Optimum Design Criteria for Maximum Torque Density & Efficiency of a Line-Start Permanent-Magnet Motor using Response Surface Methodology & Finite Element Method

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Abstract — This paper deals with optimum design criteria for maximum torque density & efficiency of a line-start permanent-magnet motor (LSPMM) using RSM(Response Surface Methodology) & FEM(Finite Element Method).

The focus of this paper is to find a design solution through the comparison of torque density and efficiency 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

Although the efficiency and power factor of an induction motor can be optimized, it becomes more difficult to improve any further due to its inherent limitations.

Therefore, a new motor technology should be developed to offer higher efficiency and power factor.

On the other hand, the new motor should be capable of directly replacing the existing induction motor. Therefore, a line-start permanent-magnet motor (LSPMM) is an attractive choice. The stator of a LSPMM is the same as that of a squirrel-cage induction motor, and the permanent magnets are inserted in the rotor of a squirrel cage induction motor.

The starting torque is generated by electromagnetic induction phenomenon at the rotor conductor bars, and the synchronously operating torque is produced by the permanent magnets. In a word, the line-start PM motor is a very high efficiency synchronous motor designed to operate at fixed voltage and frequency from the same power supplies as induction motors.

The LSPMM has many types of configurations since the inserted permanent magnets may have different shapes, materials, sizes, and positions [1]-[4].

Issues such as efficiency and torque density are important in evaluating the performance of machines.

Such characteristics depend upon the stator and rotor shapes of machine and, therefore, require a numerical evaluation and design.

The finite element approach has been gaining progressively greater importance than the equivalent circuit method in solution of non-linearity, anisotropy characteristic and motion analysis.

And the RSM has been achieved to use the experimental design method in combination with Finite Element Method and well adapted to make analytical model for a complex problem considering a lot of interaction of design variables [5]-[7] .

This paper deals with optimum design criteria for maximum torque density & efficiency of a line-start permanent-magnet motor (LSPMM) using RSM & FEM.

The focus of this paper is to find a design solution through the comparison of torque density and efficiency 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.

II. Design Algorithm and Model

The shape coordinates of the rotor have been drawn according to the variation of rotor bar and PM size.

Design variables of rotor are determined to maximize torque density and efficiency of a LSPMM. 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 rotor bar and PM size.

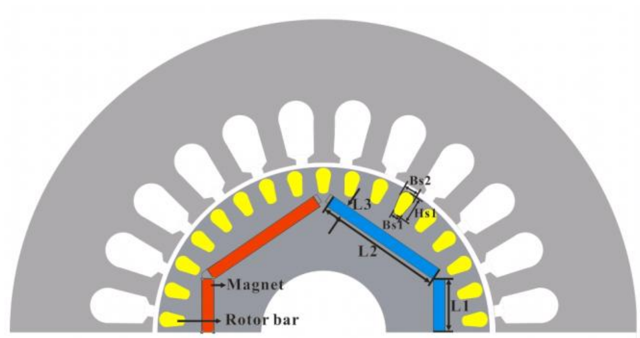

Fig.1. The design variables and variation direction of the initial model LSPMM

III. Concept of Response Surface Methodology

The RSM seeks to find the relationship between design variable and response through statistical fitting methods, which are based on the observed data from system.

The response is generally obtained from real experiments or computer simulations. Therefore finite element analysis (FEA) is performed to obtain the data of LSPMM in this paper.

There are many experimental designs for creation of response surface.

In this paper the central composite design (CCD) is chosen to estimate interactions of design variables and curvature properties of response surface in a few times of experiments. The CCD has been widely used for fitting a second-order response surface.

TABLE I Analysis of Variance

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F_0
Regression	k	SS_R	$SS_R / k = MS_R$	MS_R / MS_E
Residual	n-k-1	SS_E	$SS_E / (n-k-1) = MS_E$	
Total	n-1	S_{yy}		

It is always necessary to examine the fitted model to ensure that it provides an adequate approximation to the true response and verify that none of the least squares regression assumptions are violated. In order to confirm adequacy of the fitted model, analysis-of-variance (ANOVA), shown in Table I is used in this paper. In Table I, *n* is the total number of experiments and *k* is the number of parameters in the fitted model.

IV. Optimization Procedure

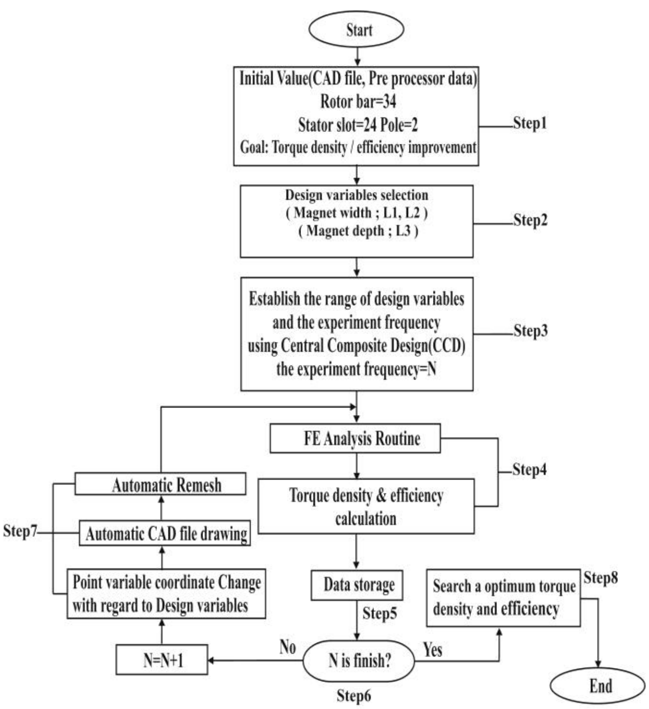

Fig.2 Flow chart of design procedure

Fig. 2 shows the process of optimization design.

The shape coordinates of the magnet in rotor have been drawn according to the variation of magnet width and depth.

Design procedure according to the flow chart is as follows;

Step1. : Set the initial value (CAD file, Pre-processor data). And the initial model is assigned to Rotor bar=34, stator slot=24.

Step2. : The magnet width(L1,L2) and depth(L3) in rotor are adopted the design variables related to torque density in the LSPMM.

Step3. : The range of design variables and experiment frequency is established by using the central composite design (CCD). The experiment frequency (N) is 54.

Step4. : Finite element analysis (FEA) is performed and torque density and efficiency is calculated.

Step5. : The torque density and efficiency obtained from FEA, are stored.

Step6. : The experiment frequency N >54?

- ▶ Yes: Search an optimum torque density and efficiency.
- ▶ No: N=N+1

Step7. : The example of the point variables of magnet width and depth is well shown in Fig. 1.

When the magnet shape of rotor according to variables (L1), (L2), (L3) is varied, the new CAD file is redrawn with regard to the change of the design variables automatically. Next the process of automatic mesh generation follows. In this way, this procedure goes on until N.

Step8. : The response surface model is created by data obtained from FEA according to an established range.

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] T. J. E. Miller, M. Popescu, C. Cossar, M. I. McGilp, G. Strappazzon, and R. Santarossa, "Line-Start Permanent-Magnet Motor single-Phase Steady-State Performance Analysis", *IEEE Transactions on Industry Applications*, vol. 40, No. 2, March/April 2004, pp.516-525.

[2] M. Popescu, T. J. E. Miller, M. I. McGilp, G. Strappazzon, N. Trivillin, R. Santarossa, "Line-Start Permanent-Magnet Motor: Single-Phase Starting Performance Analysis", *IEEE Transactions on Industry Applications*, vol. 39, No. 4, July/August 2003, pp.1021-1030.

[3] W. H. Kim, K. C Kim, S.J. Kim, D. W. Kang, S. C. Go, H. W. Lee, Y. D Chun, J. Lee, "A study on the Optimal Rotor Design of LSPM Considering the Starting Torque and Efficiency", *IEEE Transactions on Magnetics*, Vol 45, No 3, March 2009, pp.1808-1811.

[4] I.S. Jacobs and C.P. Bean, "Fine particles, thin films and exchange anisotropy," in *Magnetism*, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271-350.

[5] J.T. Li, Z.J. Liu, M.A. Jabbar, X.K. Gao: Design optimization for cogging torque minimization using response surface methodology, *IEEE Transactions on Magnetics*, Vol 40, No 2, 2004, pp.1176-1179.

[6] S. J. Park, S. J. Jeon, J. H. Lee, "Optimum design criteria for a synchronous reluctance motor with concentrated winding using response surface methodology", *Journal of Applied Physics*, vol.99, issue 8, April, 2006.

[7] 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.

[8] 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..