

# Multilevel Design Optimization of a Claw Pole PM Motor with Soft Magnetic Composite Cores Considering Cogging Torque Reduction

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In our previous study, claw pole motor (CPM) shows promising magnetic concentrating performance for permanent magnet (PM) motors with soft magnetic composite (SMC) cores. Meanwhile, the relatively complex structure also increases the core loss and cogging torque. In order to optimize the output and cogging torque of a CPM from a holistic view, the three dimensional (3D) structure and material property design parameters are all considered in this paper. For the high dimensional design optimization problem, we present a multilevel optimization scheme by dividing the parameters into subspaces according to the sensitivity analysis. The Kriging model combined with orthogonal design is used under the multilevel optimization scheme to increase the optimization efficiency by replacing the finite element analysis (FEA). Finally, the analysis shows the proposed method can significantly increase the output and decrease the torque ripple.

*Index Terms*—Multilevel design optimization, cogging torque, soft magnetic composite, CPM.

## I. INTRODUCTION

SOFT magnetic composite material possesses many unique features than the traditional silicon steel sheet, such as the 3D magnetic and thermal properties but low permeability and high hysteresis loss etc. To take full advantages of the SMC material and overcome its disadvantages, lots of novel permanent magnet motor topologies of 3D magnetic field path have been investigated in our previous study [1-3]. The claw pole PM motor (shown as Fig.1) shows promising performance on magnetic concentrating which can compensate the low permeability. However, the relatively complex pole structure increases the partial saturation which gives rise to the core loss. In addition, the cogging torque ratio also increases compared with other simple structures such as the transverse flux machine.

Confronted with the high dimensional optimization problem of CPM with structure and material property parameters, this paper proposes a multilevel optimization scheme. The Kriging model is also used for replacing the FEA model to increase the optimization efficiency in addition to the multilevel scheme. Since both of the core loss and cogging torque calculation need the periodical calculation, the actual FEA points are tens of times more than the design samples. Compared with our research before, for sake of reducing the computation burden further, the orthogonal design technique is utilized with the multilevel scheme for higher efficiency.



Fig. 1. Claw pole stator structure

## II. GENERAL LAYOUT OF THE TWO-PAGE SHORT PAPER

### A. Core loss calculation model

For the core loss calculation of the SMC electrical machine, the comprehensive model in paper [1] is used here. In this model both alternating and rotational core loss are all considered. With an elliptical rotating flux, the core loss can be calculated by

$$P_{er} = R_B P_r + (1 - R_B)^2 P_a \quad (1)$$

where  $R_B = B_{min}/B_{maj}$ ,  $B_{min}$  and  $B_{maj}$  are the values of the major and minor axes of the ellipse, respectively,  $P_a$  is the alternating core loss, and  $P_r$  is the rotational core loss under two dimensional circularly rotating flux excitation,

### B. Cogging torque calculation model

For PM machines, cogging torque can be calculated by

$$T_c = \frac{\partial W}{\partial \theta} \quad (2)$$

where  $W$  means the co-energy, and  $\theta$  is the rotor angular displacement.

To analysis the cogging torque of the whole machine with three stacks, discrete Fourier transformation (DFT) is used for decompose the cogging torque of each stack

$$T_c(\theta) = \frac{A_0}{2} + \sum_{h=0}^M [A_h \cos(h\theta) + B_h \sin(h\theta)] \quad (3)$$

Because of 120 electrical degree displacement of each stack only  $6^{th}$  and its multiple harmonics left in the whole machine, which can be expressed as

$$T_{cog} = T_{Ac} + T_{Bc} + T_{Cc} = c_{k1} \sin 6\theta + c_{k2} \sin 12\theta + \dots \quad (4)$$

where  $c_{k1}$ ,  $c_{k2}$  are the coefficient got from DFT.

Both of the core loss and cogging torque analysis model are verified from the experiment of the initial design as shown in

Table I. Specially, the back EMF constant means the value of back electromotive force divided by the speed.

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     |
| No load core loss | W     | 58         | 60       |
| Cogging torque    | Nm    | 0.35       | 0.33     |

### III. MULTILEVEL DESIGN OPTIMIZATION

#### A. Multilevel optimization scheme

Fig.2 presents the structure design parameters of the motor. Specially, since the utilization of the unequal-width claw, the claw pole head and root are defined respectively. In addition, the material properties which include the core density, relative permeability of the PM, and diameter and turns of coil, are all considered. The whole design space contains more than 15 parameters after the sensitivity analysis. As finite element model (FEM) is employed to analysis the field distribution, core loss and cogging torque the optimization, the computation costs are always huge due to the high dimension. Especially for the calculation of the core loss and cogging torque, half cycle of the waveform should be computed. That means the dimension will increase around 10 times. Since this paper is taking all the 3 dimensional and material property into account, efficient optimization strategy/method is required.

To solve this issue, a method called multi-level optimization method presented for electrical drive systems in our previous work will be introduced in this work. The multilevel optimization method has two main implementation steps. Firstly, divide the initial high dimensional design space into 3 low dimensional subspaces in terms of the significance order of all parameters. In this step, sensitivity analysis techniques are required, such as local sensitivity analysis (LSA) and design of experiment. Secondly, optimize these subspaces sequentially till convergence criterion is met.

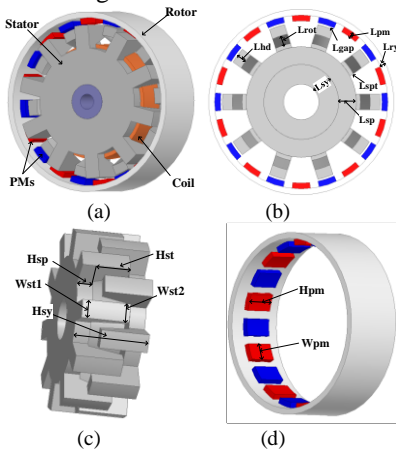


Fig. 2. Main structure design parameters

#### B. Approximation model building with orthogonal design

In addition an approximation model, Kriging model [4] will be used as surrogate models of FEM to reduce the

computation cost. For sake of calculating the core loss and the cogging torque, two separately computation processes with FEM are needed. Both of them contain the FEA points of half or whole period, respectively. Therefore, the actual calculation points by FEM are tens of time more than the sample dimension. For example, for a 4-factor-5-level experiment, 625 samples are needed according to the full factor experiment. If each of the core loss and cogging torque calculation contains 6 FEA points, the whole FEA points will be  $2 \times 6 \times 625$ , i.e. 7500. Thus, the orthogonal experiment design technique is taken advantage of here for reducing the design space. For a 4-factor-9-level experiment, only 81 samples are needed by orthogonal design technique, which offers an effective way for reduce the sample dimension along with the multilevel method.

#### C. Optimization model

Based on the above analysis methods, the optimization model can be developed for this CPM, and it has the form as

$$\min : f(\mathbf{x}) = \omega_1 \frac{T_{cog}}{T_{cog\_initial}} + \omega_2 \frac{T_{ave\_initial}}{T_{ave}} \quad (5)$$

$$s.t. \begin{cases} g_1(\mathbf{x}) = T_{ave\_initial} - T_{ave} \leq 0, g_2(\mathbf{x}) = 0.815 - \eta \leq 0 \\ g_3(\mathbf{x}) = Cost - Cost_{initial} \leq 0, g_4(\mathbf{x}) = sf - 0.7 \leq 0 \end{cases}$$

where  $T_{cog}$  and  $T_{ave}$  are the cogging torque and output torque respectively,  $\omega_1$  and  $\omega_2$  are the coefficients,  $sf$  means the slot fill rate, and  $\eta$  is the motor efficiency at rate point.

### IV. RESULTS AND DISCUSSION

By taking advantage of the orthogonal experiment design, the optimization efficiency is improved effectively. Compared with the initial design, the performance of the motor after optimization shows much better performance. The average torque increases from 2.65 Nm to 2.849 Nm, which means the output power increase from 500 W to 537 W. Meanwhile, the cogging torque decrease from 0.33 Nm to 0.105Nm, as shown in Fig.3. Both of the performance improvement illustrates the effectiveness of the multilevel optimization approach.

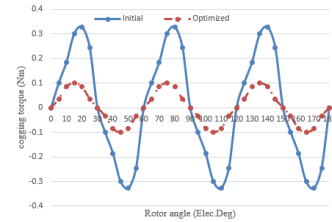


Fig. 3. Cogging torque comparison

### REFERENCES

- [1] Y. Guo, J. Zhu, H. Lu, Z. Lin and Y. Li, "Core Loss Calculation for Soft Magnetic Composite Electrical Machines," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 3112-3115, Nov. 2012.
- [2] Y. G. Guo, J. G. Zhu, and H. Y. Lu, "Accurate determination of parameters of a claw-pole motor with SMC stator core by finite-element magnetic-field analysis," *IEE Proceedings - Electric Power Applications*, vol. 153, pp. 568-574, 2006.
- [3] C. Liu; G. Lei; Y. Guo; Y. Wang; J. Zhu, "Comparative Study of Small Electrical Machines with Soft Magnetic Composite Cores," *IEEE Trans. Ind. Electron.*, to be published
- [4] G. Lei, C. Liu, J. Zhu and Y. Guo, "Techniques for Multilevel Design Optimization of Permanent Magnet Motors," *IEEE Trans Energy Convers.*, vol. 30, no. 4, pp. 1574-1584, Dec. 2015.