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Double-barrier Design in Interior Permanent Magnet Synchronous Motor for Improving Efficiency Performance

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This paper presents a study on efficiency improvement of an interior permanent magnet synchronous motor (IPMSM) by rotor structure design. Based on a provided conventional single-barrier IPMSM model, a double-barrier design model is proposed for achieving higher efficiency performance under the same output torque. With the help of an optimization technique that design of experiment (DOE) simulation combined with response surface methodology (RSM), an optimum double-barrier IPMSM model is built. In the study, the main emphasis is placed on revealing the merits of double-barrier rotor design that benefits to the motor efficiency improvement. The equivalent circuit method (ECM) coupled with finite element method (FEM) is used in this paper for calculating the machine parameters and analyzing motor efficiency performance.

Index Terms—IPMSM, efficiency performance, double-layer rotor design, DOE, RSM, ECM, FEM.

I. INTRODUCTION

THE INTERIOR permanent magnet synchronous motors (IPMSM) have wide applications to household goods, industrial use, and electric and hybrid vehicle propulsion [1]. The IPMSM have superior performance characteristics, that including high efficiency, high torque density, and wide constant power operating range [2], which make the IPMSM attractive for vehicle propulsion.

In this study, a high efficiency IPMSM used as a traction motor in vehicle propulsion system is introduced as analysis model for motor efficiency performance investigation.

In permanent magnet machines, the PMs buried insides the rotor core, which is benefit for avoiding the separation of PM caused by the centrifugal force at high speed. On the other hand, the IPMSM generates hybrid torque production that including magnet torque and reluctance torque. The magnet torque is produced by the buried magnets, and another additional reluctance torque is generated from the unique rotor structure. As Fig. 1 shows, the axis directly along the d -axis exhibits high reluctance due to the low permeability of PM, while along the q -axis that between the flux-barriers inside the IPM rotor, there exists no magnetic barrier, that having low reluctivity to magnetic flux. This variation of the reluctance around rotor creates saliency in the rotor structure, by which the reluctance torque is generated.

It can be found that a single-layer PM with one flux-barrier rotor design can also be split into several layers creating a multi-layer PM design. As some investigators reports, the multi-layer PM design can reduce flux leakage and improve the rotor saliency. Therefore, the IPMSM having multi-layer rotor design have numerous performance advantages over the single-layer rotor design, such as enhancing overall efficiency, extending high speed constant power operating range, and improving power factor [3].

In this study, a double-layer rotor design is adopted in the

optimal design for practical consideration, that as simplicity for manufacturing, the easiness of inserting PM into the rotor core and the mechanical robustness. However, the double-layer rotor design can still reveal the peculiarity of multi-layer rotor design, which owning the beneficial attributes of both the synchronous reluctance motors (SynRM) and the PM motors from the rotor structure point.

Therefore, in the case of generating specific hybrid torque produce, the increasing of reluctance torque production due to high rotor saliency can compensate the reducing magnet torque production. In general, the higher the rotor saliency creates, the lower the dependency on magnet torque. Correspondingly, the copper loss in the armature windings can decrease with the reducing of armature current.

In the paper, the optimal design of double-layer rotor structure is presented. In order to quickly determine the optimal structure of double-layer PMs buried in the rotor, the simulation approaches of design of experiment (DOE) combined with response surface methodology (RSM) is performed. In the simulation procedure, the machine parameters and performances are calculated by using finite element method (FEM) and equivalent circuit method (ECM). Finally, the machines characteristics between the prototype single-layer IPMSM model and the optimal designed double-layer IPMSM model are compared to verified the improvement of motor efficiency performance.

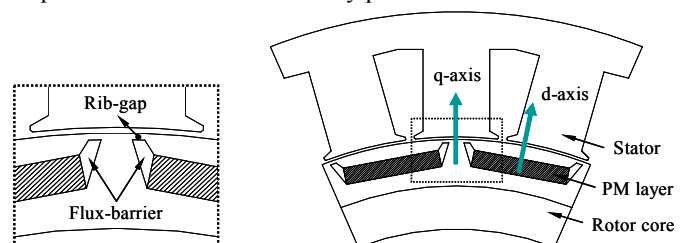


Fig. 1 Configuration of a typical IPMSM model

II. ANALYSIS MODEL DESCRIPTION

A. Analysis IPMSM Model

The analysis IPMSM model used as a traction motor in electrical vehicle propulsion system is given, as Fig. 2 shows. It has 16-pole and 24-slot, with concentrated windings arranged in stator part. In each pole region, a single-layer PM is inserted into radial cavity, and the single-layer PM is designed as “V” shape.

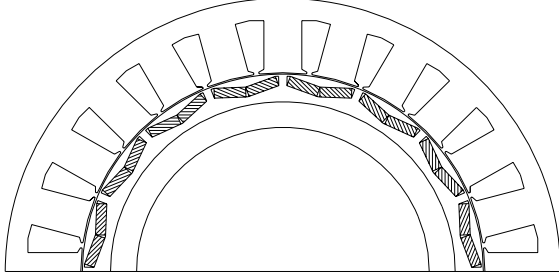


Fig. 2 Prototype single-barrier IPMSM model

B. Equivalent Circuits Method

Equivalent circuits for IPMSM based on a synchronous d - q reference frame including iron losses, are presented in Fig. 3. The mathematical model of the equivalent circuit is given as following equations. Iron loss is considered by equivalent resistance R_c , and d - and q -axis voltages and hybrid torque equations are given by (1), (2) and (3), respectively [5], [6].

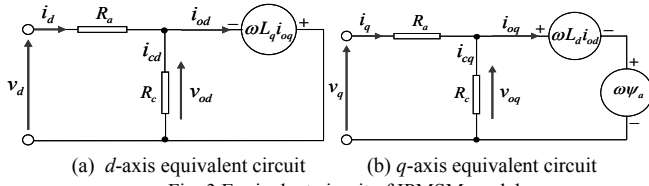


Fig. 3 Equivalent circuit of IPMSM model

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

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_d \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \quad (2)$$

$$\begin{aligned} T &= P_n \{ \psi_a i_{od} + (L_d - L_q) i_{od} i_{oq} \} \\ &= P_n \left\{ \psi_a I_a \cos \beta + \frac{1}{2} (L_q - L_d) I_a^2 \sin 2\beta \right\} \quad (3) \end{aligned}$$

Where i_d and i_q are d - and q -axis component of armature current, i_{cs} and i_{cq} are d - and q -axis component of iron loss current, v_d and v_q are d - and q -axis component of terminal voltage, R_a is armature winding resistance per phase, R_c is iron loss resistance, ψ_a is flux linkage of PM per phase(rms), L_d and L_q are d - and q -axis armature self inductance, P_n is number of pole pairs, β is the lead angle of phase current ($=\tan^{-1}(i_d/i_q)$), and the saliency ratio is defined as $\rho(=L_d/L_q)$, T is the hybrid torque production in IPMSM.

III. DOUBLE-BARRIER DESIGN OF ROTOR STRUCTURE

In order to determine an optimum structure of double-layer PM design, the simulation approach that design of experiment (DOE) coupling with response surface methodology (RSM) is performed in the following optimal design. According to the above discussion, the rotor saliency under phase current (@100[A], current angle= 40°) and the line-to-line Back-EMF under 2000[rpm] are chosen as object functions because the object functions are closely relates to efficiency performance and are able to calculate easily by FEM.

A. Design of Experiment

The approach of double-layer IPM rotor provides much more flexible variables for optimum structure design. Therefore, for investigating which design variables affect the object functions critically and determining the optimal rotor structure quickly, the simulation DOE is performed firstly. The design variables in the double-layer rotor structure are given as the Fig. 4 shows. TABLE I lists all the design variables and corresponding experiment ranges, respectively.

By performing the simulation DOE, the full factorial combination of all the design variables that (2^N+1) models are built that the four design variables [LPM_1, LPM_2, α , β] makes $(2^4+1=)$ 17 models. Then, all models are analyzed under the object functions of saliency ratio and Back_EMF. From main effect and interaction effect analyzing, the significant design variables and reasonable design ranges are decided.

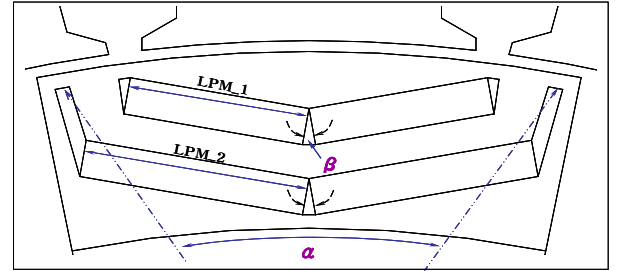
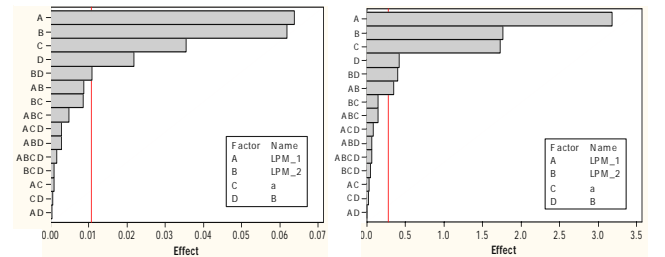
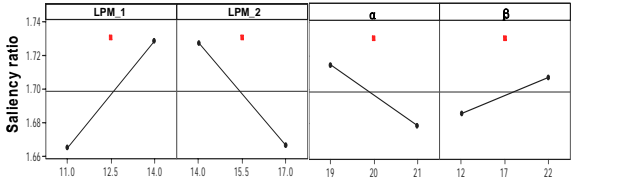


Fig. 4 Design variables of double-layer IPM rotor structure

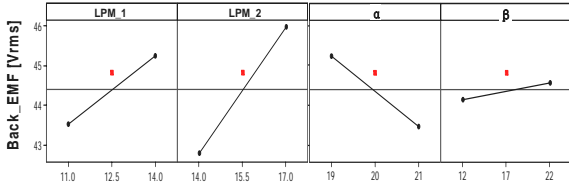
Design variable	Items of design variable	Experiment range	Unit
LPM_1	Length of 1 st PM layer	[11 ~ 14]	mm
LPM_2	Length of 2 nd PM layer	[14 ~ 17]	mm
α	Mechanical Angle of pole-arc	[18 ~ 22]	degree
β	Angle of gap of PM segments	[10 ~ 22]	degree



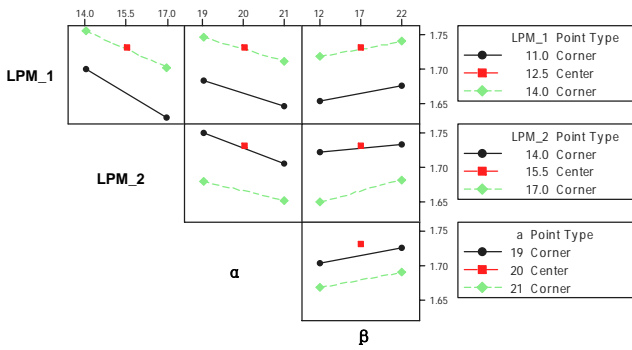
(a) Rotor saliency, (b) Back_EMF
Fig. 5 Pareto Chart of standardized effect of all design variables



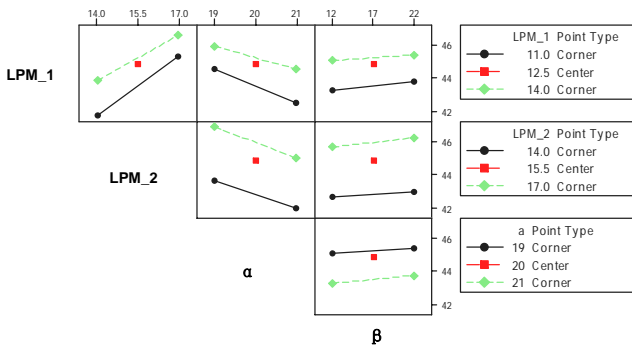
(a) Main effect analysis for saliency ratio [$@100[A]$, current angle= 40°]



(b) Main effect analysis for Back_EMF [line-to-line@2000[rpm]]



(c) Interaction effect analysis for saliency ratio [$@100[A]$, current angle= 40°]



(d) Interaction effect analysis for Back_EMF [line-to-line@2000[rpm]]

Fig. 6 Main effect and interaction effect analysis of all design variables

The effect of the design variables upon the object functions can be concluded from the above plots analysis. The design variables [LPM_1, LPM_2, α] shows significant effect on both object functions, as Fig. 5(a) and (b) show. It is also found that the length of PM layers [LPM_1, LPM_2] has significant effect on rotor saliency oppositely. And, the design variables [LPM_1, LPM_2] are associated by using the same amount of PM. Therefore, the main design variables [LPM_2, α] are determined for the next RSM optimizing analysis.

B. Response Surface Methodology

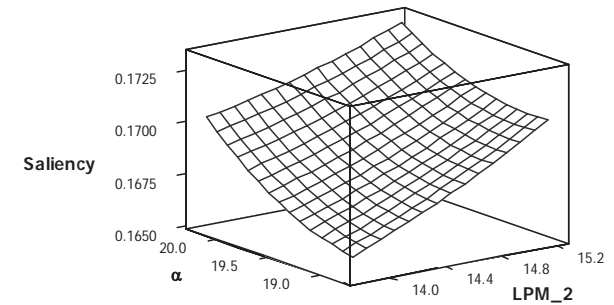
RSM is a collection of statistical and mathematical techniques used for developing, improving and optimizing process[4]. With the main design variables [LPM_2, α], the analysis models are built in more reasonable experiment

ranges by using similar approach of simulation DOE. TABLE II gives the design variables and their experiment ranges that investigated in RSM. The design variable [LPM_1] changes with [LPM_2] for simplicity consideration, and the design variable [$\beta=17^\circ$] is constant.

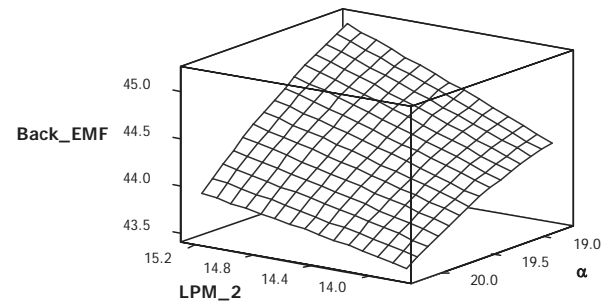
The response surface of each object function is obtained with design variables of [LPM_2, α] by performing RSM. According to the response surfaces of object function, as shown in Fig. 7(a) and (b), the maximum of saliency ratio with desired Back_EMF is achieved with the design variables [LPM_2=14.5mm, $\alpha=19.5^\circ$]. Therefore, the optimal double-layer rotor structure is determined with [LPM_1=13.5mm, LPM_2=14.5mm, $\alpha=19.5^\circ$, $\beta=17^\circ$].

TABLE II
DESIGN VARIABLES AND EXPERIMENT RANGES FOR RSM

Design variable	Items of design variable	Experiment range	Unit
LPM_1	Length of 1 st PM layer	28-LPM_1	mm
LPM_2	Length of 2 nd PM layer	14 ~ 15	mm
α	Mechanical Angle of pole-arc	19 ~ 20	degree
β	Angle of gap of PM segments	17	degree

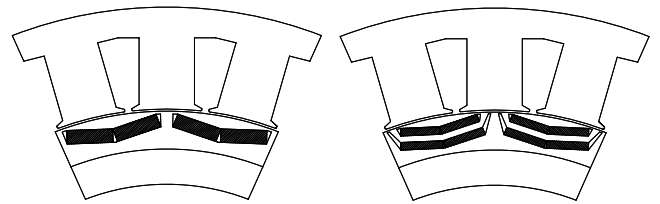


(a) Object function of saliency ratio [$@100[A]$, current angle= 40°]



(b) Object function of Back_EMF [line-to-line@2000[rpm]]

Fig. 7 Response surfaces of object functions by RSM



(a) Prototype single-layer model (b) Optimal double-layer model

Fig. 8 Configuration of IPMSM model

IV. RESULT AND ANALYSIS

The optimal designed IPMSM model with double-layer rotor structure is built with the determined design variables. The configurations of both the prototype single-layer model and optimal double-layer design model are shown in Fig. 8. Then, the characteristics are analyzed and compared.

Both of the prototype and optimal designed IPMSM models are required to satisfy the same torque performance along all the speed range in the analysis. As the Fig. 9(a) shows, the maximum torque per ampere (MTPA) control strategy is adopted at low speed range, while the flux weakening control strategy is applied to high speed operation[7],[8]. And then, the improvement of efficiency performance all over operation range is verified, as Fig. 9(b) shows.

The inductance along d - and q -axis are calculated by FEM under the phase current $I_a=100[A]$. It is found that the double-layer IPMSM model has higher rotor saliency, with larger q -inductance while smaller d -axis inductance, as the Fig. 10(b) shows. Therefore, the higher reluctance torque production is generated, and the reducing of magnet torque production is realized under the same hybrid torque production. Both of the two kinds of torque production are calculated and compared separately in Fig 11 (a) and (b).

The decrease of magnet torque production helps to alleviate the copper loss caused by the current following in armature windings. On the other hand, the iron loss exists in both stator core and rotor core decreased since the flux leakage reduction, as Fig. 12 shows. These are the essential reasons of efficiency performance improving.

In general, the presented approach of double-layer rotor design in IPMSM realizes the improvement of motor efficiency performance. Although the design process of increasing layer is different, and the cost of manufacture of rotor will increases, the double-layer rotor design can promote the IPMSM to be excellent candidates for vehicle propulsion.

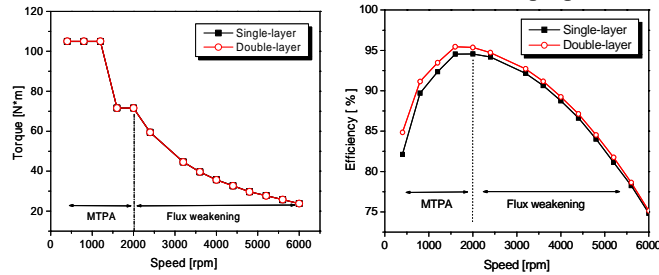


Fig. 9 Machine Performance comparison

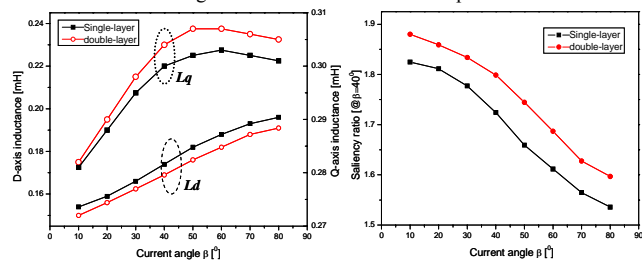


Fig. 10 Inductance characteristic comparison ($I_a=100[A]$)

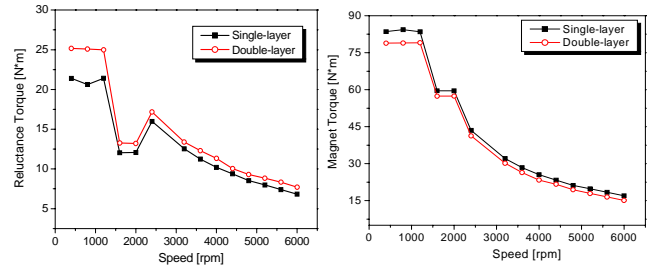


Fig. 11 Torque performance comparison

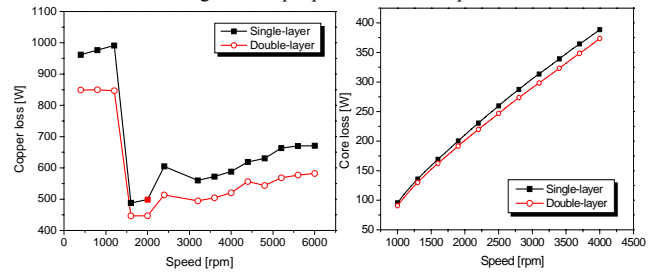


Fig. 12 Energy loss characteristic comparison

V. CONCLUSION

This paper has presented the optimal design of double-layer IPMSM for improving efficiency performance. From the above analyzing based on characteristic comparisons between the prototype single-layer IPMSM model and the optimal design double-layer IPMSM model, the efficiency performance improving through multi-layer rotor design is well verified in theory and instantiation. In conclusion to this study, the multi-layer rotor design, as compared to single-layer design, can generate higher rotor saliency that is helpful to improve machine performances without increasing PM usage.

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