Analysis of Torque Pulsation considering Interior Permanent Magnet Rotor Rib Shape using Response Surface Methodology

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Abstract — This paper deals with the analysis of torque pulsation considering interior permanent magnet rotor rib shape using response surface methodology (RSM). We determine the initial interior permanent magnet synchronous motors (IPMSM) with 6-pole NdFeB magnets rotor and 9-slot stator. We select 3 points in rotor rib and change these points using RSM. These models are analyzed by finite element method (FEM). Using these results, we find optimal model, and analyze effect of each parameter. Finally, optimal model compare with initial model.

I. Introduction

The IPMSM are widely used in compressors, spindles, and electric vehicle due to their high efficiency, high torque density and wide speed range. On the other hand, the IPMSM usually have significant torque pulsation problem, so this problem damage to drive component by mechanical resonance, vibration, and acoustic noise. The removal of torque pulsation is always very crucial for most applications which require smooth motor running. Torque ripple, caused by the interaction of the rotor field and stator currents, is affected by the total harmonic distortion (THD) of the back-emf characteristic. Cogging torque arise from the interaction between the air gap flux distribution and slotted stator structure. It is important for motor running to minimize torque ripple and cogging torque. [1]-[2]

Many papers dealt with minimizing torque ripple and cogging torque, and proposed some effective approaches. [2]-[5] In this paper, RSM is selected for this problem. Rotor rib is saturated by the PM flux, and stator MMF. This effect is more important when the rib thickness is large. Therefore, this paper deals with analysis torque pulsation changed rotor rib shape. Fig. 1 shows a one-third initial model for the IPMSM with 6-pole NdFeB magnets rotor and 9-slot stator, and parameters obtained in the shape of rotor rib to submit RSM. All RSM item solve the FEM, and fig. 2 shows the FEM mesh of initial model. The mesh of air gab is separated in minute than other part. Using FEM results, we analyze effect of each parameter, and find optimal model. Finally, optimal model compare with initial model.

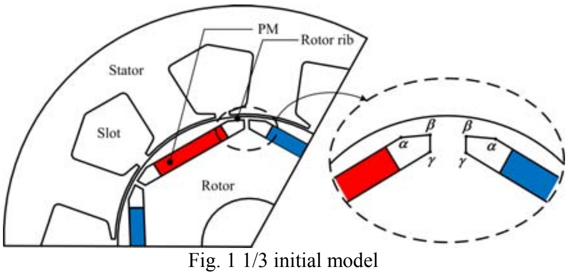

Fig. 1 1/3 initial model

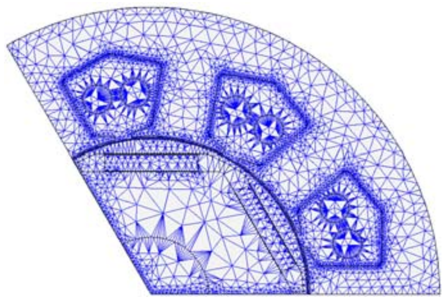
Fig. 2 FEM mesh of initial model to analyze of IPMSM

II. Response Surface Methodology

The RSM is a collection of mathematical and statistical technique useful for the analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. In general, the goal for RSM is to find the optimal response changes in a given direction by adjusting the design variables. When there is more than one response then it is important to estimate the response change that does not optimize only one response. [5]-[7] The RSM is assumed that the true functional relationship can be written as follow Eq. (1)

$$Y = f(x_1, x_2, \cdots, x_k) \tag{1}$$

where the variable (x_1, x_2, x_3,$\cdots$, x_k) is centered and scaled design unit. IPM motor model is very complicated, so include all quadratic terms and all cross product terms.

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

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

where β of Eq. 2 is regression coefficients, ε is a random error treated as statistical error, X is a matrix of the levels of the independent variable, and β of Eq. 3 is a vector of regression coefficients.

$$\hat{\beta} = (X'X)^{-1} X'Y \tag{4}$$

$$\hat{Y} = X\hat{\beta} \tag{5}$$

where $\hat{\beta}$ is a estimated vector, X' is the transpose of matrix X, and $\hat{Y}$ is a fitted response vector.

There are many experiment designs in the RSM. In this paper, central composite design (CCD) is chosen to estimate

TABLE I
Design Variables and Responses of RSM Simulation

Experiment order	Design Parameter			Results	
	Alpha [mm]	Beta [mm]	Gamma [mm]	Torque [Nm]	Torque Ripple [Nm]
1	1	2	0	7.0650	0.5063
2	1	1	1	7.0709	0.5228
3	2	0	1	7.1510	0.5880
4	2	1	2	7.1061	0.6531
5	0	1	0	7.0581	0.5447
6	2	2	1	7.1054	0.6563
7	1	1	1	7.0709	0.5228
8	1	0	2	7.0637	0.5263
9	1	0	0	7.1034	0.5861
10	0	2	1	7.0147	0.4476
11	0	0	1	7.0569	0.5143
12	0	1	2	7.0141	0.4595
13	2	1	0	7.1513	0.5804
14	1	2	2	7.0280	0.5714
15	1	1	1	7.0709	0.5228

interactions of design variable 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. [7]

The experiment number of CCD is

$$n = 2^k + 2k + n_c \qquad (6)$$

where 2^k is a experiment number for design of factorial design, $2k$ is number of spot on each axis, and n_c is number of reiteration experiment to center point.

III. Results and Discussion

Table 1 shows the design variables and responses of RSM simulation obtained by FEM. Using these results, fig. 3, and 4 are obtained to alpha, and beta parameter on the assumption that gamma parameter is constant. Gamma parameter's effect is not big to contribute to the response in RSM. Torque increases as alpha parameter is increased and beta parameter is decreased, as shown in fig. 3. However, torque ripple does not have simple role like torque, as shown in fig. 4. Cogging torque has a great effect on thickness of rotor rib, and other parameter is not big to contribute to response. Therefore, cogging torque is presented as shown in fig. 5.

In table 2, torque of optimal model is similar in initial model. However, torque ripple of optimal model is reduced by 15.57% compared with initial. More detailed analysis, experiment results and relevant equation will be presented in full paper.

TABLE II
Torque of initial and optimal model

	Initial	Optimal	Impovement
Torque[Nm]	7.0910	7.0650	-0.367%
Torque ripple[Nm]	0.5997	0.5063	-15.574%

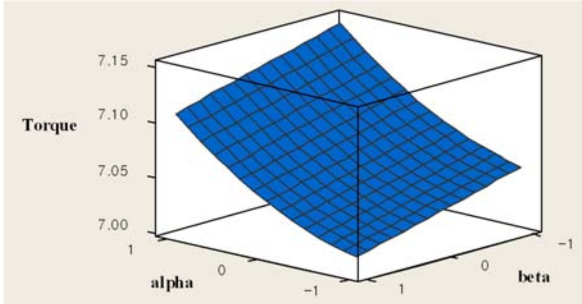

Fig. 3 Relation of torque

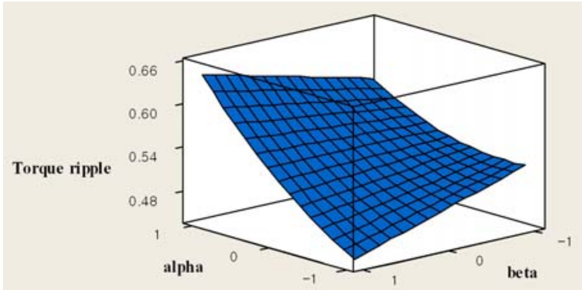

Fig. 4 Relation of torque ripple

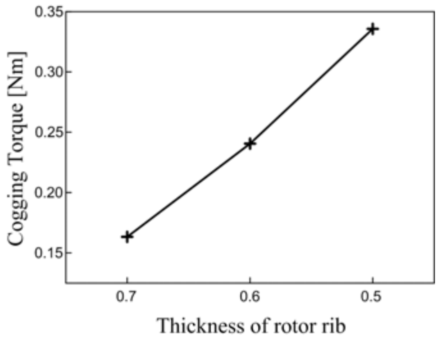

Fig. 5 Cogging torque according to thickness of rotor rib.

IV. References

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