Characteristics Analysis & Optimum Design of Axially lamianated anisotropic Rotor Synchronous Reluctance Motor Using Coupled Finite Element Method & Response Surface Methodology

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***Abstract*— This paper deals with the characteristics analysis & optimum design of axially laminated anisotropic (ALA) rotor Synchronous Reluctance Motor (SynRM) using a coupled Finite Element Method (FEM) & Response Surface Methodology (RSM). The focus of this paper is the characteristics analysis & optimum design relative to the output power on the basis of rotor materials of a SynRM. The coupled Finite Elements Analysis (FEA) & Preisach model have been used to evaluate nonlinear solutions. Comparisons are given with characteristics of a same rated wattage induction motor and those of ALA-SynRM, respectively.**

***Index Terms*— FEM, RSM, SynRM**

I. Introduction

The performance of a Synchronous Reluctance Motor (SynRM) in terms of torque and power factor depends on the two-axis inductance Ld and Lq of the machine. The large difference of (Ld-Lq) and Ld/Lq ratio is good for the machine's properties. Therefore, Considerable attention has been paid in the past to improve rotor design of SynRM [1] – [3].

Axially Laminated Anisotropic (ALA) rotors have been proposed as early as 1923 [4] in an effort to increase the Ld/Lq ratios and the Ld - Lq difference for given stators.

Essentially thin packs of axial laminations are interleaved with insulation layers on each rotor pole to produce distributed anisotropy or multiple flux barrier rotor configurations.

The ALA rotor should provide both high Ld/Lq ratio and large Ld - Lq values to secure high torque density and high power factor.

As expected, there are quite a few variables which influence the ALA rotor performance:

- the pole pitch of stator winding;
- the number of slots/pole/phase ;
- type of stator winding;
- the airgap;
- stator slot opening;
- rotor lamination stack/ insulation thickness ratio;
- rotor insulation thickness;
- magnetic saturation level;

All the factors have to be carefully looked at and investigated, because most of them are not independent from each other and may negatively influence the efficiency gains in one case or the other. Secondly, the commercial impacts have to be strongly considered, since with higher efficiency the premium paid may limit the savings seen.

The Response Surface Methodology (RSM) has been achieved to use the experimental design method in combination with Finite Element Method (FEM) and well adapted to make analytical model for a complex problem considering a lot of interaction of design variables.

The focus of this paper is found firstly a design solution through the comparison of torque and losses according to rotor shape and stator, rotor dimensions variations and, Secondly, a mixed resolution with Central Composite Design (CCD) is introduced and Analysis Of Variance (ANOVA) is conducted to determine the significance of the fitted regression model.

II. Concept of Response Surface Methodology

The RSM seeks to find the relationship between design variable and response through statistical fitting method, which is based on the observed data from system. The response is generally obtained from real experiments or computer simulations. Therefore, FEM is performed to obtain the data of SynRMs in this paper. In RSM work it is assumed that the true functional relationship y can be written as :

$$y = f(X, \theta) \tag{1}$$

where the variables $(x_1, x_2, ..., x_k)$ in Eq. (2) are in centered and scaled design units. The form of true response function f is unknown and very complicated, so it is approximated.

In many cases, the approximating function y of the function f is normally chosen to be either a first-order or a second-order polynomial model. In order to predict a curvature response more accurately, the second-order model is used in this paper. The model of Equation (3) is the second-order model

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x^2{}_j + \sum_{i \neq j}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

where β is regression coefficients, ε is a random error treated as statistical error. The observation response vector at data point of function y may be written in matrix notation as follows :

$$y = X\beta + \varepsilon \tag{3}$$

where, X is a matrix of the levels of the independent variables, β is a vector of the regression coefficients, ε is a vector of random error.

There are many experimental designs for creation of response surface. Among them, the 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. It was introduced by Box and Wilson(1951). Much of the CCD evolves from its use in sequential experimentation. It involves the use of a two-level factorial or fraction combined with 2k axial or star point:

As a result, the design involves, say, 2k factorial points, 2k axial points, and nc center runs. The factorial points represent a variance optimal design for a first-order model or first order + two-factor interaction type model.

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, ANOVA table 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.

TABLE I
ANALYSIS OF VARIANCE

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square
Regression	k	SS_R	SS_R/k
Residual or Error	n-k-1	SS_E	$SS_E/(n-k-1)$
Total	n-1	SS_T	

There are three residual sums which play important roles in judging model adequacy :

- The Residual sum of squares SS_E :
- The total sum of squares S_{yy} :
- The regression sum of squares $SS_E = S_{yy} - SS_R$

where, ; $SS_E = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2$; $SS_T = \sum_{i=1}^{n}(y_i - \bar{y})^2$

(*y_i: observed value, $\hat{y}$: predicted value, $\bar{y}$: average value)

The coefficient of determination, R^2, expressed by SST and SSR is

$$R^2 = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{S_{yy}} \tag{5}$$

The adjusted coefficient of multiple determination R_A^2 is defined as :

$$R_{adj}^2 = 1 - \frac{SS_E/(n-k-1)}{S_{yy}/(n-1)} \tag{6}$$

It is a proportion measure of the estimate of the error variance provided by the residual mean square of the error variance estimate using the total mean square. Accordingly, adequacy of the fitted model is determined by R^2 and R_{adj}^2 [4]-[5].

III. Digest Model and Specifications

In figure 1, design variables which are axial lamination stack numbers and insulation sheet thickness, etc., rotor, are determined to improve torque performance of 250kW traction ALA-SynRM. Analysis data is obtained by FEM based on central composite design mostly used in RSM, and optimum point is determined by analysis of the data. In this paper, Everett planes of Preisach model are three those (one of stator (S18, isotropy) and those of rotor (G9: x_direction, y_direction, anisotropy)). Permeability ratio accepted from experimental data are 10: 100: 1 (S18: G9 (y_direction): G9 (x_direction)) respectively.

The study was performed with the use of an experimental design method. The CCD is a design widely used for estimating second order response surfaces. And the CCD has been studied by many statistics in response surface analysis, and is perhaps the most popular class of second order designs. The design involves, say, 2k factorial points (or fractional factorial points), axial points, and center points. The factorial points represent a variance optimal design for a first_order model or a first_order + two factor interaction type model. The center points clearly provide information about the existence of curvature in the system. More detailed design procedure, results and discussion will be given in final paper.

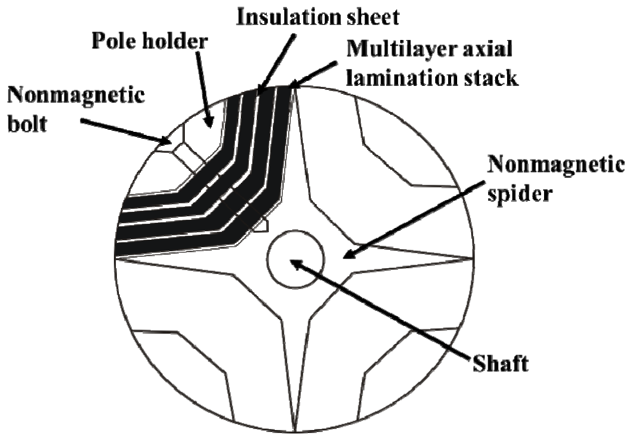

Fig. 1. The initial rotor model of 250kW traction ALA-SynRM

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