich Schmidt, Wolfgang, "Comparative Finite Element Analysis of Synchronous Reluctance Machines with Internal Rotor Flux Barrier," *IEEE Transactions Magnetics, October, 2001*

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

[4] RAYMOND H. MYERS, DOUGLAS C, MONTGOMERY, "Response Surface Methodology: Process and Product Optimization Using Designed Experiments" THIRD AVENUE, NEW YORkK, NY 10158-0012.

[5] Nicola Bianchi, Thomas M. Jahns, "DESIGN, ANALYSIS, AND CONTROL OF INTERIOR PM SYNCHRONOUS MACHINES," IEEE-IAS Electrical Machines Committee. October 2004.

<Table 2> Specification of the Prototype IPMSM model

Parameters	Single-layer Values	Double-layer Values	Unit
Stator outer radial	138.5	138.5	mm
Stator inner radial	100.8	100.8	mm
Number of Turns	51	51	
Rotor outer radial	100	100	mm
V_{PM} /pole	158*32	158*32	mm^3
PM layer	15.8*5*2	(13+16.2)*2.71	mm^3
Pole/slot	16/24	16/24	
Rated speed	2000	2000	rpm
MTPA@2000rpm	105	105	N*m
Current@2000rpm	106.3	99.76	ampere
Efficiency @2000rpm	94.56%	96.07%	

THE KOREAN INSTITUTE OF ELECTRICAL ENGINEERS

'06

대한전기학회 제37회 하계학술대회 논문집

Proceeding of the 37th the KIEE Summer Annual Conference 2006

- 일 시 : 2006년 7월 12일(수) ~ 14일(금)
- 장 소 : 용평리조트(강원도 평창군)

B

- 전기기기
- 전력전자
- 전기교통신기술
- 신재생에너지시스템
- 친환경전기기기
- S-Session(학부생 발표)

주 최 : 대한전기학회
후 원 : 한국전력공사 · 한국학술진흥재단
한국과학기술단체총연합회

EMP 47 **유한요소법을 이용한 전력용 변압기의 2차원 온도분포 예측**
········· 이정근, 김중경, 주수원, 한성진 751

EMP 48 **동기형 릴럭턴스 전동기의 토크와 역률의 최대화를 위한 설계 및 해석**
········· 김원호, 김기찬, 원성홍, 안준선, 최승길, 이 주 753

EMP 49 **방열기를 갖는 유입자냉식 변압기의 온도분포 해석**
········· 김중경, 한성진, 오연호, 박경엽 755

EMP 50 **전기자동차를 위한 컨프레샤용 BLDC Motor 구동드라이브에 관한 연구**
········· 정경수, 전장건, 최형래, 우 도, 이동헌, 이상훈, 박성준, 정태욱 757

EMP 51 **BLDC 모터 구동을 위한 신경회로망 PI파라미터 자기 동조 시뮬레이터**
········· 배은경, 권중동, 김태우, 김대균, 전지용, 이승환, 이훈구, 김용주, 한경희 759

EMP 52 **신경회로망을 이용한 IPMSM 드라이브의 온라인 파라미터 추정**
········· 박기태, 최정식, 고재섭, 이정호, 김종관, 박병상, 정동화 761

EMP 53 **단상 유도형 동기전동기의 파라미터 변화에 따른 동특성 해석**
········· 오세영, 정대성, 임승빈, 이 주 763

EMP 54 **극 수와 슬롯 수 조합에 따른 집중권 방식 매입형 영구자석 동기전동기의 Normal Force 및 설계 파라미터의 비교에 관한 연구**
········· 하승형, 권순오, 반지형, 정재우, 홍정표 765

EMP 55 **BLDC 전동기의 코깅토크 저감을 위한 고정자 설계**
········· 유대일, 임승빈, 김기찬, 원성홍, 이 주 767

EMP 56 **실험계획법을 이용한 Magnetic suspension의 최적설계**
········· 정재우, 김성일, 하승형, 홍정표, 이주훈 769

EMP 57 **매입형 영구자석 동기전동기의 극 수 슬롯 수 조합에 따른 특성에 관한 연구**
········· 반지형, 권순오, 하승형, 홍정표 771

EMP 58 **직접 구동용 5kW AFPM 풍력 발전기 특성 해석**
········· 김형길, 김철호, 서영택, 오철수 773

EMP 59 **고효율 영구자석 릴럭턴스 전동기의 설계 및 해석**
········· 장 붕, 권순오, 홍정표 775

EMP 60 **반응 표면법을 이용한 Multi-layer 매입형 영구자석 동기정동기의 효율 향상**
········· 방 량, 권순오, 이상호, 장 붕, 홍정표 777

EMP 61 **농형 유도전동기의 회전자 바 손상에 따른 특성 해석**
········· 김병국, 김미정, 조윤현, 임성환, 황돈하, 강동식 779

EMP 62 **역기전력을 고려 한 브러시리스 전동기의 토크리플 저감에 관한 구동 방식에 대한 연구**
········· 손 도, 남기용, 이근호, 홍정표 781

EMP 63 **매입형 영구자석 전동기의 파라미터 검증을 위한 인덕턴스 산정**
········· 이석희, 이상호, 반지형, 홍정표 783

EMP 64 **전기자 권선 방법에 따른 매입형 영구자석 동기 전동기의 특성 비교**
········· 박수범, 권순오, 김성일, 홍정표 785

EMP 65 **산업용 잉크젯 플로터의 압전세라믹 헤드에 의한 드롭제어**
········· 최근수, 윤신용, 백수현, 김 용 787