

반응 표면법을 이용한 Multi-layer 매입형 영구자석 동기정동기의 효율 향상

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

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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. INTRODUCTION

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 addition 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

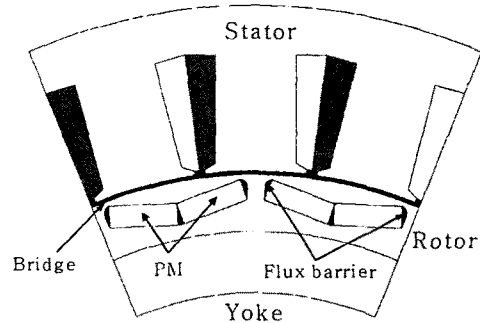
2.1 Prototype IPMSM Model

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 casiness of inserting PM into the rotor core and the mechanical robustness.

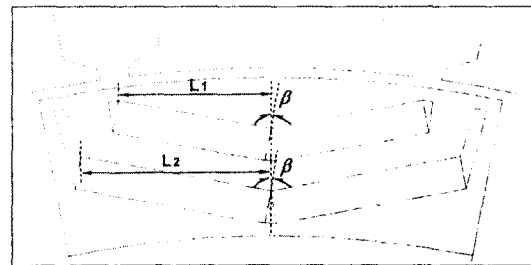


<Fig 1> Prototype single V-shape IPMSM model

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.

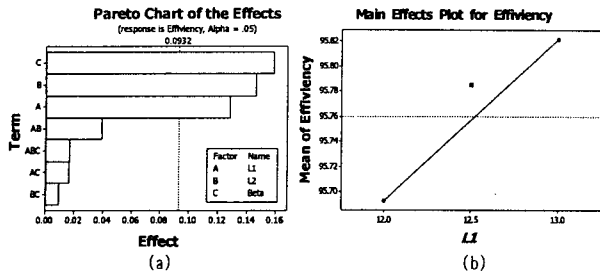
In the DOE analysis, the significant design parameters are selected from the investigation of main and interaction effect analysis. In this double-layer design, parameters ($L2$ and β) are determined for further detail optimal design in next RSM analysis. The parameter ($L1$) is taken off from the DOE 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. Therefore, 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

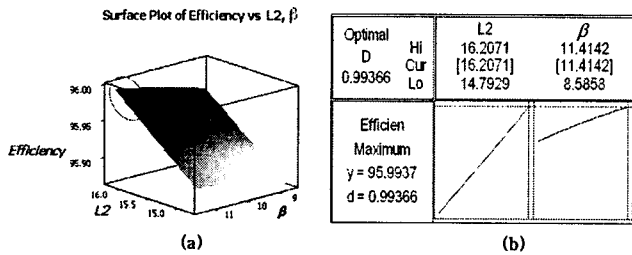
Experiment (2^3+1) No.	$L1$ [12, 13]	$L2$ [13, 15]	β [0, 9]	Efficiency %
1	12.0	13.0	0	95.50
2	12.0	15.0	9	95.86
3	13.0	13.0	9	95.84
4	13.0	13.0	0	95.7
5	13.0	15.0	0	95.8
6	12.0	15.0	0	95.71
7	12.5	14.0	4.5	95.79
8	12.0	13.0	9	95.7
9	13.0	15.0	9	95.95



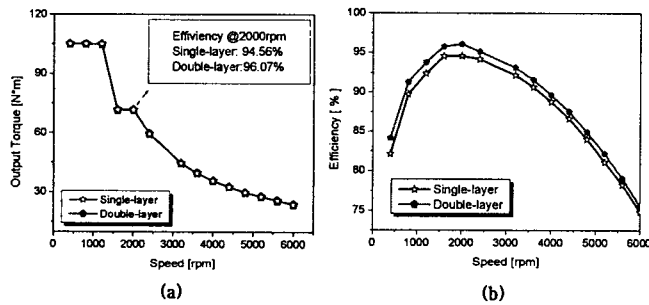
<Fig 3> DOE analysis (a) Main effect and (b) L2 effect analysis

2.1.2 Response Surface Methodology (RSM)

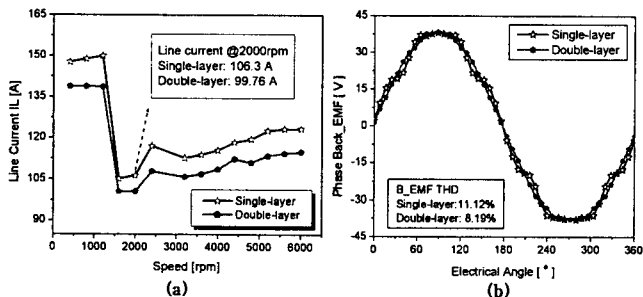
RSM is applied to find the optimum combination of the significant design parameters more detail. From the DOE analysis, the maximum efficiency is predicted to exist near the design ($L1=13$, $L2=15$, and $\beta=9^\circ$). And, considering their trends of variation, the RSM is dealt with the range of ($14.5\text{mm}<L2<16\text{mm}$, and $9^\circ<\beta<11.5^\circ$). 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.



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



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

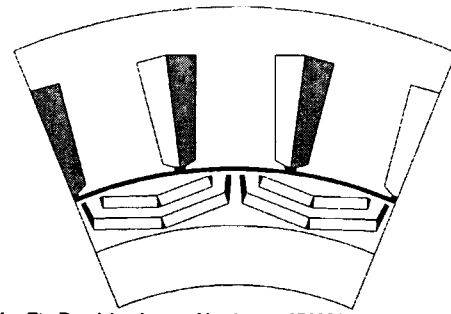


<Fig 6> IPMSM models characteristics analysis #2 (the same MTPA output) (a) Stator windings current comparison; (b) Back_EMF characteristics comparison

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 by 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



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

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%.

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.

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<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%	