Topology Optimization of Hybrid Magnetic Torque Converter based on Box-Behnken Design

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This paper derives an effective shape by topology optimization of hybrid magnetic torque converter (MTC) based on Box-Behnken design (BBD). Analysis between independent variable selected by BBD and reaction variable using the finite element method (FEM) based on 2-D numerical analysis. Also, regression equation of reaction variable according to the independent variable by multiple regression analysis and analysis of variance (ANOVA) derived and validity of optimization design by comparing characteristics optimized model derived from response surface analysis and initial model demonstrated.

***Index Terms*—Topology optimization, Hybrid magnetic torque converter (MTC), Box-Behnken design (BBD), Multiple regression analysis, Analysis of variance (ANOVA), Response surface analysis.**

I. Introduction

THE MAGNETIC TORQUE CONVERTERS (MTCs) is a non-contact machine for torque transmission and acceleration and deceleration. These MTCs have some advantages such as no mechanical loss and maintenance-free operation. Furthermore, they have inherent protection characteristics. On the other hand, compared with the conventional MTC which has PMs are attached to the surface in all of the rotor, on-off control is possible on the hybrid MTC proposed in this paper because the one of the two rotors utilizes the coils in the stator instead of PM. This hybrid MTC with the stator structure has low transmission torque and high ripple than the conventional MTC. Therefore, optimal design on the shape of the stator must be necessary. In this paper, the topology optimization of hybrid MTC was conducted by the Box-Behnken design (BBD) which is one of response surface methodology (RSM). Also, the analysis between independent variables and reaction variables selected by BBD were used by the finite element method based on 2-D numerical analysis.

II. Topology Optimization Method

A. Box-Behnken Design and Response Surface Methodology

The BBD is an experiment design to combine the 2^k factorial layout plan with the blanced incomplete block design (BIBD) to establish a basic plan and then to add the test number n_c to estimate a secondary response surface equation. Therefore, BBD is used to efficiently estimate the first and the second terms of the response surface estimate equation, when it is obvious that optimal design factors are neither a low level, nor a high level; and when it is obvious that all experiments are conducted in a stable process area [2]. Also, in the RSM, a statistical model suitable for response surface is assumed and then, under various conditions of independent variables, experiments are performed to obtain experiment data. The obtained experiment data is analyzed through regression analysis, to estimate a response surface. The estimated response surface is used to analyze the sensitivity of response variables to the changes in independent variables, or to find out a set of levels of independent variables that maximize or minimize response variables [3-5]. The RSM is one of designs of experiment, when finds the optimal condition through analysis of variance (ANOVA) or a design of experiment and then analyzes the interaction formula for independent variables $x_1, \cdots x_n$ and response variables y values. In other words, it is used for finding the optimal response condition based on several factors. If there is a radius of curvature among the response variables, a response surface design is used, to identify the relationship among two or more factors. When a unknown function between the independent variables $x_1, \cdots x_n$ and the response variables y is expressed as f, it can be expressed as $y = f(x)$ and this unknown function is called a response function. When the number of independent variables x is k and the response function y is assumed as a secondary regression model, it can be expressed as shown in (1)

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \sum_{i \le j}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

where ε represents a statistical error, which is generally assumed as normal distribution with the mean of zero and the variance of σ^2. Therefore, when the response function estimated from the approximation function is expressed in vector form

$$y = X\beta + \varepsilon \quad (2)$$

where X is the matrix of design variables, β is the regression coefficient vector, and ε is the random error vector. In addition, the regression coefficient vector is estimated using the least squares method that takes the square sum of random errors as the minimum. The least square estimator of the regression coefficient vector is as shown in (3)

$$\beta = (X'X)^{-1}X'y. \quad (3)$$

Therefore, in this study, the above equations were used to calculate estimation equations of the response functions such as power and torque ripple, and to predict the response functions according to the changes in independent variables.

B. Multiple Linear Regression

In multiple regression analysis, regression analysis including interaction term between second order term or third, and response variables is referred to as a polynomial regression analysis. In order to perform the experiment design the BBD and determine whether each factor is a significant term using the ANOVA, F-test is used. When P-value derived from this test is smaller than 0.05, the corresponding factor is considered to have significance. However, if the P-value is greater than 0.05, the corresponding factor is not a significant factor and accordingly considered to be a factor that does not affect response variables. Therefore, when performing the ANOVA in this paper, the factors of which P-value are greater than 0.05, i.e. the ones that are not significant, sequentially from larger values are removed.

C. Objective Function

Considering the torque ripple and power characteristic by topology optimization, the multiobjective optimization model of this hybrid MTC can be defined as

$$\textbf{\textit{Minimize}}: \begin{Bmatrix} f_1(\mathrm{x}) = IT_r \\ f_2(\mathrm{x}) = OT_r \end{Bmatrix} \quad (4)$$

$$\textbf{\textit{Subject to}}: \begin{Bmatrix} g_1(\mathrm{x}) = 15,700 - IP \le 0 \\ g_2(\mathrm{x}) = 15,700 - OP \le 0 \\ g_3(\mathrm{x}) = 2.475 \le Gr \le 2.525 \end{Bmatrix} \quad (5)$$

where f_1 and f_2 are the torque ripple of inner rotor and outer rotor respectively. *IP* and *OP* in g_1 and g_2 are the power of inner rotor and outer rotor. *Gr* in g_3 is the gear ratio. In optimizing the topology, the response variables are to focus on improving the torque ripple and optimization was performed so as to have the minimum value. The constraints are that satisfy the inner and outer output power of 15.7 kW and the gear ratio of 2.5 ± 1 %.

III. Numerical Analysis and Optimization Results

The shape of the initial and optimized model of hybrid MTC and is shown in Fig 1. The inner rotor utilizes coils instead of PM and the pole pieces are sandwiched between inner rotor and outer rotor. The 12-slot stator has one-phase concentrated windings, with the diameter of the wire and the number of turns per coil being 1.8 mm and 20, respectively. The outer rotor consists of a yoke made of silicon steel and 30 segment-type permanent magnets of *Br*=1.23 T. The pole piece consists of 21 steel formed by 35PN230 laminated silicon steel sheets. Also, the gear ratio is 2.5 by number of poles of outer rotor and inner rotor. Table I shows the optimization results, and Fig. 2 shows the torque waveform.

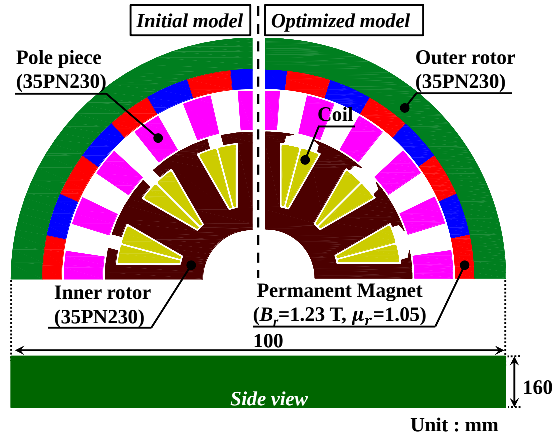
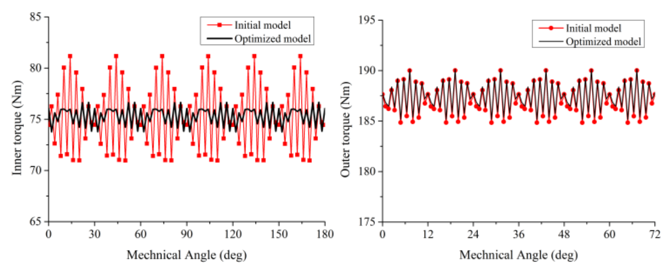


Fig. 1. Schematic view of hybrid MTC model.

TABLE I
Optimization Results

	Initial model	Optimized model
Inner torque (Nm)	75.23	75.32
Outer torque (Nm)	187.17	187.45
Inner torque ripple (%)	13.57	3.82
Outer torque ripple (%)	2.76	2.66
Inner power (kW)	15.7	15.7
Outer power (kW)	15.6	15.7
Gear ratio	2.48	2.48



(a) (b)

Fig. 2. Torque waveforms. (a) Inner torque, (b) Outer torque.

As a result of optimization, torque ripple of inner rotor was reduced by 71.8 % from that of the initial model and torque ripple of outer rotor was reduced by 3.6 %. Hereby, the validity of optimized design of the hybrid MTC by BBD was proved. Detailed contents in the topology optimization procedure will be presented in full paper.

IV. References

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