Optimal Rotor Design of Interior Permanent Magnet Motor by Response Surface Methodology for High Torque

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Abstract

The purpose of this paper is to optimize rotor shape of interior permanent magnet (IPM) motor for high torque and compact system. V-shaped permanent magnet arrangement is introduced to improve both magnetic torque and reluctance torque of prototype IPM, and it is named V-type IPM. The performances are evaluated as torque per rotor volume (TRV) because it needs high power per volume to use as vehicle parts. To obtain the higher TRV, response surface methodology (RSM) is applied as an optimizing method, and the experimental samples are gotten from 2-dimensional finite element analysis (2D FEA). After optimization of V-type IPM, the accuracy of expectation is verified by comparison with the results of 2D FEA. In addition, the effect of shape optimization is shown by the comparison of TRVs of prototype and optimized V-type.

1. Introduction

As permanent magnet performance is progressed, there is growing interest in applying permanent magnet motors to electric vehicles for high efficiency and weight reduction. Interior permanent magnet (IPM) motor is one of the attractive motors for the applications. Since the motor generates both magnetic torque and reluctance torque, it can have high power density per motor volume.

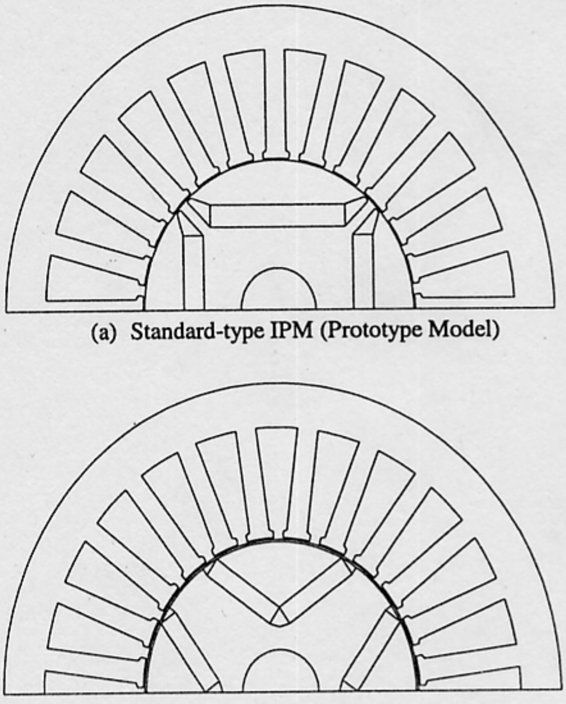
This paper presents rotor design of IPM motor for high torque. Even though torque per rotor volume (TRV) [1] of the prototype is 73[kNm/m^3], higher TRV is inquired for more compact system. To get 80[kNm/m^3] or more, V-type magnet arrangement in the rotor is investigated because it is possible to obtain more magnetic flux and reluctance torque by changing the magnet arrangement. Response surface methodology (RSM) is used as a method searching optimal position of permanent magnet in the rotor. It is easy to approach and efficient in seeking an optimal condition for a complex problem considering a lot of interaction of the design variables in an unknown system [2]. In addition, Empirical design, based on 2-dimensional finite element method (2D FEM), is performed to estimate response function.

2. Analysis Model

There are two analysis models, standard-type and V-type. Fig. 1 shows the configurations. Prototype motor is the standard-type, and target motor to improve TRV is the V-type. The prototype motor has 4 poles and 24 slots. The permanent magnet is NdFeB. The coil is distributed winding, and the current waveform is sine wave. In structure, its stack length is 75 [mm], and a radius of the rotor is 27 [mm]. The target model will be changed only magnet volume and the arrangement in the rotor.

3. Design of Experiments

In order to determine the equations of response surface, there are many experimental design methods. Between them, the most preferred classes of experimental designs are the orthogonal first-order design and the central composite design (CCD) [2]. In this paper, CCD is chosen to estimate



(a) Standard-type IPM (Prototype Model)

(b) V-type IPM (Target Model)

Fig. 1 Configurations of analysis models the equations, interactions of the design variables and curvature properties of unknown system in a few times of experiments [3]. Without screening design variables, Fig. 2 shows three variables estimated to have an effect on average torque of IPM motor by experience. The coded variables are written as follows :

$$x_i = \frac{2\zeta_i - (\zeta_{iL} + \zeta_{iH})}{\zeta_{iH} - \zeta_{iL}}, \quad i = 1, 2, 3 \qquad (1)$$

where ζ_i is the actual setting in the original units of the ith factor, and ζ_{iL} and ζ_{iH} are the low and high levels of ζ_i respectively. Real values and coded values of design variables are shown in Table 1. Moreover, design area and design table are shown in Fig. 3 and Table 2 separately [4].

4. Optimization Using the RSM

4.1 Concept of RSM

RSM procedures seek to the relationship between design variable and response, and they determine the optimum system response through statistical fitting method using observed data. The response is generally obtained from real experiments or computer simulations. Thus, 2D FEM is used in this paper. It is supposed that the true response η can be written as follows :

$$\eta = F(\zeta_1, \zeta_2, \cdots, \zeta_k) \qquad (2)$$

where the variables $\zeta_1, \zeta_2, \cdots, \zeta_k$ in Eq. (2) are expressed in natural units of measurements, so called natural variables. The experimentally obtained response Y differs from the expected value η due to random experimental error. Because the true response function F is unknown and perhaps very complicated, we must approximate it. The relation Y between F may be written as [2] :

$$Y = F(x_1, x_2, \cdots, x_k) + \varepsilon \qquad (3)$$

where ε denotes the random error, which consists of measurement error caused by sources such as the production equipment, the testing equipment, and the people who run the equipment [4].

In many cases, the true response η is normally chosen to be either a first-order or a second-order polynomial, which is based on Taylor series expansion [3]. In general, the first-order model is as follows :

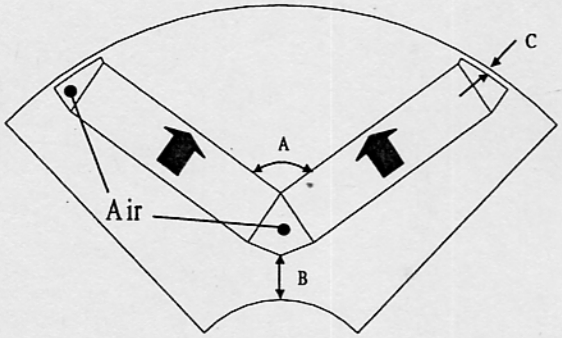


Fig. 2 Design variables

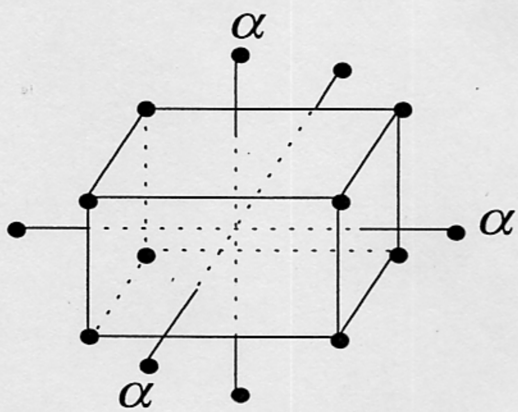


Fig. 3 Design area

Table 1. Real values and coded values

Coded values		1.682	1.0	0	1.0	1.682
Real values	A [°]	99.91	104	110	116	120.05
	B [mm]	2.359	2.7	3.2	3.7	4.041
	C [mm]	0.316	0.35	0.4	0.45	0.484

Table 2. Design table

Experiment No.	Design variables		
	x_1	x_2	x_3
1	-1.0	-1.0	-1.0
2	1.0	-1.0	-1.0
3	-1.0	1.0	-1.0
4	1.0	1.0	-1.0
5	-1.0	-1.0	1.0
6	1.0	-1.0	1.0
7	-1.0	1.0	1.0
8	1.0	1.0	1.0
9	-1.682	0.0	0.0
10	1.682	0.0	0.0
11	0.0	-1.682	0.0
12	0.0	1.682	0.0
13	0.0	0.0	-1.682
14	0.0	0.0	1.682
15	0.0	0.0	0.0

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \quad (4)$$

and the second-order model is as follows :

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x^2{}_j + \sum_{i \neq j}^{k} \beta_{ij} x_i x_j \quad (5)$$

In order to predict the response more accurately, the second-order model is used to fit a curvature response in this paper.

From the above approximating function, the estimated response $\hat{Y}$ at n data points can be written matrix form as follows :

$$\hat{\mathbf{Y}} = \mathbf{X}\hat{\beta} \quad (6)$$

where the caret (^) denotes estimated values. In Eq. (6), $\mathbf{X}$ is matrix of model terms evaluated at the data points, and the vector $\hat{\beta}$ contains the unknown coefficients which are usually estimated to minimize the sum of the squares of error terms, which is a process known as regression.

4.2 Estimation of the regression coefficients

The regression coefficients of the predictive model are estimated by the model of least squares using the general formulation as follows :

$$\hat{\beta} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y} \quad (7)$$

where, $\hat{\beta}$ is the matrix of parameter estimates. $\mathbf{X}^T$ is the transpose of the matrix $\mathbf{X}$, and $\mathbf{Y}$ is the matrix of the observed average torque. Using the estimated coefficients, the second-order predictive model can be written as follows :

$$\hat{\mathbf{Y}} = \hat{\beta}_0 + \sum_{j=1}^{k} \hat{\beta}_j x_j + \sum_{j=1}^{k} \hat{\beta}_{jj} x^2{}_j + \sum_{i \neq j}^{k} \hat{\beta}_{ij} x_i x_j \quad (8)$$

where $\hat{\beta}_0$, $\hat{\beta}_j$, $\hat{\beta}_{jj}$, $\hat{\beta}_{ij}$ are the coefficients, and they are shown in Table 3. The observed and predicted values of average torque are presented in Table 4. The adequacy of the predictive second-order model can be seen by closeness between the observed and predicted values. The observed values are obtained by 2D FEM.

4.3 Optimization

The optimization using RSM is performed to maximize average torque of V-type IPM motor. Considering the rotor volume of V-type IPM motor and the difficulty of fabrication, V-type IPM motor should generate at least 13.75[Nm] to get 80[kNm/m^3] or more, and the width of link should be over 0.3[mm]. With reflecting these constraints, optimized results are shown in Table 5. The predictive value and the observed value of optimized model are very close, and TRV of optimized is 80.5[kNm/m^3]. This value is increased about 9.67[%] than TRV of standard-type IPM motor While volume increase of permanent magnet is 11.1[%]. Fig. 4 shows analysis results of standard-type and optimized V-type. Moreover, Fig. 5 and Fig. 6 present contour plot of the maximum average torque, for variable A, angle, B, height, and C, linkwidth, respectively. From these figures, it is easily able to predict the relationship between the response and design variables. Furthermore, as making narrow interest region, errors of approximate function can be reduced.

Table 3. Regression coefficients of predictive model

Coefficients	Estimated value
β_0	13.7454
β_1	0.0236
β_2	0.0318
β_3	-0.0032
β_{11}	0.0085
β_{22}	-0.0170
β_{33}	0.0009
β_{12}	-0.0113
β_{13}	0.0001
β_{23}	-0.0005

Table 4. Response of torque average

Experiment No.	Predictive Value [Nm]	Observed Value [Nm]	Residual
1	13.6725	13.6695	0.003
2	13.7431	13.7423	0.0008
3	13.7607	13.7532	0.0075
4	13.7859	13.781	0.0049
5	13.667	13.671	-0.004
6	13.7377	13.7443	-0.0066
7	13.7534	13.7532	0.0002
8	13.7788	13.7809	-0.0021
9	13.7287	13.7344	-0.0057
10	13.8088	13.8065	0.0023
11	13.6441	13.6409	0.0032
12	13.7508	13.7559	-0.0051
13	13.753	13.763	-0.01
14	13.7424	13.7353	0.0071
15	13.745	13.7453	-0.0004

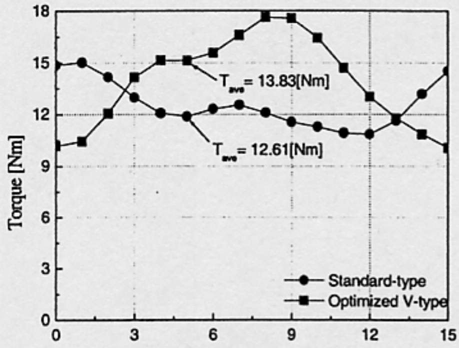


Fig. 4 Results of Torque analysis

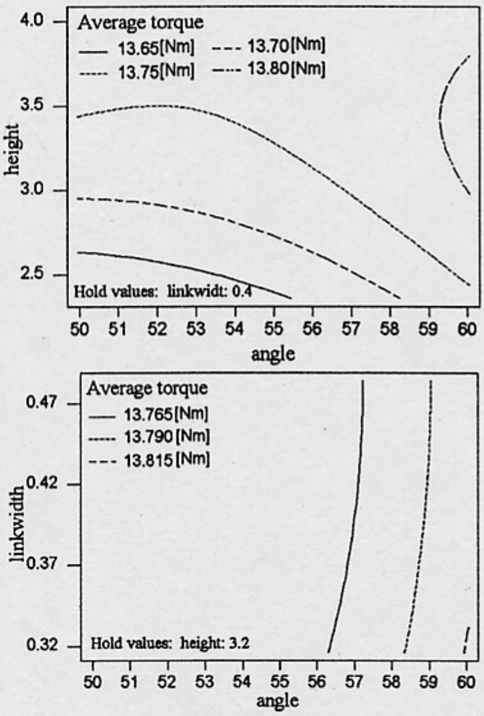


Fig. 5 Contour plot of maximum average torque

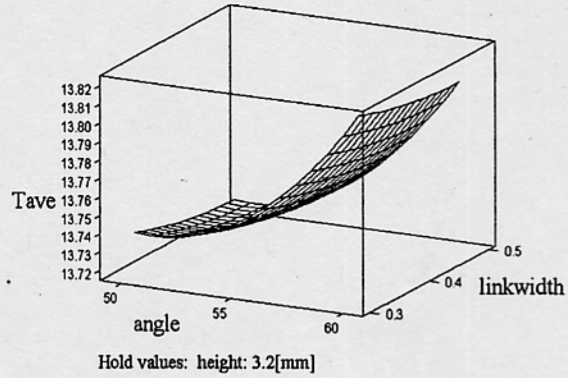


Fig. 6 Response Surfaces of maximum average torque

Table 5. Optimized results

Optimized values		Optimized T_{ave}	Observed T_{ave}	TRV
A	60.05 [°]	13.82 [Nm]	13.83 [Nm]	80.5 [kNm/m^3]
B	3.4 [mm]			
C	0.316 [mm]			

5. Conclusion

In this paper, shape optimization using RSM based on 2D FEM is performed to maximize average torque of V-type IPM motor. As a result, this paper verifies more great average torque of V-type than standard-type. Although experiment in all area can be time-consuming, it is possible that better value emerge out of design region. Therefore, if the possibility can be neglected, RSM making a close relationship of design variables and output variables can be good statistical approximation method.

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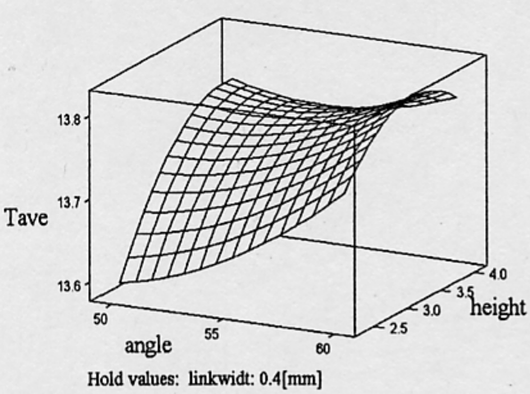

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