Multidisciplinary Design Optimization of Machines with Soft Magnetic Composite Cores for Batch Production

Gang Lei, Chengcheng Liu, Jianguo Zhu, and Youguang Guo

School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney, NSW 2007, Australia

This paper presents a multidisciplinary design optimization (MDO) method for permanent magnet (PM) machines with soft magnetic composite (SMC) cores. Then a robust multiobjective optimization approach based on MDO is presented for these PM-SMC motors to achieve high manufacturing quality in batch production. The MDO analysis process mainly includes electromagnetic and thermal analyses. Finally, to demonstrate the effectiveness of the proposed method, a PM transverse flux machine with SMC core is investigated to minimize the material cost and maximize the output power under several constraints from multidisciplinary design. As shown, the proposed method can increase the reliability of all Pareto schemes significantly. And this obtained robust Pareto solutions will benefit the batch production of PM-SMC motors.

***Index Terms*—Finite element analysis, optimization, permanent magnet machines, soft magnetic materials, thermal analysis.**

I. INTRODUCTION

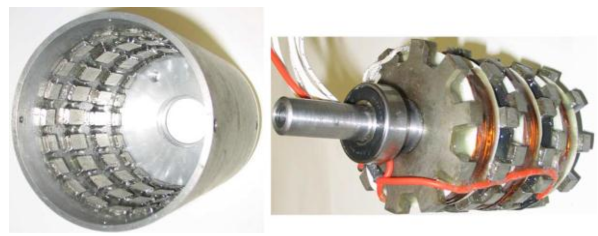
RECENTLY, a relatively new type of material called as soft magneticcomposite (SMC) material has been introduced to design and fabricate the stator cores for several kinds of permanent magnet (PM) motors, such as transverse flux machine (TFM) and claw pole motor, due to the unique characteristics of this kind of material. SMC is made of ferromagnetic powder particles surrounded by an electrical insulating film. Compared with traditional silicon steel sheets, motor cores made of SMC material have several advantages, the most important one is that SMC cores are isotropic both mechanically and magnetically, so they are suitable for the design of 3-D flux path [1]-[4].

As a new material, SMC cores have unique magnetic characteristic and manufacturing method, multidisciplinary design optimization (MDO) is needed to get the best performances of PM-SMC motors, especially the thermal analysis. Meanwhile, there are two important issues in the batch production of them, which have to be considered to improve the industrial application. One is the robust design against noise factors in manufacturing process [5], [6], and the other is the presentation of Pareto solution for multiobjective requirements. This work presents a robust and multiobjective approach for the MDO of PM-SMC motors to improve their quality in the batch production.

II. PM-SMC MOTORS

Fig.1 shows a PM TFM designed to deliver an output power 640 W a rated speed 1800 rev/min.It has 20 poles in the PM rotor; and there are 60 SMC teeth in the stator. The stator is made of SMC SOMALOY 500 [1], [2].

As the SMC core is compressed by module, core's density is a noise factor in the manufacturing process. It is directly related to the B-H curves of that core. Fig. 2 illustrates three magnetization curves with respect to three density values respectively for a kind of SMC core [5]. From this figure, it can be found that there are significant differences of B-H data between different density values.



(a) (b)

Fig. 1. Prototype of a PM TFM, (a) PM rotor, (b) 3 stack SMC stator

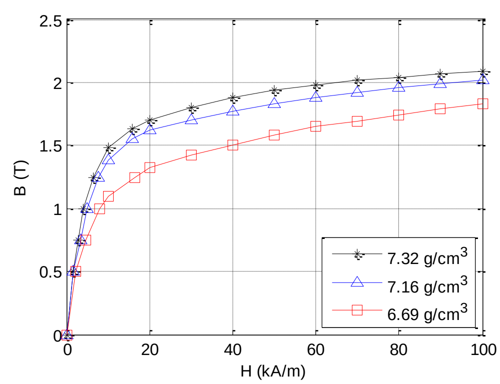


Fig. 2. B-H curves with respect to different SMC density values

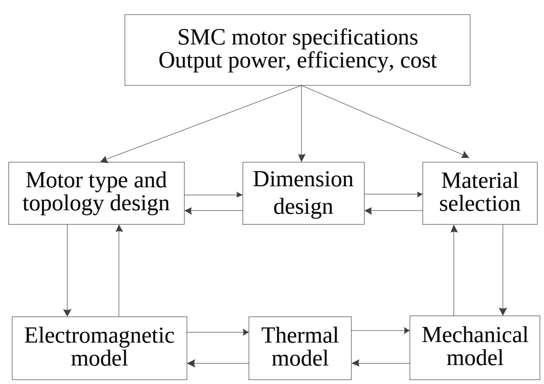


Fig.3. Multidisciplinary design framework for PM-SMC motors

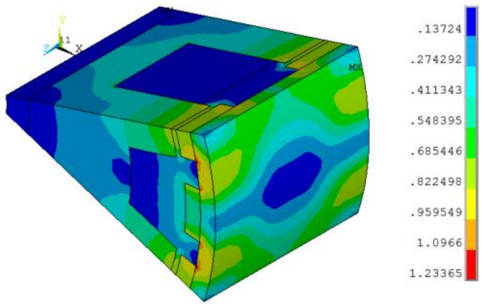


Fig. 4. Illustrations of electromagnetic field analysis

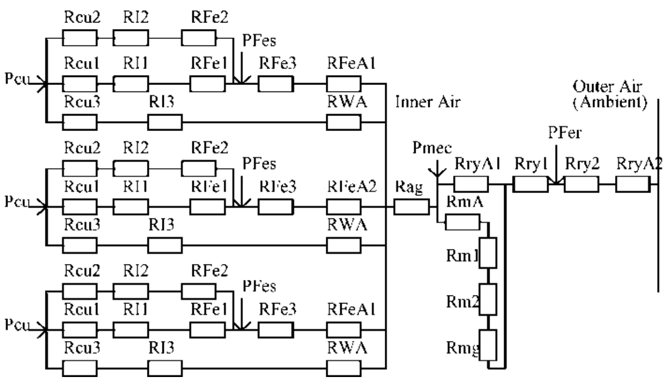


Fig.5. Thermal network model for PM-SMC TFM

III. Design Example

Fig. 3 shows the multidisciplinary analysis framework of PM-SMC motors. Fig. 4 shows an illustration of the electromagnetic field analysis for a TFM shown in Fig. 1. Fig. 5 shows the thermal network model for the thermal analysis of this TFM. The thermal resistances of conduction in the following sections are defined: rotor yoke (R_{ry}), magnets (R_{m}), air gap (R_{ag}), stator yoke (R_{Fe1}), stator side discs (R_{Fe2}), stator teeth (R_{Fe3}), and copper wire (R_{cu}). Mode details can be found in [1] and [2].

The deterministic multiobjective optimization model for this TFM can be defined as (1)

$$\begin{aligned} \min: \quad & \begin{cases} f_1(\mathbf{x}) = Cost \\ f_2(\mathbf{x}) = -P_{out} \end{cases} \\ \text{s.t.:} \quad & g_1(\mathbf{x}) = 0.795 - \eta \le 0, \\ & g_2(\mathbf{x}) = 640 - P_{out} \le 0, \\ & g_3(\mathbf{x}) = sf - 0.7 \le 0, \\ & g_4(\mathbf{x}) = T_{PM} - 65 \le 0, \\ & g_5(\mathbf{x}) = T_{Coil} - 65 \le 0. \end{aligned} \tag{1}$$

where objectives are material cost and output power, η is efficiency, sf is slot factor, T_{PM} and T_{Coil} are temperature rises in PM and winding. And the robust multiobjective model can be defined based on a technique called design for six-sgima.

$$\begin{aligned} \min: \quad & \{\mu[f_k(\mathbf{x})], k=1,2\} \\ \text{s.t.:} \quad & \mu[g_i(\mathbf{x})] + 6\sigma[g_i(\mathbf{x})] \le 0, i = 1,\dots,5 \end{aligned} \tag{2}$$

The mean (μ) and standard deviation (σ) terms are calculated by using Monte Carlo method with sample size 10000. 6 is the sigma level requied by the manufacturing quality.

IV. Results and Discussion

Fig.6 shows the Pareto solutions obatined by the deterministic model (1). Compared to the Pareto curve obtained from non-MDO design optimiation, It can be seen that the MDO curve is lower than the non-MDO curve, which means that for the same output power, the cost required by MDO method is larger than the other one. Fig. 7 shows the probability of failure (POF) curve for both Pareto solutions. It is found that the mean POF of MDO method (19%) is smaller than that of the non-MDO one (41%). Furthermore, if model (2) is optimized by the proposed method, all POFs are almost 0, which means the probability of products are almost 1. Therefor, the proposed method will benefit the batch production of PM-SMC motors

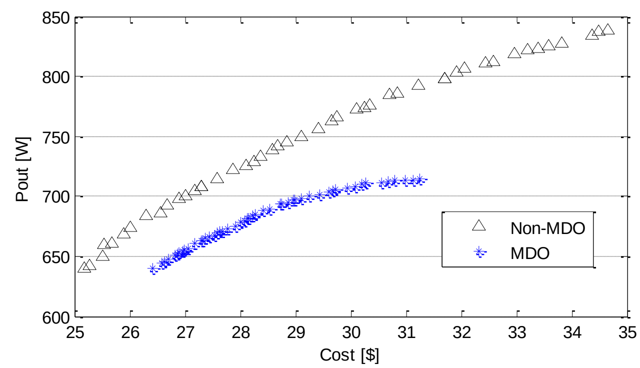


Fig.6. Pareto solutions for non-MDO and MDO method

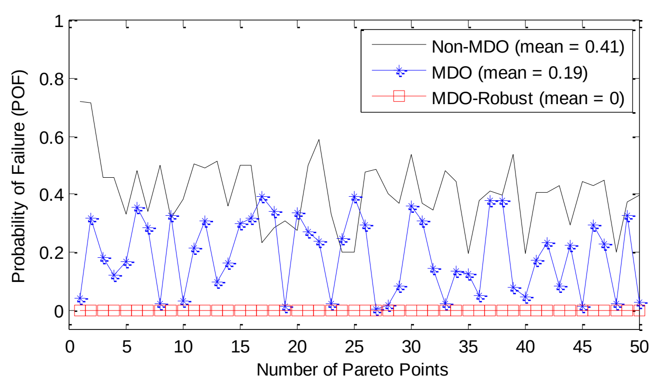


Fig.7. POFs of Pareto solutions for non-MDO and MDO method

References

[1] J. G. Zhu, Y. G. Guo, Z. W. Lin, Y. J. Li, and Y. K. Huang, "Development of PM transverse flux motors with soft magnetic composite cores," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 4376-4383, 2011.

[2] Y. G. Guo, J. G. Zhu, P. A. Watterson, and Wei Wu, "Development of a PM transverse flux motor with soft magnetic composite core," *IEEE Trans. Energy Convers*., vol. 21, no. 2, pp. 426-434, 2006.

[3] G. Gvetkovski and L. Petkovska, "Performance improvement of PM synchronous motor by using soft magnetic composite material," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 3812-3815, 2008

[4] D. H. Kim, J. K. Sykulski, and D. A. Lowther, "The implications of the use of composite materials in electromagnetic device topology and shape optimization," *IEEE Trans. Magn.*, vol. 45, no. 3, pp. 1154-1157, 2008.

[5] G. Lei, J. G. Zhu, Y. G. Guo, J. F. Hu, W. Xu and K. R. Shao, "Robust design optimization of PM-SMC motors for Six Sigma quality manufacturing,"*IEEE Trans. Magn.*, vol. 49, no. 7, pp. 3953-56, 2013.

[6] G. Lei, J. G. Zhu, Y. G. Guo, K. R. Shao and W. Xu, "Multi-objective sequential design optimization of PM-SMC motors for Six Sigma quality manufacturing,"*IEEE Trans. Magn.*, vol. 50, no. 2, Article 7017704, 2014.