Torque Ripple Reduction of Multi-layer design Interior Permanent Magnet Motor Using Response Surface Methodology

Liang Fang, Soon-O Kwon, Peng Zhang, Jung-Pyo Hong
Changwon National University, Gyeongnam, 641-773, KOREA

***Abstract*—This study concerns with torque ripple reduction of interior permanent magnet synchronous motors (IPMSM) by multi-layer design of permanent magnets buried in the rotor part. With the help of response surface methodology(RSM), the ripple at constant output torque and the back E.M.F harmonics distortion are investigated in the multi-layer IPM rotor design. Finally, the reduction of torque ripple between the prototype model and optimal redesigned multi-layer model are verified through the results comparison by finite element method(FEM).**

***Index Terms*—IPMSM, torque ripple, back E.M.F, RSM, multi-layer IPM design, FEM.**

I. Introduction

An interior permanent magnet synchronous motor (IPMSM) is a high efficiency motor and operates in a wide speed range[1]. It is used in public welfare and the industrial field, especially in vehicle propulsion systems in recent years[2]. However, the IPMSM has significant torque ripple production, which causes serious operating noise and vibration[3].

In an IPM motor, there are three sources of the torque ripple coming from the construction of the magnetic and electric circuit of a machine[4]:

1) cogging effect: interaction between the rotor magnetic and variable permeance of air gap due to the geometry of stator slots;
2) distortion of the sinusoidal or trapezoidal distribution of the magnetic flux density in the air gap;
3) differences between permeances of the air gap in the *d* and *q* axes.

The most comprehensive literature review and comparison of methods of the torque ripple reduction is given in [5]. Through the motor structure optimizing design, the torque ripple reduction can be well achieved.

In this paper, a single layer IPMSM used in a hybrid electric vehicle (HEV) propulsion system is introduced as the prototype analysis model. For reducing the torque ripple at the critical threshold of constant torque output (at 1200rpm), the same amount of buried PM in the prototype single layer design IPMSM is split into several layers creating a multi-layer IPM design. The IPMSM having multi-layer IPM design rotor have numerous performance advantages over a single layer rotor design, such as relative high overall efficiency, extended high speed constant power operating range, and so on. In this study of torque ripple reduction, the characteristic of back E.M.F harmonics is investigated at the same time. The latter one is considered in term of the value of total harmonic distortion(THD), which has significant effect on the performance of a designed motor. The minimum of THD value denotes the desirable sinusoidal distribution of the induced back E.M.F waveform in the stator windings, which interacts with the supply current waveform produces electrical torque as well as introduces ripple[6]. Also, the energy loss by the high harmonics is well decreased. Therefore, the back E.M.F THD characteristic be analyzed in the multi-layer IPM rotor redesign study is valuable.

With the help of design of experiment(DOE) and response surface methodology(RSM), the optimization of multi-layer IPM design model is analyzed with the discussing of the motor characteristic responses. Then, the finite element method(FEM) is used for verifying the reduction of torque ripple and improvement of back E.M.F harmonics.

II. Model Analysis and Design

A. Prototype Single layer IPMSM Model

The 1/8 of the existing prototype IPMSM model is presented in Fig. 1. It has 16-pole and 24-slot, with a single PM layer buried inside the rotor part for each pole.

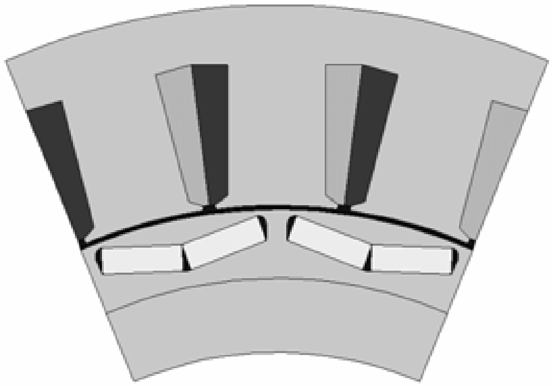

Fig. 1. Prototype (V-shape) Single layer IPMSM model

This work was supported by grant No. RTI04-01-03 from the Regional Technology Innovation Program of the Ministry of Commerce, Industry and Energy (MOCIE)

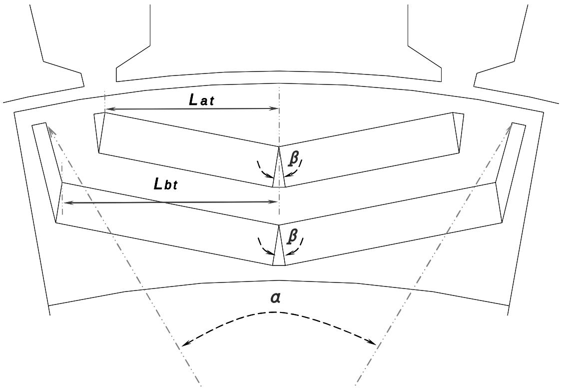

Fig. 2. double layer IPM design model and design parameters

B. Multi-layer IPM Design Analysis

From the view of rotor part structure, the multi-layer designed IPMSM have the beneficial attributes of both the synchronous reluctance motor (SRM) and IPM motor. As in some of SRM researches, the motor characteristics and performances can be improved by increasing the layers in the rotor part. On the other hand, the PM insertion is a complex and relative costly process. Therefore, in this torque ripple reduction study, the double layer IPM design is chosen for rotor part redesign because of the considerations such as the simplicity for manufacturing, the easiness of inserting PM into rotor core and the mechanical robustness.

The introduced prototype IPMSM model as shown in Fig.1, is already optimizing designed as the "V-shape" based on the single layer construct. Correspondingly, for comparing analogically, the double layer IPMSM also adopts "V-shape" PM layers. The redesign IPM rotor model is generally displayed in Fig.2.

From the Fig. 2, some design parameters are labeled as (L_{at}, L_{bt}, α, β). As some finished work, the parameter (L_{at}) is fixed at ($L_{at}=12.5mm$) for simplicity consideration. Therefore the design parameters (L_{bt}, α, β) are chosen for the double layer IPM rotor redesign, that is the length of lower PM layer, the pole angle of PMs and the angle of shape "V" are considered in ordinal.

III. DOUBLE LAYER IPMSM DESIGN

A. Design of Experiment (DOE)

In this paper, full factorial design is used firstly and the reason is written as follows [7]. In the DOE analysis, the selected design parameters (L_{bt}, α, β) for the double layer IPM rotor redesign are investigated and the interaction effects between them are evaluated without confounding. The TABLE I lists that all the combinations and an additional middle values point of these three design parameters. Totally ($2^3+1=9$) initial models are built. By using FEM, the responses of torque ripple(at 1200rpm) and back E.M.F THD in each model are calculated. Then, according to the responses, the important design parameters are detected. Moreover, the predictions of the responses according to the variation of the design parameters are determined primarily.

From the design parameter general effect analysis in Fig. 3, the design parameters (L_{bt}, α) show great effect on the responses of torque ripple and back E.M.F THD. Therefore, both of (L_{bt}, α) as the important design parameters are further analyzed from the main effect of themselves and interaction effect of each other, as Fig. 4 and Fig. 5 show. For reducing the torque ripple and improving back E.M.F THD characteristic, the desirable responses are predicted closed to ($L_{bt}=16.0mm$, $\alpha=19^o$). On the other hand, although the design parameter (β) has not important effect on the responses, the suitable value should be determined for the following optimization. By the main effect analysis, ($\beta=22.5^o$) is the chosen. Therefore, the further optimization analysis should be done with the important design parameters (L_{bt}, α) near the predicted design point ($L_{bt}=16.0mm$, $\alpha=19^o$, $\beta=22.5^o$).

TABLE I
DOE Full Factorial Design Array

No.	α	β	L_{bt}	Torque ripple (%)	Back E.M.F THD (%)
1.	19.0	25.0	13.0	10.440	11.213
2.	19.0	20.0	16.0	6.045	3.615
3.	19.0	20.0	13.0	10.265	10.918
4.	20.0	20.0	16.0	7.516	1.600
5.	20.0	20.0	13.0	10.550	9.357
6.	20.0	25.0	16.0	8.835	1.503
7.	19.0	25.0	16.0	6.600	3.542
8.	20.0	25.0	13.0	10.300	9.796
9.	19.0	25.0	13.0	10.440	11.213

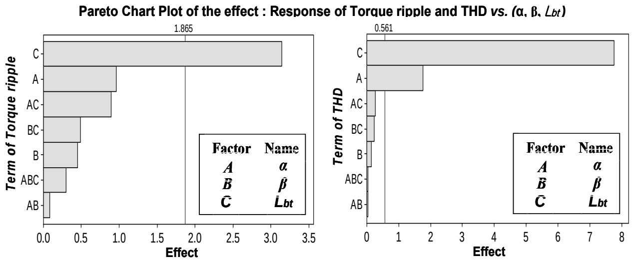

Fig. 3. Standardized Effects: Torque ripple and Back E.M.F THD

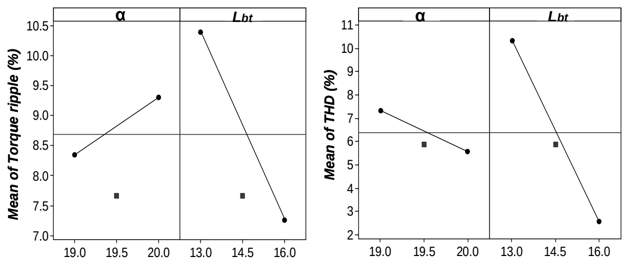

Fig. 4. Main Effects of important design parameters (L_{bt}, α)

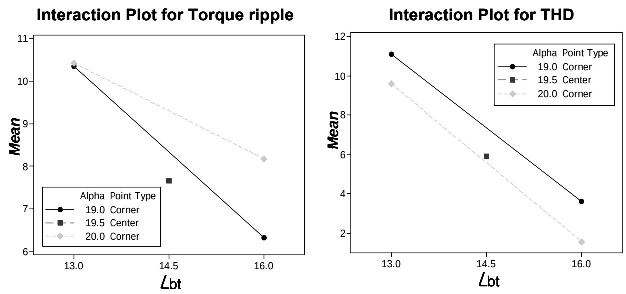

Fig. 5. Interaction Effects of important design parameters (L_{bt}, α)

B. Response Surface Methodology (RSM)

RSM is a collection of statistical and mathematical techniques used for developing, improving and optimizing process[8].

In RSM optimization analysis, the important design parameters (L_{bt}, α) determined from the DOE effect investigation, are discussed more particular for finding an optimal double layer IPMSM model. TABLE Π lists the experimental array of RSM. The torque ripple and back E.M.F THD characteristics of each experimental model are analyzed by FEM. The FEM results are observed on the response surface. The responses distribution of torque ripple and back E.M.F THD are shown in Fig. 6, in which the corresponding square region of low torque ripple and THD values are found. Fig. 7 shows the overlap region of the two responses, with the condition of (torque ripple response between 6%~7%, and THD between 2%~3%).

TABLE Π
Experimental Array of RSM

No.	α	L_{bt}	Torque ripple (%)	Back E.M.F THD (%)
1.	19.7243	16.7500	7.81	1.31342
2.	19.3000	16.7500	7.19	2.37294
3.	19.3000	16.7500	7.19	2.37294
4.	18.8757	16.7500	6.55	4.14985
5.	19.3000	17.8107	7.48	2.65375
6.	19.3000	15.6893	6.83	3.70117
7.	19.3000	16.7500	7.19	2.37294
8.	19.3000	16.7500	7.19	2.37294
9.	19.0000	16.0000	6.76	4.71332
10.	19.3000	16.7500	7.19	2.37294
11.	19.3000	16.7500	7.19	2.37294
12.	19.6000	17.5000	7.31	1.97000
13.	19.6000	16.0000	7.30	1.31642
14.	19.0000	17.5000	6.65	1.84504

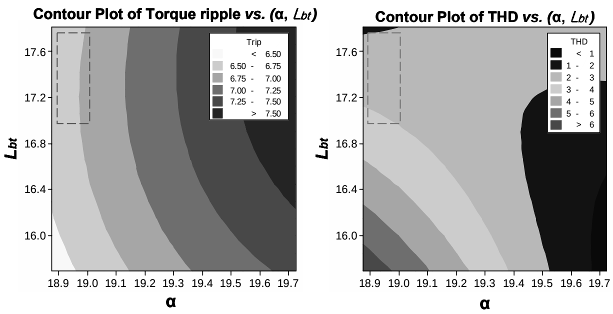

Fig. 6. Responses distribution of Torque ripple and Back E.M.F THD

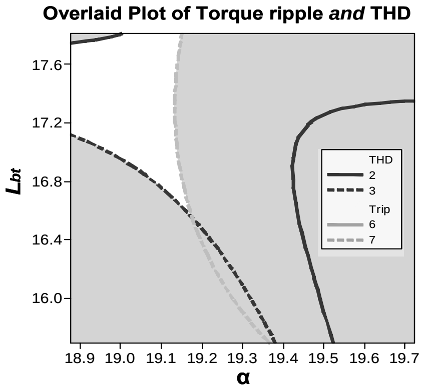

Fig. 7. Overlap region of torque ripple and back E.M.F THD

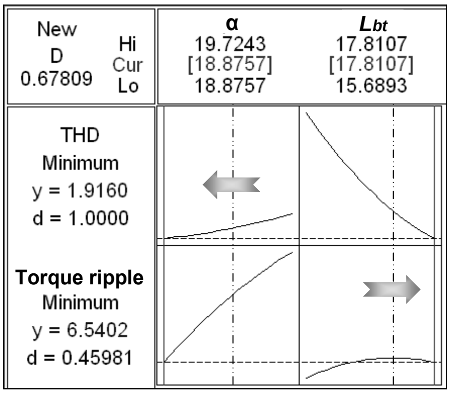

Fig. 8. Optimization analysis of design parameters and response

C. Optimal Model and Analysis

According to the distribution of responses, the variation of the characteristics of torque ripple and back E.M.F THD according to the design parameters (L_{bt}, α) are analyzed, as Fig. 8 shows. For considering the limitation of the design region in the rotor part, the final double layer IPM rotor is determined with the design parameters ($L_{bt}=17.5mm$, $\alpha=18^o$, $\beta=22.5^o$). As the optimal model, the reduction of torque ripple and improvement of back E.M.F THD are generally achieved.

IV. Characteristics Discuss

In the RSM analysis, the optimal designed double layer IPMSM model is theoretically built, with the decreased torque ripple and improved back E.M.F THD characteristic. But, RSM is a kind of analytical method in essence, with inevitable error existing in the obtained results [8]. Therefore, it is necessary to build the double layer designed IPMSM model with the final design parameters combination ($L_{bt}=17.5mm$, $\alpha=18^o$, $\beta=22.5^o$), and the characteristics of the redesigned model are preciously calculated by FEM again. Then, the reduction of torque ripple and the improvement of back E.M.F THD characteristic are confirmed by results comparison. Fig. 10 shows the output torque (at 1200rpm) comparison, which indicates the torque ripple is decreased from 8.8% of prototype model to 5.3% of the optimal designed double layer model. Fig. 11 and Fig. 12 show the back E.M.F harmonic distributions. The great improvement of back E.M.F is achieved with the THD decreased from 11.5% to the 1.82%.

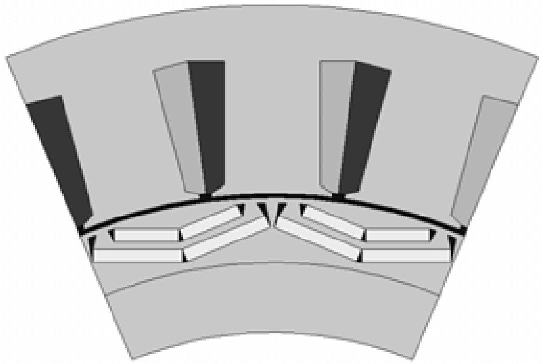
Fig. 9. Optimal redesigned double layer IPMSM mode

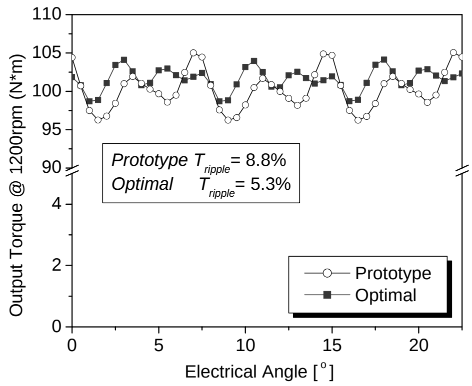

Fig. 10. Output torque waveform comparison

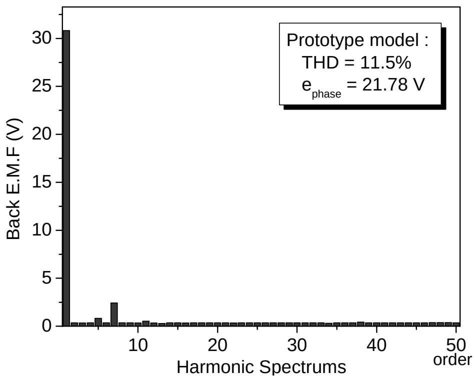

Fig. 11. Prototype model back E.M.F THD characteristic

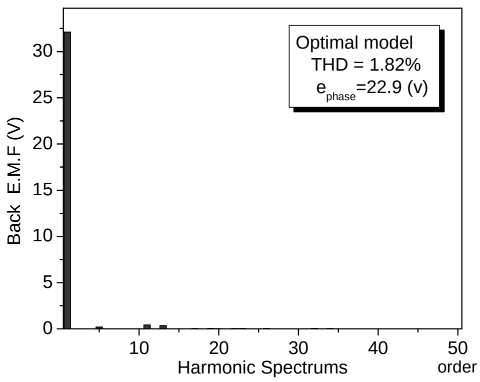

Fig. 12. Optimal design double layer IPMSM model back E.M.F THD characteristic

V. Conclusion

In this paper, the torque ripple reduction of the prototype single layer IPMSM is well achieved through the double layer IPM design in the rotor part. In the optimization analysis of the double layer IPM rotor redesign, the optimal double IPMSM model is built with lower torque ripple and more sinusoidal back E.M.F characteristic. The validity of the proposed multi-layer IPM design is confirmed by the characteristics comparisons between the prototype and optimal redesigned IPMSM models. Also, this study suggests that any motor characteristics and performances improvement can be achieved with the proposed approach.

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A Study on the Improvement of Construction Error in Permanent Magnet Stepping Motor with Claw Pole

Dae Sung Jung, Seoun Bin Lim, Ju Lee

Hanyang University, Korea

DS2F1-07 PDF

Reduction of Torque Ripple Using Harmonic Current Injection in Interior Permanent Magnet Synchronous Motor

Ji-Hyung Bahn [1], Sung-Il Kim [1], Jung-Pyo Hong [1], Geun-Ho Lee [2]

[1]Changwon Nat'l Univ, Korea, [2]Gyeongnam Provincial Namhae Collage, Korea

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DS2F1-08 PDF

The Acoustic Noise Reduction in Interior Permanent Magnet Motor by Structural and Electromagnetic Design

Sang-Ho Lee [1], Suk-Hee Lee [1], Jung-Pyo Hong [1], Sang-Moon Hwang [2]

[1]Changwon National University, Korea, [2]Pusan National University, Korea

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DS2F1-09 PDF

A Sensorless Speed Control of IPMSM Using an Adaptive Integral Binary Observer

Hyoung Lee, Hyung Seok Kang, Young Seok Kim

Inha Univerrity, Korea

DS2F1-10 PDF

The Comparison of Characteristic and Operating Performance by Pole-Slot Combinations in Interior Permanent Magnet Synchronous Motor with Concentrated Winding

Seung-Hyoung Ha, Soon-O Kwon, Ji-Hyung Bahn, Jung-Pyo Hong

Chnagwon Nat'l. Univ, Korea

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Optimum Design of Interior Permanent Magnet Synchronous Motor Using Taguchi Method

Ikuro Morita, Yuuki Hotta

University of Tokushima, Japan

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Sensorless Drive for Brushless DC Motor Using Simple Voltage Detecting Circuit

Sung-Chul Go [1], Seung-Joo Kim [1], Sol Kim [2], Seung-Bin Lim [1], Joon-Seon Ahn [1], Seung-Kil Choi [3], Ju Lee [1]

[1]Hanyang University, Korea, [2]Yuhan College, Korea, [3]Ansan College, Korea

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Torque Ripple Reduction of Multi-Layer Design Interior Permanent Magnet Motor Using Response Surface Methodology

Liang Fang, Soon-O Kwon, Peng Zhang, Jung-Pyo Hong

Changwon National University, Korea

DS2F1-14 PDF

Prediction of Efficiency and Torque Characteristic on Concentrated Winding IPMSM with Wide Speed Range

Sung-Il Kim [1], Ji-Hyung Bhan [1], Jung-Pyo Hong [1], Ki-Chae Lim [2]

[1]Changwon National University, Korea, [2]Dongsung Electric Machine Co. Ltd, Korea

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Improvement of Ozone Yielding Characteristic Using a DSP Controlled Multilevel Resonant Inverter

Sung-Geun Song [1], Feel-Soon Kang [2], Sung-Jun Park [1], Yu Tao [1], Chae-Joo Moon [3]

[1]Chonnam National University, Korea, [2]Hanbat National University, Korea, [3]Mokpo National University, Korea