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Cogging Torque Optimization of Axial-Flux Motor

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Abstract - The selection of optimum parameters in electromagnetic design usually requires optimization of multimodal, non linear functions. This leads to extensive calculations which pose a huge inconvenience in the design process. This paper proposes a novel algorithm for dealing efficiently with this issue. Through the use of contour line concept coupled with Kriging, the algorithm finds out all the peaks in the problem domain with as few function calls as possible. The proposed algorithm is applied to the magnet shape optimization of an axial flux permanent magnet synchronous machine and the cogging torque was reduced to 79.8% of the initial one.

1. INTRODUCTION

The objective functions encountered in electromagnetic (EM) problems often exhibit nonlinear effects, computationally expensive evaluations and multiple optima [1], [2]. In order to deal with such problems, it is often desirable to obtain not only the global optimum but also the local optima as diverse solutions suggest alternative solutions against the limited conditions. Therefore, designers usually prefer to have a wide range of solutions to select from instead of only the most suitable one according to function evaluation [1].

There have been some attempts at applying the niching genetic algorithm (NGA) to multimodal function optimization [3]-[6]. Most of the approaches adopted were for identifying niches and estimating their radii. However, excessive application of the niching concept requires relatively high number of objective function evaluations and the powerful advantage of maintaining a set of suboptima to locate multiple optima is lost. This can be particularly inconvenient in EM design when each estimation of the objective function calls for a numerical solution by means of the finite element method.

In this paper, a novel algorithm for multimodal function optimization in EM design is developed. A new concept is proposed to realize the multimodal function optimization scheme. The concept constructs a level curve through the employment of efficient interpolation schemes in order to estimate problem region and allows only one solution to survive for each level group. Hence, the proposed algorithm is more efficient and practical than conventional ones because a smaller number of function evaluations is required. Moreover, it has additional advantage of easy implementation. The results obtained over the test function and the EM optimization problem show the applicability of the proposed algorithm.

2. PROPOSED ALGORITHM

The main feature of proposed method is reduction of the computational effort required by the algorithm while improving the convergence characteristics. It employs basic concepts of Kriging method and ES and thus, demonstrates more straightforward convergence characteristics compared to the conventional hybrid approach.

2.1 Initialization and Generate Initial Population

Initialize the parameter value.

$\alpha_{\min}$, $\alpha_{\max}$	The variation if design variable.
α_i	Variation range of the ith design variable.
α_{init}	Initial value for α_i

And generate the initial population.

2.2 Construction of Surrogate Model and Contour

The proposed algorithm employs Kriging to devise a surrogate model of the real fitness function. Kriging method is known to be able to approximate a complex and highly nonlinear function [7].

First, we construct the metamodel from already evaluated samples, initial parent set and the level curve from information obtained through the metamodel. We can get the spatial arrangement through the Kriging method instead of real function evaluations. So, we can reduce the computational effort required by the algorithm. This contour map is implemented using MATLAB's contour function [8].

2.3 The Hassle Free Construction of New Domain

The metamodel is constructed on a predefined lattice region. However, all lines joining points of equal elevation on level curve are not located on the diagonal pattern. This allows for the hassle free construction of a special area involved in level surface for searching the local peak in that region.

2.4 Check for Local Peak Validity

We extract information, which includes values and coordinates, from the contour line in contour map. In order to decide that the local solution is effective or not, we compare a value of contour line with the peak value in the domain involved in the level surface. If a peak in the domain is larger than the value of the corresponding contour line, that point presents local peak in that level surface and the number of hits is increased on the point.

The proposed method has a unique advantage in that one can find N local peaks of a multimodal function at a certain iteration when the number of valid groups is N. The valid groups are termed as special regions in the problem space which involve all level lines surrounding the same peak value. So, we can obtain the global peak and all local peaks employing as few function calls as possible in a single run. Therefore, we can reduce the number of function calls.

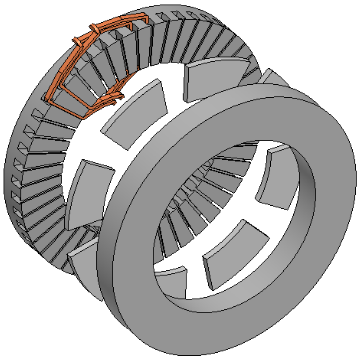
2.5 Generation of Subpopulation

Among the initial population with n randomly generated individuals, μ solutions are selected as members of the initial evolution range. The remaining individuals are reserved for updating of surrogate model.

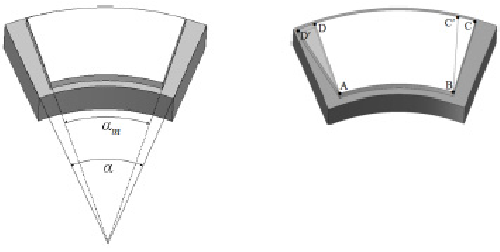
Although the proposed algorithm can find the peaks well, the algorithm still has a problem. The problem stems from the fact that the interpolated points through Kriging method are located only on the lattice region. The error between the estimated and the exact solution depends on grid interval. Even though the grid interval is decreased, it is limited by memory size. So, we adopt the concept of annealing in ES. If a local solution is improved within the evolution range, the variation of the design variable is increased by dividing it by 0.2. If a local solution is not improved, the variation of the design variable is decreased by multiplying it by 0.2. The initial variation of the design variable α_{init} is given to the newly generated evolution groups.

2.6 Shaking and Convergence Check

The λ samples are randomly generated in the whole space outside the evolution groups. The above cycle is repeated until most solutions are not improved anymore.



<Figure 1> Axial flux permanent magnet machine



(a) (b)

<Figure 2> Design variables. (a) Pole-arc α_m to pole-pitch α ratio. (b) Magnet skewing. Magnet ABCD is skewed to ABC'D'.

<Table 1> Specification of Reference Axial Flux PM Machine

Rated power [kW]	7
Permanent magnet	Nd-Fe-B [Br= 1.2 T]
Stator diameter [mm]	140 to 210
Pole number	8
Mechanical air-gap [mm]	1
Number of phase	3
Number of slots	48
Magnet pole-arc/pole-pitch ratio	0.7
Axial thickness of stator yoke [mm]	22
Axial thickness of magnet [mm]	5

3. RESULT

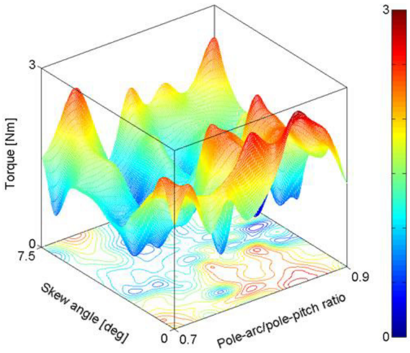
The usefulness of the proposed method is verified by means of a practical EM optimization problem. The proposed algorithm was applied on the design of an electromagnetic device. As a practical optimization example, axial flux permanent magnet synchronous machine (AFPMSM) is selected. The initial structure of the analysis model is presented in Fig. 1.

This paper is concerned with the minimization of cogging torque, since it is often a significant consideration during the design. The design variables are shown in Fig. 2. If the value of cogging torque is similar, solution with lower total harmonic distortion (THD) of EMF and lower amplitude of EMF is preferred. Therefore, we first selected several solutions which had low cogging torque and then calculated the THD of EMF and peak of EMF only for the candidate solutions. The machine parameters are given in Table 1.

The three representative results of optimal design by the proposed method are shown in the Table 2. These additional optima provide a range of design options for the designer. We select the case 2 as the best compromise solution because this candidate has low cogging torque and low THD of EMF. It is found that a skewing angle of 7.5 degree allows cogging torque of about 0.32 Nm, i.e. about 79.8% less than the cogging torque calculated with no skewing. Fig. 3 represents the contour plot of the cogging torque for design variables.

<Table 2> Optimization Result

Solutions	Case 1	Case 2	Case 3
θ_{skew}	6.1	7.5	5.25
α_m/α	0.76	0.70	0.78
Amplitude of EMF at 3900rpm [V]	124.5	125.6	124.3
Peak-to-peak cogging torque [N·m]	0.35	0.32	0.30
THD of EMF [%]	11.43	5.98	13.62



<Figure 3> Contour plot of the cogging torque for design variables.

4. CONCLUSION

In this paper, a novel algorithm for multimodal function optimization in electromagnetic design is proposed. Using the new concept of contour line, the proposed method can find multiple peaks effectively in the problem domain. The proposed algorithm reduces the computational cost of the optimization process significantly by eliminating the need for a large number of function evaluations. This reduction makes the proposed algorithm particularly suitable for electromagnetic problems. The proposed method was verified by applying to various cases and showed very good performance.

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