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Optimal Design of a Novel Asymmetrical Rotor Structure to Obtain Torque and Efficiency Improvement in Surface Inset PM Motors

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This paper proposes an optimal design of a novel asymmetrical rotor structure for surface inset PM motors to obtain torque and efficiency improvement. Different from the conventional approach, the proposed design of asymmetrical rotor structures is employed to improve the torque production by creating rotor asymmetry to allow the reluctance torque and the magnetic torque reach a maximum at the same current phase angle. In order to evaluate the contribution, the frozen permeability method (FPM) is utilized to segregate the torque into its reluctance and magnetic torque components. For demonstrating the design concept and obtaining a criterion for improving torque by making full use of torque components, an optimal design by iterative computation is first to be performed utilizing finite element method (FEM). Based on the obtained criterion, the optimal design by algorithms such as Kriging method and genetic algorithm is applied to further improve the torque and efficiency. As a result, the performance of the proposed surface inset PM motor by 2-step optimization is dramatically improved compared with that of the conventional surface inset PM motor. Furthermore, a comparison between the optimized surface inset PM motor and a conventional surface-mounted PM (SPM) motor is also performed under the same operating condition, which demonstrates that the optimized surface inset PM motor can significantly save the magnet amount compared to the conventional SPM motor for producing the same output torque.

***Index Terms*—Asymmetrical rotor, finite element method, frozen permeability method, genetic algorithm, magnetic torque, optimal design, reluctance torque, surface inset PM motor, surface-mounted PM motor.**

I. Introduction

PERMANET magnet synchronous motors (PMSMs) are continuously increasing their scope for various industrial and domestic applications due to their superior performance such as high efficiency and high torque (power) density [1]. Depending on the magnet configuration, PMSMs can be mainly classified as: surface-mounted PM motor, surface inset PM motor, bread-loaf PM motor, buried or an interior PM motor. It has been shown that surface inset PM motors have higher mechanical robustness, lower magnet eddy-current losses, better field weakening capability compared to surface-mounted PM motors, while they have less manufacturing cost compared to interior PM motors. Hence, surface inset PM motors are recognized as a better option when a compromise between the performance and cost is considered [2].

Accordingly, extensive literature can be found on the research of the surface inset PM motors especially on aspects of analytical methods [3], [4]. Essentially all the reported research is predicated on a fact that the motors are designed such that the rotor shape maintains circumferential symmetry such that two axes of symmetry for each rotor pole can be defined, namely the direct or d-axis and the quadrature or q-axis. These axes of symmetry are, in turn, located such that the q-axis is 90 electrical degrees from the d-axis. It is well known that one of the significant features in surface inset PM motors is the presence of magnetic saliency which contributes to the production of the reluctance torque. By convention, an elegant d-q rotor frame equivalent circuit can be developed for analyzing the torque characteristics using the Park transformation, where it is displayed that the magnetic torque and the reluctance torque reach the maximum value at different current phase angles theoretically by 45 electrical degrees with respect to each other. Consequently, the resultant torque is obtained as the vector sum of the two torque components rather than the algebraic sum. Hence, only a portion of each torque component is effectively utilized.

In this paper, a novel surface inset PM motor with an asymmetrical rotor structure is proposed to improve the torque production by creating rotor asymmetry for making the reluctance torque and the magnetic torque reach a maximum at the same current phase angle. The frozen permeability method (FPM) is utilized to segregate the torque into its reluctance and magnetic torque components based on finite element method (FEM) [5], [6]. An optimal design by iterative computation is first performed to demonstrate the design concept and obtain a criterion for making full use of each torque component. Based on the obtained criterion, an optimal design obtained by a genetic algorithm is utilized to further improve the torque and efficiency. Finally, a comparison between the optimized surface inset PM motor and a surface-mounted PM (SPM) motor is performed under the same operating condition, which demonstrates that the optimized surface inset PM motor can significantly save the magnet amount compared to the SPM motor for producing the same output torque.

II. Optimal Design by Iterative Computation

A. Motor Specification and Typical Torque Characteristics

Fig. 1 (a) shows the topology of the conventional surface inset PM motor. The stator has 6 slots with concentrated windings. The rotor core is inset with 4-pole ferrite magnets and the airspace exhibits between the magnets and rotor poles.

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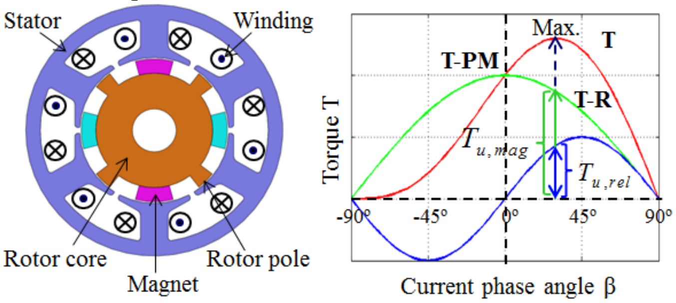
The motor specification is listed in Table I.



(a) Topology (b) Typical torque characteristics

Fig. 1. Topology of the conventional model and typical torque characteristics. T: Total torque, T-PM: Magnetic torque, T-R: Reluctance torque.

TABLE I
SPECIFICATION OF THE INVESTIGATED MOTOR

Item	Unit	Value
Number of magnet poles	-	4
Number of stator slots	-	6
Rated speed	rpm	4800
Current density	Arms/mm^2	3
Stator outer diameter	mm	88
Stator inner diameter	mm	51
Airgap length	mm	0.5
Rotor outer diameter	mm	50
Rotor inner diameter	mm	15
Motor axial length	mm	52
Remanence of Ferrite PM	T	0.42

By convention, the electromagnetic torque can be obtained from the d-q rotating reference frame expressed as

$$T=\frac{3p}{2}[\lambda_{pm}I_a\cos\beta+\frac{1}{2}(L_d-L_q)I_a^2\sin 2\beta] \qquad (1)$$

where p is the number of pole pairs, β is the spatial angle of the stator current vector measured with respect to the q-axis, L_d and L_q are the inductances of the d- and q-axes respectively, I_a is the peak value of phase current and λ_{pm} is the peak fundamental value of magnet flux linking the stator windings. The first term in (1) is termed the magnetic torque while the second term is the reluctance torque due to the saliency.

Based on (1), the typical torque characteristics are plotted as shown in Fig. 1(b). In order to evaluate the contribution of the proposed design concept, a utilization factor (UF) defined as the ratio of the utilized torque and the peak torque of each torque components can be adopted as

$$UF_{mag}=\frac{T_{u,mag}}{T_{pk,mag}};\ UF_{rel}=\frac{T_{u,rel}}{T_{pk,rel}}; \qquad (2)$$

where $T_{u,mag}$ and $T_{u,rel}$ are the utilized magnetic torque and the utilized reluctance torque, which contribute to the maximum resultant torque as shown in Fig. 1 (b), respectively. $T_{pk,mag}$ and $T_{pk,rel}$ are the peak torques of each torque components.

B. Optimal Design by Iterative Computation

As opposed to the conventional design techniques, the improvement of the torque production in this paper is achieved by making the reluctance torque and the magnetic torque reach their maximum at the same current phase angle. An optimal design by iterative computation is first to be performed to demonstrate the design concept and obtain the criterion for making full use of the magnetic torque and reluctance torque.

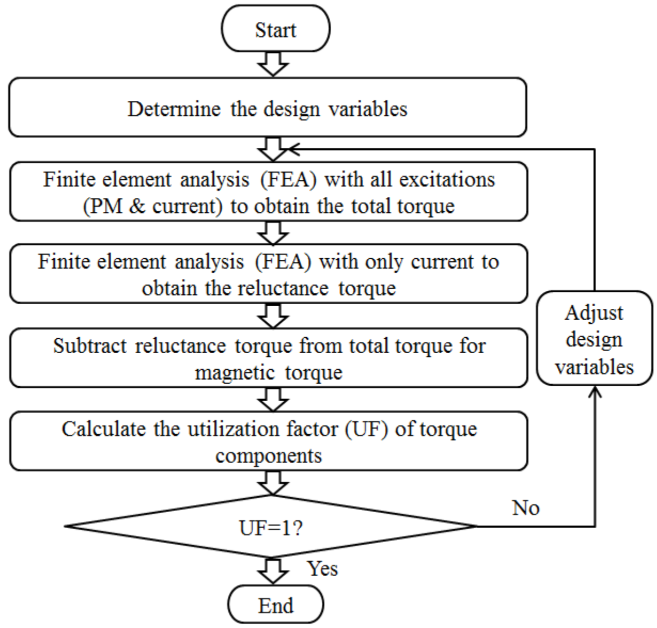
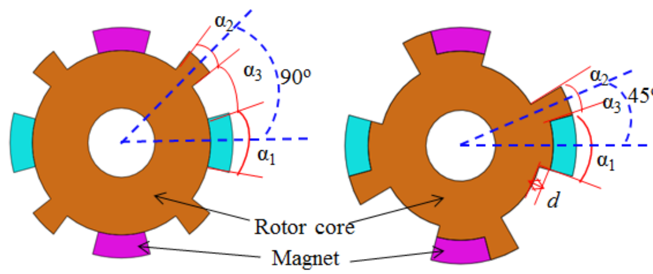


Fig. 2. Optimal design process by iterative computation.



(a) Design variables (b) Design results

Fig. 3. Design variables and results by iterative optimization.

In order to provide valuable insights to the contribution, the frozen permeability method (FPM) is utilized to separate the torque into the reluctance torque and magnetic torque based on the finite element method (FEM). The total torque was firstly obtained with both PM and current excitations. Then the magnets were removed and the reluctance torque was determined. The magnetic torque was then calculated by subtracting the reluctance torque from the total torque. A detailed design process is shown in Fig. 2.

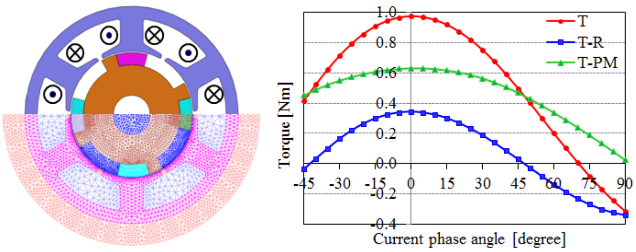
The span angle of magnet α_1, the span angle of the rotor pole α_2 and the relative placement angle of the magnet to the rotor pole α_3 are assumed as variables as shown in Fig. 3(a). By an iterative optimization process involving a large number of solutions, the criterion for making the UF of each torque component reach unity is

$$\frac{\alpha_1+\alpha_2}{2}+\alpha_3=45^o \ \ \text{(electrical degrees)} \qquad (3)$$

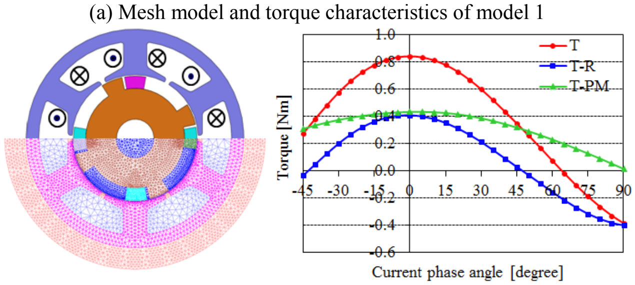
Fig. 3(b) shows the design results by iterative optimization process. Two models conformed to the criterion (3) are displayed to demonstrate the design concept as shown in Fig. 4, and the parameters are illustrated in Table II. Different from the torque characteristics in conventional PM motors, the magnetic and reluctance torque in both of the proposed models reach the maximum value at the same current phase angle.

TABLE II
PARAMETERS OF THE TWO MODELS BY ITERATIVE OPTIMIZATION

Item	Unit	Model 1	Model 2
α_1	degree	60	40
α_2	degree	30	40
α_3	degree	0	10
UF of magnetic torque	%	100	100
UF of reluctance torque	%	100	100



(a) Mesh model and torque characteristics of model 1



(b) Mesh model and torque characteristics of model 2

Fig. 4. Torque characteristics of proposed models by iterative optimization. T: total torque; T-R: reluctance torque; T-PM: magnetic torque.

III. OPTIMAL DESIGN BY ALGORITHMS

A. Optimal Design Process by Algorithms

Based on the proposed design strategy, an optimal design procedure is performed to further improve the torque and efficiency as shown in Fig. 5. Firstly, the objective functions, constraints and design variables are determined. Then the Latin Hypercube Sampling is applied in a Design of Experiment process for the selection of sampling points and the Kriging method is performed for the approximation modeling. Using a Genetic algorithm, optimal points for the design variables were obtained. Finally, the optimal design results are verified by FEM.

B. Objective Function, Constraints, and Design Variables

The objective functions for maximizing the torque and efficiency is shown in (4). The constraints are the obtained criterion by iterative optimization and the magnetic flux density in the rotor core and rotor pole as shown in (5). The design variables are shown in Fig. 3(b) and (6), while α_1 is the span angle of magnet pole and d is the depth of rotor core.

- *Objective functions:*
  Maximize the average torque and efficiency (4)
- *Constraints:*
  $$\frac{\alpha_1+\alpha_2}{2}+\alpha_3=45^o \quad (\alpha_3=0)$$
  Magnetic flux density < 1.8 T (5)
- *Design variables:*
  $45^o \leq \alpha_1$ *(Span angle of magnet pole)* $\leq 90^o$
  $0\ mm \leq d$ *(depth of rotor core)* $\leq 5\ mm$ (6)

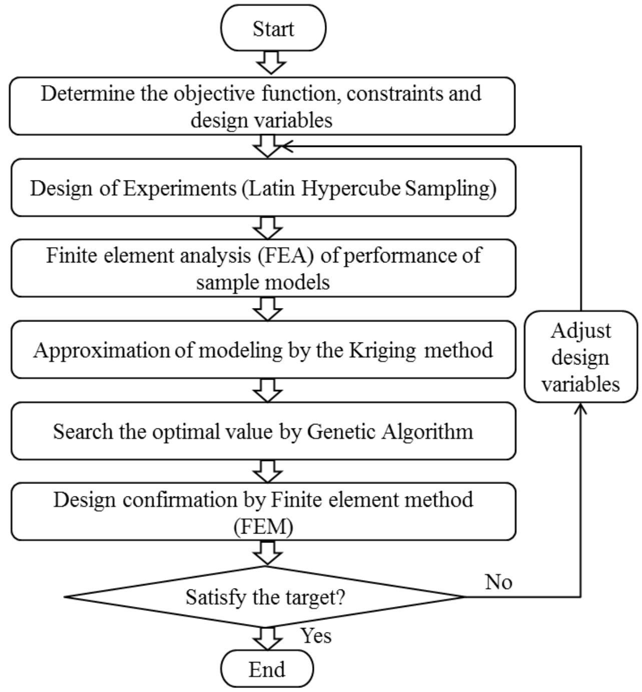
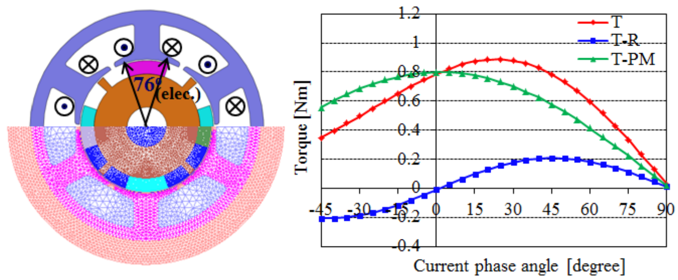
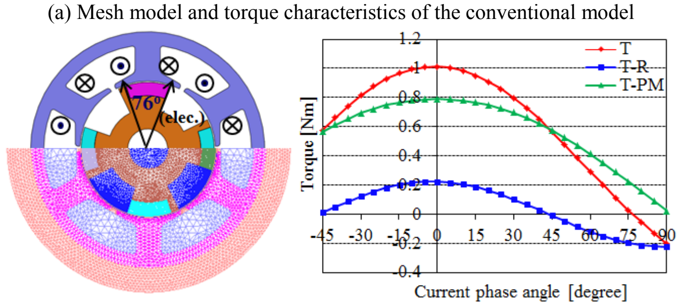


Fig. 5. Optimal design process by algorithms.



(a) Mesh model and torque characteristics of the conventional model



(b) Mesh model and torque characteristics of the optimized model

Fig. 6. Comparison of torque characteristics by algorithm optimization. T: total torque; T-R: reluctance torque; T-PM: magnetic torque.

C. Optimal Design Results

The optimal design variables for the optimized motor are $\alpha_1 = 76^o$ (α_2=14°; α_3=0), and d = 4.9 mm, respectively. In order to compare the results obtained to a conventional design, a FEM solution was also computed for a surface inset PM motor with a symmetrical rotor and the same magnet pole span. The comparison of torque characteristics is shown in Fig. 6, and the comparison of electromagnetic torque is shown in Fig. 7. Compared to the conventional motor, the maximum torque of the proposed optimal motor is increased by 14.2% and the efficiency is increased by 1.1%, while the torque ripple is decreased by 38.0%, respectively. The comparison of detailed performance data is summarized in Table III.

TABLE III
COMPARISON OF PERFORMANCE DATA IN CONV. AND PROP. MOTOR

Item	Unit	Conv. motor	Prop. motor
Max. torque	Nm	0.887	1.013
UF of reluctance torque	%	75	100
UF of magnetic torque	%	91	100
Torque ripple	%	100.9	62.6
Output power	W	445.9	509.2
Copper loss	W	29.4	
Iron loss	W	11.4	11.1
Efficiency	%	91.62	92.63

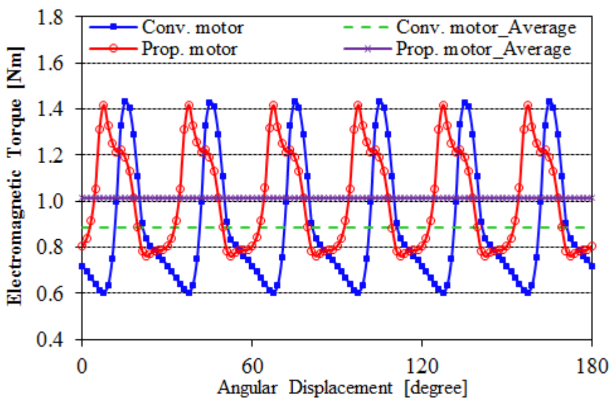


Fig. 7. Comparison of electromagnetic torque in Conv. and Prop. motor.

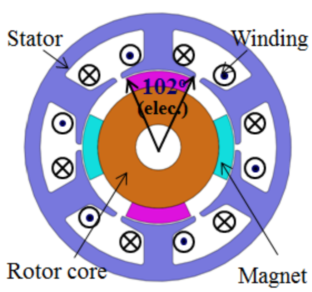


Fig. 8. Topology of the conventional SPM motor.

TABLE IV
COMPARISON OF PERFORMANCE DATA IN SPM AND PROP. MOTOR

Item	Unit	SPM motor	Prop. motor
Max. torque	Nm	1.013	
Torque ripple	%	62.6	41.6
Magnet volume	cm^3	20.83	15.52

D. Comparison with SPM Motor

In the proposed optimal motor, the maximum torque occurs at 0^o current phase angle which is the same as that of the SPM motors. Thus, a comparison between the proposed surface inset PM motor and a conventional SPM motor as shown in Fig. 8 is performed by assuming to apply the same operating condition. As a result, it demonstrates that the proposed surface inset PM motor can save the magnet amount by 25.5% as compared to the conventional SPM motor for producing the same output torque as listed in Table IV, while the deficiency is that the proposed surface inset PM motor produces a little more torque ripple than the SPM motor as shown in Fig. 9.

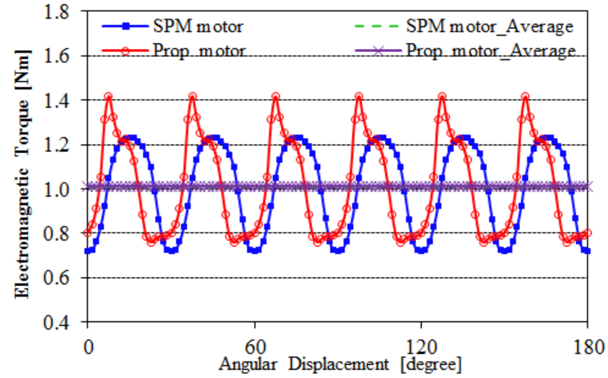


Fig. 9. Comparison of electromagnetic torque in SPM motor and Prop. motor.

IV. CONCLUSION

This paper has proposed a novel optimal design strategy for surface inset PM motors to improve torque and efficiency. The proposed motor adopts asymmetrical rotor structure aiming to improve torque production by producing rotor asymmetry thereby making the reluctance torque and the magnetic torque reach a maximum at the same current phase angle. Firstly, an iterative optimal design has been performed to demonstrate the design concept and obtain a general criterion for making full use of torque components based on FEM. Then an optimization using the Kriging method and genetic algorithm was applied for further improving torque and efficiency.

As the results show, the proposed optimal motor exhibits good performance with improved torque and efficiency as well as reduced torque ripple as compared with that of the conventional motor. Furthermore, the proposed optimal motor can significantly save the magnet amount when compared to a conventional SPM motor for producing the same output torque assuming to apply the same operating condition.

ACKNOWLEDGMENT

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