# Optimum Design Solution for Maximum Torque Density & Minimum Torque Ripple of Flux Switching Motor using Response Surface Methodology

Jung Ho Lee *Member IEEE*, Byeong Du Lee, Han Sang Song
Dept. of Electrical Engineering, Hanbat National University
Dukmyung-Dong, Yuseong-Gu, Daejeon, 305-719, KOREA
E-mail: changen018@nate.com

***Abstract* — This paper deals with optimum design criteria for maximum torque density & minimum torque ripple of Flux Switching Motor (FSM) using RSM & FEM.**

**The focus of this paper is to find a design solution through the comparison of torque density and torque ripple according to rotor shape variations. And then, a central composite design**

**(CCD) mixed resolution is introduced, and analysis of variance (ANOVA) is conducted to determine the significance of the fitted regression model.**

## I. Introduction

The flux switching motor (FSM) is a new class of electric motor and is a combination of the switched reluctance motor and the inductor alternator [1]. FSM has a salient pole rotor and may have a salient or non-salient stator. The stator winding comprises a field winding and armature winding each spanning a full rotor pole pitch. The field winding carries dc current and the armature winding carries ac current [2]. The unique benefit of the inductor alternator and the proposed flux switching motor is that one of the two windings can carry dc current leaving only one winding requiring electronic control. Issues such as efficiency and torque ripples are important in evaluating the performance of a FSM. Such characteristics depend upon the stator and rotor shapes of machine and, therefore, require a numerical evaluation and design. This paper deals with optimum design criteria for maximum torque density & minimum torque ripple of Flux Switching Motor (FSM) using RSM & FEM. The focus of this paper is to find a design solution through the comparison of torque density and torque ripple according to rotor shape variations. And then, a central composite design. (CCD) mixed resolution is introduced, and analysis of variance (ANOVA) is conducted to determine the significance of the fitted regression model[3]-[5].

## II. Design Algorithm and Model

The shape coordinates of the rotor have been drawn according to the variation of salient pole width and salient pole edge. Design variables of rotor are determined to maximize torque density and to minimize torque ripple of a FSM. And then, analysis data is obtained through finite element method based on central composite design mostly used in RSM. And optimum point is determined through analysis of the data.

Fig. 1 shows the point variables and variation direction example for the shape change according to width and edge of the salient pole. Points of W1-W6 and P1-P6 move as a condition that salient pole width is varied. In order to change the shape of salient pole edge, points of G1-G6 is fixed, and points of W1-W6 are moved to arc directions.

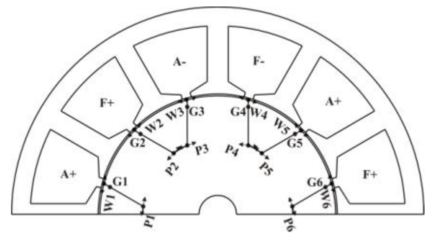



Fig.1. The design variables and variation direction of the initial model FSM

## III. Optimization procedure

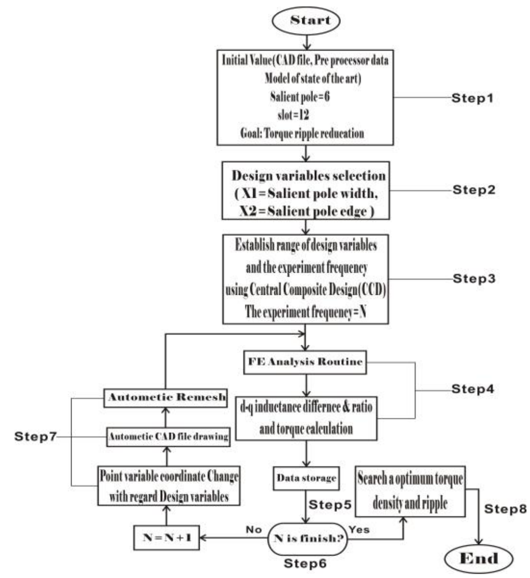



Fig. 2. Flow chart of design procedure

Step1 : Set the initial value (CAD file, Pre-processor data Model of state of the art). And the initial model is assigned to Salient pole=6, slot=12.

Step2 : Salient pole width (X1) and salient pole edge (X2) in rotor are adopted the design variables related to torque density in the FSM. However, the ribs have a fixed value due to inherent manufacturing limitations.

Step3 : The range of design variables and experiment frequency is established by using the central composite design (CCD). The experiment frequency N.

Step4 : Finite element analysis (FEA) is performed and d-q inductance difference & ratio and torque ripple is calculated.

Step5 : The d-q obtained from FEA, are stored.

Step6 : The experiment frequency N ?

▶ Yes: Search a optimum torque density and ripple.

▶ No: N=N+1

Step7 : The example of the point variables and variation direction of Salient pole width and salient pole edge is well shown in fig. 1.

When the rotor shape according to variables (X1), (X2) is varied, they have a difficulty in performing a lot of the pre-processor for FEA.

For this reason, the new CAD file is redrawn with regard to the change of the design variables automatically.

Step8 : The response surface model is created by data obtained from FEA according to an established range. Therefore, it is possible to get optimum torque density.

## IV. Result & discussion

### A. Optimized shape design solution

Fig. 3-6 shows configuration and torque characteristic of initial model, only optimized pole width model and optimized pole width & edge model, respectively.

As shown in Fig. 4, whereas torque ripples of FSM of optimized width is improved and has the lower value than those of initial model, reverse torque value remained.

When W1 is 5.259mm, W2 is 5.259mm, P1 is 0mm(arc), P2 is -4.2426mm(arc) through edge optimization, the torque ripple of the FSM is minimized and reverse torque is almost removed, as shown in Fig. 5.

And the average torque of initial model is 0.0639 [Nm], the average torque of optimized model is 0.1341 [Nm]. As a result, torque characteristics are improved.

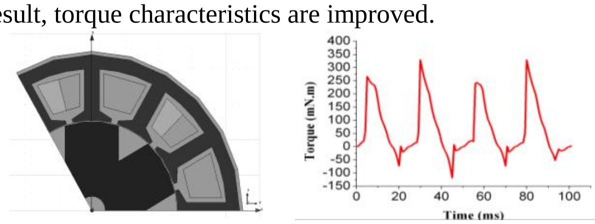



Fig. 3. Configuration and torque characteristic of initial model

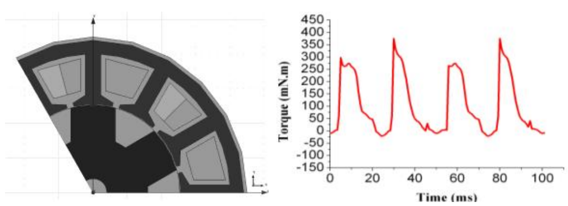



Fig. 4. Configuration and torque characteristic of optimized pole width

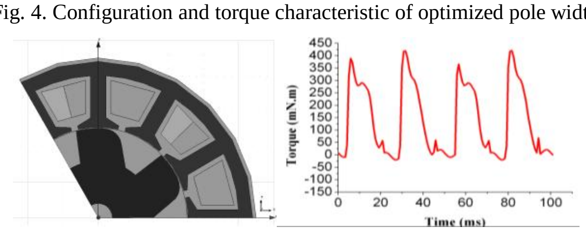


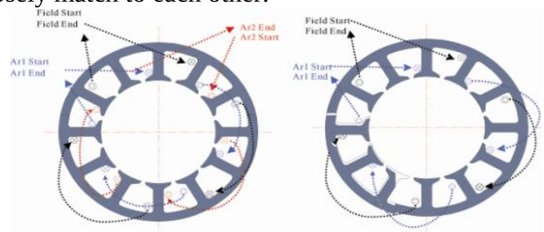

Fig. 5. Configuration & torque characteristic of optimized pole width and edge

### B. New Type Armature Winding & Considering Dead Time

Instead of the on/off of armature1 and armature windings in Fig. 6(a), single armature winding, which current directions can be changed by IGBT, is selected, as shown in Fig. 6(b). And then, production cost and copper loss are reduced.

In order to reduce flux disturbance when current is switched, the dead time is considered in driving system.

Fig. 7 shows the torque characteristics of shape optimized model Fig. 5, applying armature-field winding (500-500 turns) and dead time. As a result, torque characteristics are considerably improved. Fig. 8 show the torque, current, output and efficiency characteristics of simulation and experiment according to speed, respectively. These results closely match to each other.




(a) Initial Winding method (b) New type Winding method

Fig. 6. Initial Winding method and new type Winding method

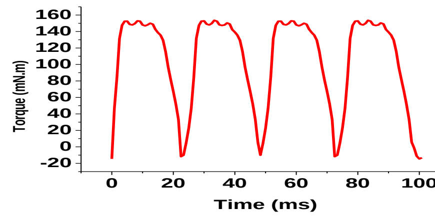



Fig. 7. Improved torque characteristics of proposed design model

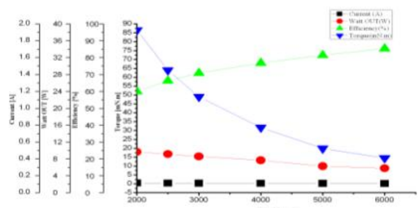


Fig. 8. Torque, current, output and efficiency characteristics of optimized model

More detailed results and discussion will be given in final paper. And the mathematical expressions for response surface methodology will be also given in extended version.

## V. References

[1] C. Pollock and M. Wallace, "The Flux Switching Motor, A DC Motor without Magnets or Brushes", IEEE IAS Annual Meeting, October 1999.

[2] K.F. Raby, "Inductor alternators for 10 KC/S", Technical Monograph, Engineering Department, The British Thomson-Houston Company Ltd., 27th April 1950.

[3] J. M. Park, S. I. Kim, J. P. Hong, J. H. Lee, "Rotor design on Torque Ripple Reduction for a synchronous reluctance motor with concentrated winding using response surface methodology", *IEEE Transactions on Magnetics*, vol. 42, No. 10, pp.3479-3481. Oct. 2006.

[4] Y. C. Choi, J. H. Lee, J. P. Hong, "The Torque Ripple Reduction of A Concentrated Winding Synchronous Reluctance Motor according to Stator & Rotor structure variations using RSM", *Journal of Applied Physics*, Volume 103, issue 7, pp. 07F133-07F133-3 (2008).

[5] Y. C. Choi, H. S. Kim, J. H. Lee, "Design Criteria for Maximum Torque Density & Minimum Torque Ripple of SynRM according to the Rated Wattage using Response Surface Methodology", IEEE Transactions on Magnetics, vol, 44, No. 11, pp.4135-4138. Nov 2008