Multiobjective Design Optimization of PM-SMC Motors for Six Sigma Quality Manufacturing

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***Abstract*—In our previous work, soft magnetic composite (SMC) material was employed to design and manufacture cores for two kinds of permanent magnet (PM) synchronous motors, namely transverse flux machine (TFM) and claw pole motor. Considering the industry applications of these PM-SMC motors, multiobjective design optimization and manufacturing quality are needed to investigate. This paper presents a multiobjective design optimization method for these motors to achieve six sigma quality manufacturing. The proposed method is based on the robust optimization framework of design for six sigma (DFSS). Manufacturing quality and cost are included in the design and optimization models. From the design analysis of a PM-SMC TFM, it can be found that the obtained multiobjective design schemes can provide good products with higher reliability and lower manufacturing cost.**

***Index Terms*—Design optimization, electromagnetic fields, permanent magnet machines, reliability engineering.**

I. INTRODUCTION

Industrial applications of electrical machines often involve simultaneous design and optimization of several objectives, such as minimizing cost, weight and torque ripple, and maximizing power density and efficiency. These objectives usually contradict to each other [1]-[3]. Therefore, the corresponding design and optimization of motors are actually multiobjective issues.

For the multiobjective design optimization of electrical machines, most current works are based on the deterministic design method and they have not investigated uncertainty analysis of performance with respect to the unavoidable noise factors in the manufacturing process. Moreover, manufacturing cost and quality are not investigated in the design of these motors by far. Therefore, the reliabilities of the designed motors cannot be ensured with respect to these noise factors [4], [5]. Consequently, this design method cannot ensure that the designed motors are of high performance; here "high performance" means high efficiency with high reliability and robustness.

Furthermore, for the practical design of electrical machines, the computational effort is usually extremely expensive as finite element analysis is needed in the design optimization process. To deal with this problem, an alternative method is to use approximate techniques. In this work, Kriging model will be employed to construct the approximate models for motors' objectives and constraints.

The main aim of this paper is to present multiobjective robust design methods for the PM-SMC motors to achieve six sigma quality manufacturing.

II. PM-SMC TRANSVERSE FLUX MACHINE

In our previous work, several PM electrical machines with three-dimensional flux structure, such as claw pole motors and transverse flux machines (TFM) were developed with cores designed by using soft magnetic composite (SMC) material [6]-[8]. SMC is a new type of soft magnetic material made of fine magnetic powders and it has many unique advantages, such as isotropic magnetic property, low loss, cheap and easy to compress by moulds. Therefore, SMC cores are suitable for manufacturing motors with complex structures. In this work, a PM-SMC TFM will be investigated to illustrate the performance of the proposed method.

Fig. 1 shows the magnetically relevant parts of the PM-SMC TFM. This motor is designed to deliver a power of 640 W at 1800 r/min. Fig. 2 shows the finite element analysis model. Fig.3 shows the B-H curves of the manufactured SMC cores with different SMC density values. Actually, these cores are fabricated with different manufacturing conditions. From this figure, we can see that the magnetic character of SMC core highly depends on the manufacturing conditions. Therefore, we need to consider this issue for the industrial application of these motors. From our design experience, eight parameters, which are significant to the performance of this machine, are selected as optimization factors for the motor in this work. They are x_1 and x_2: circumferential angle and axial width of PM; x_3 and x_4: circumferential width and axial width of SMC tooth, x_5: air gap; x_6 and x_7: number of turns and diameter of copper wire winding; and x_8: manufacturing condition. The multiobjective optimization model of this motor can be defined as

$$\min:\begin{cases} f_1(\mathbf{x}) = \text{Cost(PM)+Cost(Cu)} \\ f_2(\mathbf{x}) = -T \end{cases}$$
$$\text{s.t.}\ \begin{cases} g_1(\mathbf{x}) = 0.795 - \eta \le 0, \\ g_2(\mathbf{x}) = 640 - P_{\text{out}} \le 0, \\ g_3(\mathbf{x}) = sf - 0.8 \le 0, \\ g_4(\mathbf{x}) = J_c - 6 \le 0, \end{cases} \quad , \qquad (1)$$

where f_1 considers the costs of PM and copper (Cu) winding; f_2 is the mean of practical torque output by this system; η and P_{out} (unit: W) in g_1 and g_2 are the motor's efficiency and output power respectively; sf and J_c (unit: A/mm^2) in g_3 and g_4 are the fill factor and current density of the winding respectively.

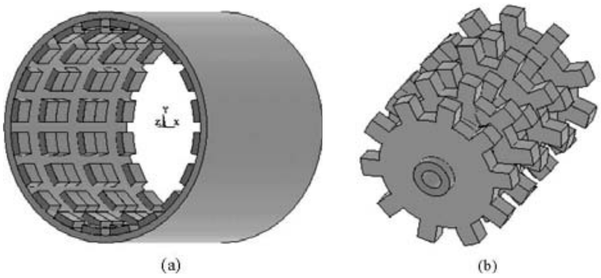

Fig. 1. Magnetically relevant parts of PM TFM: (a) rotor and (b) stator.

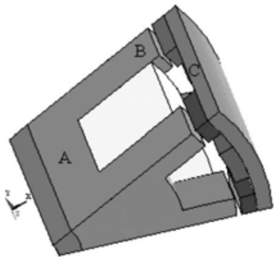

Fig. 2. Magnetic field analysis model for TFM

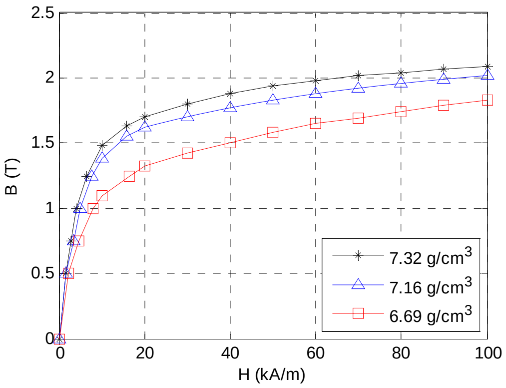

Fig. 3. B-H curves with respect to different SMC density values

Under the robust optimization framework of design for six sigma (DFSS) [4], [5], [9], we can define the robust multiobjective optimization model of this motor as

$$
\begin{aligned}
&\min:\begin{cases} F_1=\mu_{f_1}(\mathbf{x})\\ F_2=\mu_{f_2}(\mathbf{x})\end{cases}\\
&s.t.\ \begin{cases} \mu_{g_i}(\mathbf{x})+n\sigma_{g_i}(\mathbf{x})\le 0,\ i=1,\dots,4\\ x_{li}+n\sigma_{x_i}\le\mu_{x_i}\le x_{ui}-n\sigma_{x_i},\ i=1,\dots,8\end{cases}
\end{aligned}
\quad, \qquad (2)
$$

where two objectives are the means of the deterministic objectives; μ and σ are the mean and standard deviation of the corresponding terms; n is the sigma level. Generally, sigma level n can be equivalent to a probability or reliability with respect to a normal distribution [9]. In this work, the value of n is selected as 6. In quality control theory, six sigma level quality means only 3.4 defects per million for the long term quality control of industry products.

III. RESULTS AND DISCUSSIONS

Fig. 4 shows the optimization results of this TFM. From the figure, we can see that the front of robust optimal results is lower than that of deterministic design optimization, which means that the cost of robust design scheme is higher than deterministic design scheme for the same output torque. However, the failure rates of robust design schemes are less than 3.4 over a million, which is ensured by the optimization model (2). In other words, the reliabilities of all robust design schemes are higher than the deterministic design schemes. Furthermore, the manufacturing costs of all robust design schemes are also lower than those of deterministic design schemes. Therefore, the obtained multiobjective robust optimal points have achieved six sigma quality manufacturing.

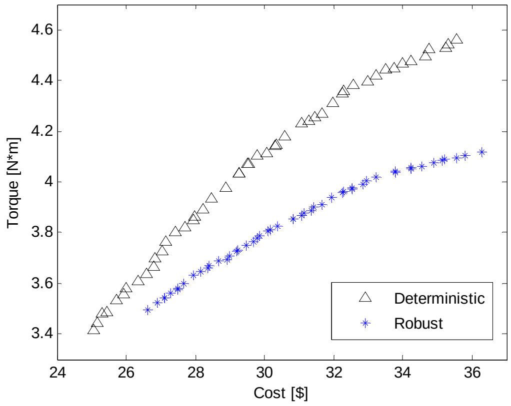

Fig. 4. Pareto solutions for the PM-SMC TFM

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