Programmable Design of Magnet Shape of Permanent Magnet Synchronous Machine for Minimization of Torque Pulsation

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Abstract — Magnet shape is very essential for the performance of permanent magnet machines, because it is directly related to their torque characteristics. This paper deals with programmable design of magnet shape for permanent magnet synchronous machine for minimization of torque pulsation based on electromagnetic field theory. The method is based on dividing the magnets into several radial layers and solutions by matrix computation of boundary conditions for magnetic field. The results are validated by nonlinear finite element (FE) analyses and experiment.

I. INTRODUCTION

Due to their high efficiency, high power density, and low maintenance costs, permanent magnet (PM) machines are emerging as a key technology for applications as home appliances, industrial tools, electric vehicle, etc[1]. However, PM machines inherently has a cogging torque and a back-emf ripple which cause a torque ripple, resulting in vibrations and noises. The cogging torque can be easily eliminated by employing slotless structure for a stator. In recent studies, other methods such as slot/pole combinations and an adjustment of pole arc ratio have been proposed to make a back-emf close to a sine wave form in a synchronous PM machine. In particular, the optimum magnet pole shape design becomes most common practice to reduce harmonic components of back-emf [2]-[6]. This method is mainly achieved by finite element (FE) analyses. However, in case of optimum magnet pole shape design using FE analyses, time-consuming is very severe. Our work is motivated by the desire to perform optimum magnet pole shape design for the reduction of torque ripple without FE analyses. Therefore, this paper deals with magnet pole shape design of the slotless PM machine for minimization of torque ripple based on electromagnetic field theory. First, on the basis of magnetic vector potential and 2-d polar coordinate system, magnetic field solutions by PMs are derived for the initial model. Using magnetic field solutions, analytical solutions for back-emf and torque are also obtained. And then, magnet pole shape is optimized using these solutions. In particular, the analytical expressions for magnet that has circumferential nonhomogeneous thickness were not considered sufficiently in previous research. So, by employing analytical model required to mathematical modeling of magnetization considering magnet shape shown in Fig. 1 for our analyses, problems stated above can be easily solved. And the reliable optimization result can be obtained rapidly.

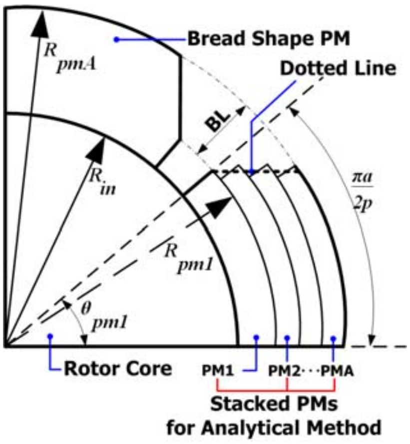

Fig. 1. schematic model for analytical method

II. THE ANALYTICAL MODEL

Fig. 1 shows the schematic model for optimizing permanent magnet shape. Modeling the magnetization of permanent magnet that has circumferential non-homogeneous thickness were not impossible, so the vertically stacked permanent magnet is applied, and the method modifying pole arc ratio of each permanent magnet is adopted. The pole arc ratio varies with the dotted line, and if the assumption that the magnet is divided infinitely is considered, the analysis model is identical with the original model. In Fig. 1, R_{pm1} and R_{pmK} is given by

$$R_{pm1} = R_{pmA} - BL \tag{1}$$

$$R_{pmK} = \frac{(K-1)(R_{pmA} - R_{pm1})}{A-1} + R_{pm1} \tag{2}$$

Where the subscript K denotes K^{th} magnet. From (1) and (2), K^{th} magnet pole arc ratio a_{pmK} is given by

$$a_{pmK} = p\frac{\arcsin\dfrac{R_{pm1}\sin\delta}{R_{pmK-1}} + \arcsin\dfrac{R_{pm1}\sin\delta}{R_{pmK}}}{\pi} \tag{3}$$

III. TORQUE RIPPLE MINIMIZATION

Analytical solutions for flux density due to PMs are derived in terms of magnetic vector potential and a 2D polar coordinate system. And magnetic field solutions at the air-gap are derived for the initial model. Using magnetic field solutions, analytical solutions for back-emf and torque

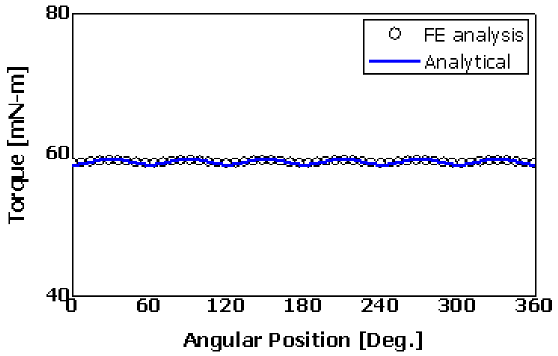

Fig. 2. Theoretical torque of initial model

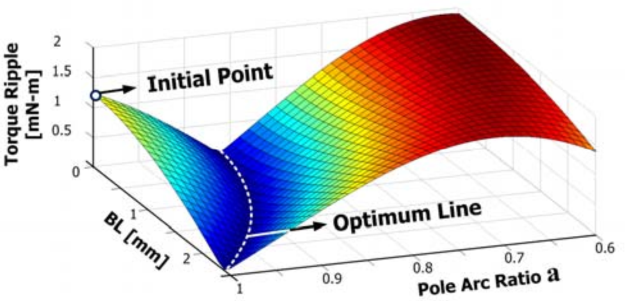

Fig. 3. 3D torque ripple variation data vs. pole arc/pole pitch ratio and BL

are also obtained. As shown in Fig. 2, analytical result for electromagnetic torque of initial model is shown in good agreement with FE analyses. Based on the calculated torque, the torque ripple data were obtained by the variation of both the pole arc ratio and BL as shown in Fig.3, and the optimum line was then able to be derived.

IV. MANUFACTURED OPTIMUM MODEL

Fig. 4 shows the manufactured optimum model. And the specification of design model is shown Table I.

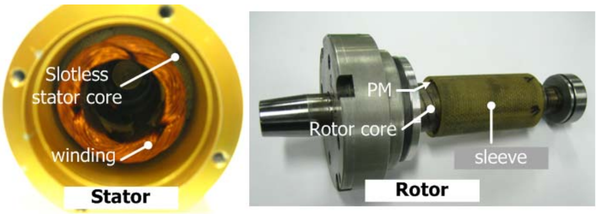

Fig. 4. Manufactured model

TABLE I
SPECIFICATION OF DESIGN MODEL

Design specification	Value
PM outer radius [R_{pmA}]	13.75[mm]
Shaft radius [R_{in}]	4.5[mm]
Stator winding outer radius [R_{wo}]	20[mm]
Stator winding inner radius [R_{wi}]	15.75[mm]
Pole number	4
PM material	NdFeB
Remanence	1.1[T]
Magnetization direction	Parallel
Turns per phase	280
Stack length	50[mm]

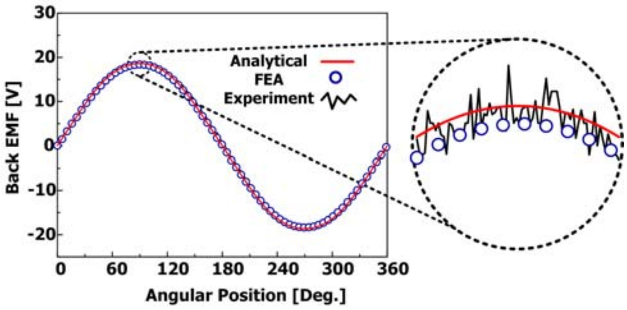

Fig. 5. comparison of the back-emf by analytical method, FEA, experiment

As shown in Fig. 5, analytical results for back-emf of optimized model obtained by electromagnetic field theory are shown in good agreement with FE result and experimental result.

V. RESULTS AND DISCUSSION

This paper deals with programmable design of permanent magnet of permanent magnet synchronous machine for minimization of torque pulsation. An analytical method based on the Maxwell equations is introduced to predict air-gap magnetic flux density distribution and torque and back-EMF. And FEA and experiment are employed to evaluate the results. In particular, the analytical expressions for magnet that has circumferential nonhomogeneous thickness were not considered sufficiently in previous research. So, by employing analytical model required to mathematical modeling of magnetization considering magnet shape for our analyses, problems stated above can be easily solved. And the reliable optimization result can be obtained rapidly. The more detailed discussion, results and analytical equations will be presented in final paper.

VI. REFERENCES

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