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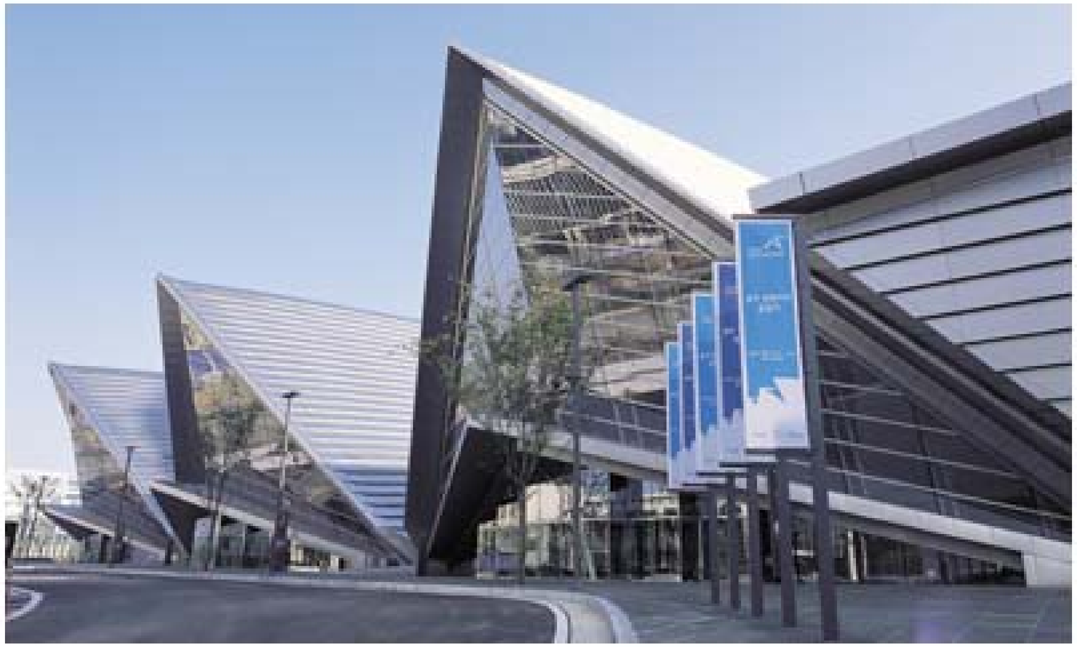

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- Optimal Shape Design of Double-barriers in Single-layer Interior PM Synchronous Motor for Reducing Torque Pulsation

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Optimal Shape Design of Double-barriers in Single-layer Interior PM Synchronous Motor For Reducing Torque Pulsation

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Abstract —A proposed novel double-barrier design with single-layer IPMSM is well proved to be effective for reducing pulsation torque, torque ripple and cogging torque, in published work [1], in which the torque characteristics be sensitive to the unique "connected" double-barrier structure is generally studied. This extended paper presents a few specific models for examining the effect of design variables in double-barrier design on pulsation torque reduction. With the help of response surface methodology (RSM), each of proposed models is optimized and analyzed. The pulsation torque calculation verified in previous work, that equivalent circuit method (ECM) coupling with finite element analysis (FEA) is still performed in this paper. In final, a more effectively and economic model of novel double-barrier IPMSM design on pulsation torque reduction is determined.

I. Introduction

The interior permanent magnet synchronous motors (IPMSM) have advantage of high torque per rotor volume, while their significant pulsation torque always bothering designers in IPMSM design, that vibration and acoustic noise, and smooth operation are strictly required [2], [3]. For reducing the pulsation torque, which usually consisting torque ripple and cogging torque, the unique flux-barrier structure is flexibly utilized in IPM rotor design [4], [5]. A double-layer IPM design [6], as Fig. 1 shows and a novel double-barrier IPM design proposed in work [1], as Fig. 2 shows. Both of them are proved to be effective on pulsation torque reduction.

In this extended paper, a few specific double-barrier models are built for investigating the effectiveness of novel double-barrier IPM design on pulsation torque reduction in detail. With the help of response surface methodology (RSM), the effect of design variables in each proposed models on pulsation torque reduction is analyzed. Then, the simple novel double-barrier model with main effect design variables for minimizing pulsation torque is determined. The IPMSM torque characteristic is analyzed by using equivalent circuit method (ECM) [7] coupled with FEA, as used in work [1].

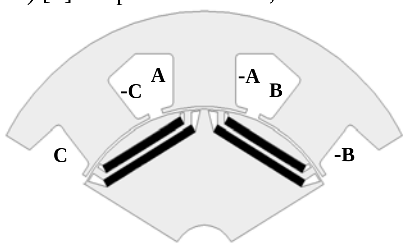


Fig. 1. Configuration of popular double-layer IPMSM model

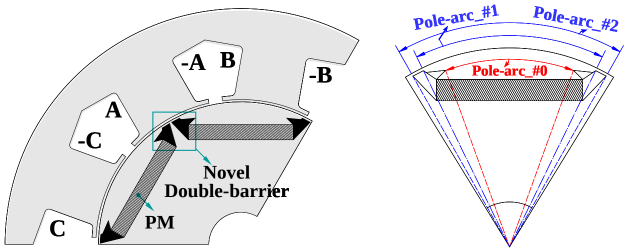


Fig. 2. Configuration of novel double-barrier IPMSM model

II. Double-barrier Designs in Single-layer IPM Rotor

The unique flux pattern in novel double-barrier IPM rotor field is displayed in Fig. 3. The effect of the "inner" flux-barriers on redistributing magnetic flux is visually illustrated, that concentrating the main magnetic flux to cross into air gap along central axis direction, while the "cuniform" regions formed between the "inner" flux-barriers and rotor surface can effectively shunt the flux flowing into air gap on both sides. It is obvious that the geometry of "cuniform" region has obvious effect on the flow quantity of flux, by which sinusoidal magnetic field in air gap can be formed, which benefits to improve the torque performance of IPMSM.

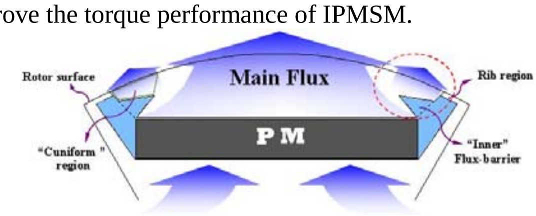


Fig. 3. Graphical illustration of magnetic flux distribution of novel design

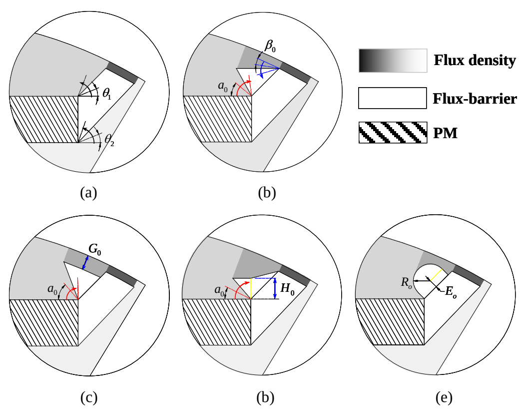


Fig. 4. Models of flux-barrier design creating different "cuniform" region

TABLE I
RANGES OF DESIGN VARIABLES FOR OPTIMIZATION IN RSM

Design variables	Modeling of novel double-barrier Design				
	(a)	(b)	(c)	(d)	(e)
θ_1 [°]	20 ~ 106	65	65	65	65
θ_2 [°]	37 ~ 53	54	54	54	54
α_0 [°]	*	30 ~ 60	40 ~ 80	30 ~ 60	*
β_0 [°]	*	20 ~ 30	*	*	*
G_0 [mm]	*	*	1.0~ 1.5	*	*
H_0 [mm]	*	*	*	1.0 ~1.5	*
R_0 [mm]	*	*	*	*	0.7 ~ 0.9
E_0 [mm]	*	*	*	*	0.5 ~ 1.4

III. MODELING OF DOUBLE-BARRIER DESIGN

The proposed novel double-barrier IPMSM model is built and optimized only according to the magnet pole-arcs variation as a basic study in previous work [1]. But, the unique "cuniform" region varying for redistributing the flux pattern in rotor, further realizing pulsation torque reduction did not be embodied. Therefore, this paper proposes a few specific novel double-barrier design models, which detailed describe the "cuniform" region with their feature design variables, as in Fig. 4 shows. TABLE I lists the experiment ranges of each design variable for analyzing their effectivity on pulsation torque reduction. The design objectives in RSM, including torque ripple at rated operation, cogging torque (peak-peak), and total harmonic distortion (THD) of back electromotive force (Back-EMF), are calculated using the test proved method presented in work [1]. By performing RSM simulation, the responses of each design objective according to each design variables are investigated, as Fig. 5 illustrates. The desired minimum value points can be determined, or the decrease tendency of design objectives can be predicted, which help to build an optimum model with reasonable values of design variables [9].

IV. RESULTS AND DISCUSS

The pulsation torque characteristics, including torque ripple and cogging torque are reduced by optimizing the shape of flux-barriers in each proposed model, by following the presented optimization process in work [1]. By using the given design variables, the optimized IPMSM models are built with their respective "fittest value" of design variables, as Fig. 5 determined. Then, the simulation results of predicted in RSM are verified by using FEA and experiment method [10].

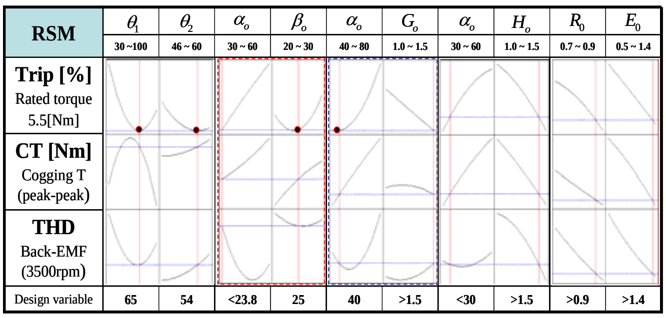


Fig. 5. Responses of design objectives with design variables in RSM

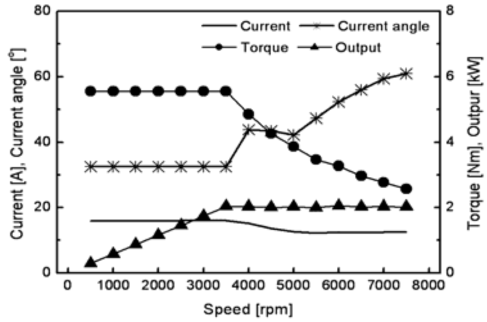
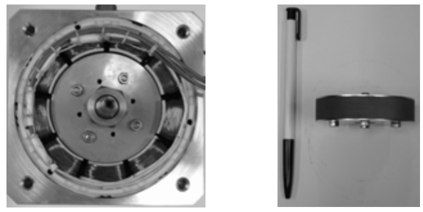
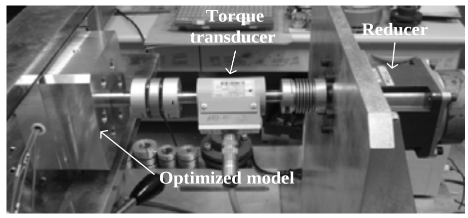


Fig. 6. Speed versus output characteristics of IPMSM.

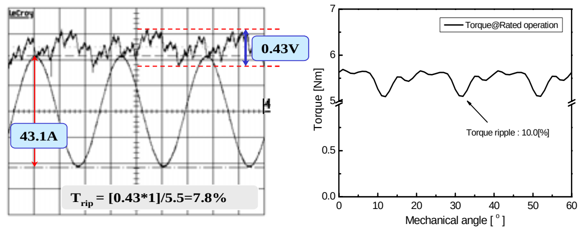


(a) Fabricated double-layer design IPMSM



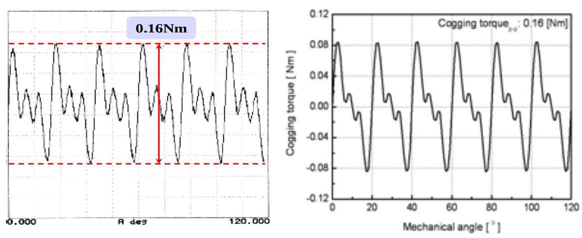
(b) Testing apparatus for torque characteristic measurement

Fig. 7. Output torque test of optimized double-layer design IPMSM



(a) Test result [1V indicates 1Nm] (b) FEA result

Fig. 8. Torque ripple of double-layer IPMSM @Rated torque=5.5[Nm]



(a) Test result (b) FEA result

Fig. 9. Cogging torque results of double-layer IPMSM.

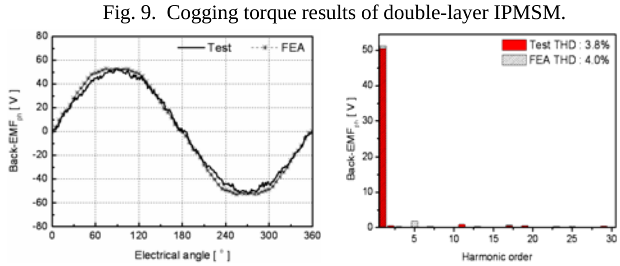


Fig. 10. No-load Back-EMF and THD results @ at 3500rpm

As the work [1] given, for confirming the predicted machines characteristics, as Fig. 6 illustrates, the optimized double-layer design IPMSM model is fabricated and tested, as Fig. 7 shows, The torque ripple at rated load operation of base speed 3500[rpm] is tested and the tested result 7.8[%] lower than the analysis result 10.0[%] is found, as Fig. 8 shows. The error is thought caused by the influence of the reduction gear inertial. In additional, the cogging torque and Back-EMF characteristics are tested, and the tested results show good agreement with FEA results, as Fig. 9 and Fig. 10 give. The slightly different may be caused by manufacturing.

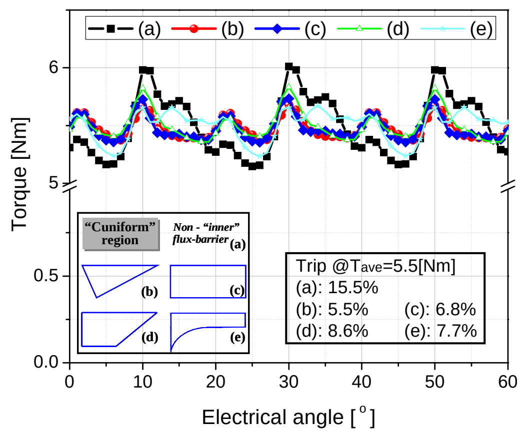


Fig. 11. Torque ripple results comparison of each optimized model

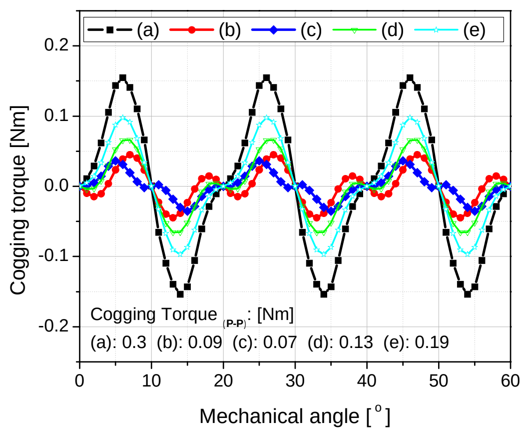


Fig. 12. Cogging torque results comparison of each optimized model

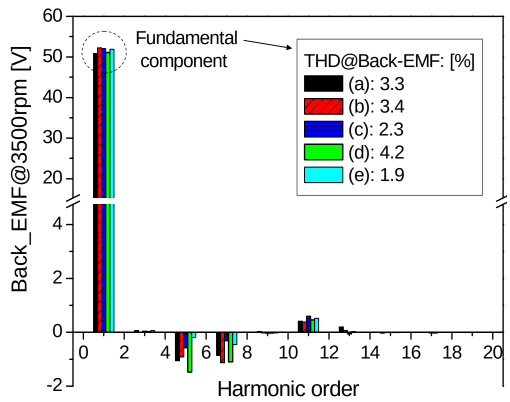


Fig. 13. THD of Back-EMF results comparison of each optimized model

According to the presented RSM analysis given in Fig. 5, all the optimized four IPMSM models are built and analyzed using the test confirmed FEA method, and compared for examining the effectiveness of these flux-barrier designs with distinct characteristics on torque pulsation reduction, by which the design of model (b) and model (c) are more effective for reducing both torque ripple and cogging torque are obviously observed, as Fig 11 and Fig.12 show, as well as their Back-EMF characteristics as Fig. 13 shows. On the other hand, their design variables are simple and suitable for furthest optimizing the "cuniform" regions. Compare with other models, the model (b) and (c) designs are more economic and effectivity on pulsation torque reduction of IPMSM.

V. Conclusion

Based on the previous work of novel double-barrier design of single-layer IPM rotor structure, this paper further examined the effectivity of different flux-barrier shape designs in the novel double-barrier model for reducing pulsation torque. As the presented results comparison, the proposed model (b) and model (c) featuring of simple design variables and economic structure, but significant effect on both torque ripple and cogging torque reduction. Therefore, these two specific models prefer to be applied to low pulsation torque IPMSM with the double-barrier IPM rotor design.

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