Robust Tolerance Design Optimization of a Claw Pole PM Motor with Soft Magnetic Composite Cores

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Tolerance optimization methods have been widely investigated in the mechanical engineering for pursing the optimal balance between reliability and cost. However, for motor design, the current tolerance optimization methods may not be suitable since it is usually a multidisciplinary problem and high reliability is needed. This paper proposes a robust tolerance optimization approach for a claw pole permanent magnet (PM) motor with soft magnetic composite (SMC) cores. First, in the optimization process, both of the output and thermal performance are all considered, and design of six sigma method is utilized for guaranteeing the high reliability. Then to optimize the overall cost, both of the material and manufacturing tolerances are all taken into account. Finally, through the analysis, the proposed method shows good performance in increasing motor's reliability and decrease the whole cost, which will benefit the actual production.

***Index Terms*—Robust optimization, tolerance optimization, soft magnetic composite, claw pole PM motor.**

I. Introduction

RECENCTLLY the manufacturing processes of electrical machines are attracting much more attention of the researchers who are doing the design and optimization work. For a specific application high performance, reliability and low cost are always designers want [1-2]. In our previous work, robust optimization approaches have been proposed [1]. In the process of pursuing high performance, these methods take the specific manufacturing tolerances of the design parameters into account to guarantee the reliability at the same time. However, in the actual production of motors, there are still several problems need to be considered. Firstly, the manufacturing tolerances are relatively controllable. As known, when we consider tolerances in the optimization process, big tolerance usually means low manufacturing cost, but high performance diversity. In order to guarantee the reliability, some other dimension parameters will change for compensation of performance. This will lead to the increase of the whole cost inversely. Therefore, it is more meaningful when we consider the material cost and manufacturing cost related to tolerances at same time. Secondly, it is more complete when we analysis and optimize the motor performance in multiphysics, such as the electromagnetic and thermal properties etc.

This paper proposes a tolerance robust optimization for a claw pole PM motor considering its performance, overall cost and reliability. Both of the dimension parameters and their manufacturing tolerances are all optimized. In order get more complete optimization results, both of the electromagnetic and thermal analysis models are developed. For sake of decreasing the high parameter dimension, some optimization techniques are utilized such as the approximation model, multilevel method etc. Finally, for reliability estimation of the optimal results, the probability of failure (POF) is taken as a criterion by using the Monte Carlo Analysis (MCA).

II. Multilevel design analysis

A. Motor prototype

Fig. 1 shows the main stator structure of the claw pole motor prototype developed in our previous work. It was designed to deliver an output power of 500 W at 1800 r/min. The operating frequency is 300 Hz.

Fig. 1. Claw pole stator structure

B. Finite element analysis model

Since the relative permeability is relatively lower than silicon steel sheet, it is relatively harder to use the analysis model as the traditional motors. Therefore, in order to get accurate electromagnetic analysis results, finite element analysis (FEA) model is developed in this research

C. 3D thermal network model for temperature rise analysis

For sake of predicting the temperature rise in a fast way, a 3D thermal network [3] is utilized in this paper. In the solid body, the heat transfer and steady temperature rise can be calculated by

$$\begin{aligned}&(T_b - T_a)/R_{ab} + (T_c - T_a)/R_{ac} + (T_d - T_a)/R_{ad} \\ &+ (T_e - T_a)/R_{ae} + (T_f - T_a)/R_{af} + (T_g - T_a)/R_{ag} = -q\end{aligned} \quad (1)$$

where T means the temperature nodes in 3dimensions, R means the thermal resistance between nodes, and q in watt is the rate of heat. Table I lists the calculated and measured key motor parameters for this machine by the models mentioned above which shows the reliability of the models for the optimization in next step.

TABLE I

KEY PARAMETERS VALIDATION OF THE INITIAL DESIGN

Par.	Unit	Calculated	Measured
Back EMF constant	V/rpm	0.0272	0.0271
Phase inductance	mH	5.54	5.79
Coil temperature rise	℃	74	71
PM temperature rise	℃	22	23

III. TOLERANCE DESIGN OPTIMIZATION

A. Optimization scheme and strategy

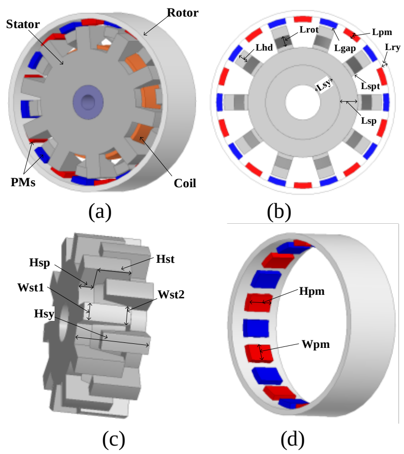

Fig. 2. Main 3D structure parameters

The definition of the 3D independent design parameters are shown as Fig.2. As presented, the whole optimization dimension is huge, and it can be very time consuming if we optimize the parameters at the same time. If we add the tolerance of each parameter, the design dimension will be doubled. Thus, a multilevel optimization scheme is developed in this paper. The initial high-dimensional design is divided space into 3 subspaces (X1, X2 and X3) by sensitivity analysis techniques. The parameters and their tolerance of high sensitivity for the objective function are optimized preferentially. In order to decrease the computation burden, Kriging model is employed as the approximation model for the FEM in the electromagnetic field calculation.

B. Tolerance optimization

For the analysis model to be investigate in this paper, after the application demand is given as shown in part II, the objective becomes to minimize the whole cost and maximize the efficiency with the structure parameters and their tolerances at the same time. The objective function and constraints can be defined as

$$\min: f(\boldsymbol{x},\boldsymbol{\delta}_x)=\omega_1\frac{Cost}{Cost_{initial}}+\omega_2\frac{\eta_{initial}}{\eta}$$
$$s.t.\begin{cases} g_1(\boldsymbol{x},\boldsymbol{\delta}_x)=500-P_{out}\le 0, g_2(\boldsymbol{x},\boldsymbol{\delta}_x)=0.815-\eta\le 0\\ g_3(\boldsymbol{x},\boldsymbol{\delta}_x)=sf-0.7\le 0, g_4(\boldsymbol{x},\boldsymbol{\delta}_x)=T_{coil}-75\le 0\end{cases} \quad (2)$$

where $\boldsymbol{\delta}_x$ means the tolerances of the design parameters, $Cost_{initial}$ and $\eta_{initial}$ are the initial cost and efficiency, respectively, ω_1 and ω_2 are the coefficients, P_{out} is the output power , T_{coil} is the temperature rise of coil, sf is the slot fill rate, and η is the efficiency. Specifically, the price related to the tolerance can be calculated by $Cost(\delta)=a_1+a_2+\delta^{-a3}$ in [4]. Under the framework of a robust design approach called the design for six sigma [1], the robust optimization model of equation (2) can be expressed as

$$\begin{aligned}&\min:\mu_f(\boldsymbol{x})\\ &s.t.:\mu_{g_i}(\boldsymbol{x})+6\sigma_{g_i}(\boldsymbol{x})\le 0, i=1,\ldots,6.\\ &\boldsymbol{x}_l+n\sigma_{\boldsymbol{x}}\le\mu_{\boldsymbol{x}}\le\boldsymbol{x}_u-n\sigma_{\boldsymbol{x}}\end{aligned} \quad (3)$$

where μ_x and σ_x are the mean and standard deviation of design variables due to their tolerances, respectively. The values of objective function and constraint function of the performance can be estimated by the Monte Carlo analysis (MCA) method.

IV. RESULTS AND DISCUSSION

Fig.3 illustrates the temperature rise in the coil and output power distribution with MCA data after the robust tolerance optimization. As shown, the temperature rise is successfully controlled under 75 ℃. The mean value of the output power is around 515 W, little higher than the required 500 W. This guarantees the output in mass production to satisfy the application. To analysis the motor's reliability the probability of failure (POF) is taken as a criterion, which is defined as

$$POF=1-\prod_{i=1}^{m}P(g_i\le 0) \quad (4)$$

The POF is almost 0 after the MCA, which shows the high reliability of the optimal results.

Moreover, the obtained optimal performance of the motor is much better than those of the original design, including the higher efficiency (81.5% versus 84.9%), and lower whole cost ($45.85 versus $41.5).

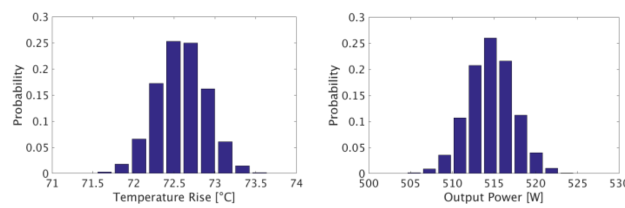

Fig. 3. Distribution of the temperature rise and output power

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