A Novel Multi-Objective Optimization Method for the Optimal Design of Interior Permanent Magnet Synchronous Machine

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A multi-objective optimization method is developed for design optimization of a V-shaped interior permanent magnet synchronous machine (IPMSM). This method is capable to find the Pareto optimal solution with less time for the given multi-objective problem. In this paper, the method is demonstrated to maximize the output torque of V-shaped IPMSM while minimizing the sinusoidal distortion rate of the air-gap flux density waveform. The process includes three steps: (1) Building the first level Kriging models to get several local areas which contain the local optimal points; (2) A trade-off between the Kriging response surfaces of different objective functions to get one or several local areas which contain global optimal points and using the selected areas to get the second level Kriging models; (3) Genetic algorithm can be used to obtain the Pareto Front based on second level Kriging models. Finally, the optimization method is verified by finite element method (FEM).

Index Terms—Multi-objective design optimization, Kriging models, Genetic algorithm, Pareto Front

I. INTRODUCTION

INTERIOR permanent magnet synchronous machines (IPMSM) have been extensively adopted in electric vehicles due to the low weight, high torque density and desirable flux-weakening capability [1]. Many researches have been done for design optimization of IPMSM based on Kriging model. Reference [2] developed a novel algorithm which is capable of finding all the local and global minimum of a given single- or multi-objective function for design optimization of V-shaped IPMSM. In order to guarantee the precision, different order Kriging models are constructed in [3], and this method can contribute to reduce the computational burden. Reference [4] introduces a multi-objective optimization design method based on the combined design of experiments approach and response surface method applying to a new magnetic planetary geared permanent magnet brushless machine for hybrid electric vehicles, and this method also pursues computational efficiency, at the same time, the precision is not reduced. Reference [5] proposes a sequential multi-objective robust optimization approach which makes the computational costs significantly reduced compared with the motor before optimization. These researches regard high computational efficiency as one of their targets. The multi-objective optimization method proposed in this paper can provide computational savings by focusing its search only to the areas where local optima are present or the areas can balance all the objectives. Besides, some local areas can be abandoned after a trade-off between different optimization objectives according to the different operating situations of the IPMSM.

II. MACHINE GEOMETRY AND VARIABLES

This section shows the structure geometry and the variables for design optimization of an 8-pole, 48-slot, V-shaped magnet IPMSM. The motor’s geometry is showed in Fig. 1 and the independent design variables of the motor and their ranges are presented in Table I. These variables are used to optimize these two objectives. And the flow chart of the process is showed in Fig.2.

![Fig 1. Geometry of V-shaped magnet IPMSM](image)

![Fig 2. Flow chart of the optimization process](image)

### TABLE I

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator tooth width(w1)</td>
<td>4.5</td>
</tr>
<tr>
<td>Stator slot height(h1)</td>
<td>18</td>
</tr>
<tr>
<td>Magnet length(l1)</td>
<td>15</td>
</tr>
<tr>
<td>Magnet width(wm)</td>
<td>4</td>
</tr>
<tr>
<td>Thickness of iron bridge 1(a1)</td>
<td>1.2</td>
</tr>
<tr>
<td>Thickness of iron bridge 2(b1)</td>
<td>1</td>
</tr>
</tbody>
</table>

III. OPTIMIZATION PROBLEM SETUP AND SOLUTION

This section presents the process of the IPMSM design optimization and solutions obtained using the novel optimization method. The design optimization target may be different with the difference of operating conditions. In this paper, the targets are minimizing the sinusoidal distortion rate
of the air-gap flux density waveform \(B\) and maximizing output torque \(T\). In the optimization process, the flux density in the teeth and in the yoke are constrained.

\[
\text{Min: } f\{T, -k_b\} \\
\text{s.t. } B_{\text{teeth}} \leq 1.6T \\
B_{\text{yoke}} \leq 1.3T
\]

The surrogate model built by introducing the design of experiments method to the Kriging model with the sampling points obtained using Latin hypercube sampling. The first level Kriging models are built with 40 sampling points in the range of six variables. It doesn’t need very high precision because the models are only used to find the aimed local areas which are needed to build the second level models. The first level models are showed in Fig. 3, and it shows the relationship about the two objectives with four of the six variables.

![Fig. 3. First level Kriging models](image)

According to Fig. 3 (a), the total harmonic distortion of the air-gap flux density waveform \((k_B)\) is almost unchanged within the given range of \(h_1\) and \(w_1\). Thus, the multi-objective optimization problem about these two variables turns into a single objective one. However, in Fig. 3 (c) and (d), the situation is different, and the new method can be used to solve this problem. Fig. 4 shows the 2-D contour line of Fig. 3 (c) and (d). Local area 1 has the optimal solution of the output torque. At the same time, local area 2 has the minimum of the sinusoidal distortion rate of the air-gap flux density waveform. To get the trade-off of the two objectives, local area 3 is chosen. These three areas are used to get new sampling points, and these points can build the second level Kriging models using the same way of building the first level Kriging models, and the computational cost can be decreased sharply with this method.

![Fig. 4. 2D contour line of these two objectives](image)

**IV. OPTIMIZATION RESULT OBTAINED BY THE PROPOSED METHOD**

When the second level Kriging models are built, the two objective functions can be obtained. Then, the genetic multi-objective optimization algorithm can get multiple Pareto optimal solutions in single calculation. Based on the second level model, the Pareto front is obtained as shown in Fig. 5. Three points have been used to verify the results, and the maximum error is less than 5%.

![Fig. 5. Pareto Front](image)

**REFERENCES**


