Robust Optimization for Reducing Cogging Torque of Permanent Magnet Motor with Static Analysis Assisted Technique

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Electric machine designers have interest of design uncertainties such as manufacturing tolerances and external perturbations, which can distort the estimated performance of machines. However, analyzing an electric machine is nonlinear problem which demands a large computational cost for finite element analysis (FEA), especially in robust optimization problems due to the large number of function evaluations. To deal with the problem, this paper proposes a robust optimization algorithm for optimal design of cogging torque reduction of permanent magnet motor. The developed algorithm is verified using a mathematical test function. Finally, in order to cut down a burden of computational cost for electric machine analysis, a technique utilizing static analyses is developed and applied to optimal design of permanent magnet machine. As results, the robust optimal design solution is obtained within a reasonable computational cost.

Index Terms—Robust optimization, optimal design, permanent magnet motor, cogging torque.

I. Introduction

Robustness of an optimal solution is an important issue in optimization problems that should be considered in engineering design problems. There are several uncertainties which cause a mismatch between the performances of a design as intended and that of a prototype. First, manufacturing tolerance may exist a limitation stemming from the feasibility of production. The optimal solution is usually a set of numerical values, but manufacturing tolerance may not allow design values completely to correspond to them. Secondly, unpredictable perturbations can have a severe effect on target performance. With regard to robustness, the optimal solution should be less sensitive to the minute variations of the design parameters [1-3].

In order to find robust solutions for electromagnetic designs, researchers have studied various viewpoints such as sensitivity analysis, the gradient index (GI) approach, and an approach based on the worst target function value. However, there still exists an inevitable computational burden due to the large number of finite element analyses (FEA) to analyze required to analyze nonlinear problems [2-3].

Recently, interior permanent magnet synchronous machines (IPMSMs) are widely used in many applications due to their high torque density with the availability of reluctance torque according to the difference between the d-axis and q-axis reluctance. However, the complex magnetic structure of IPMSMs also introduces the disadvantages of high torque ripple and cogging torque, both of which should be reduced for less acoustic noise and to ensure smooth operation. Regarding the issues of torque ripple and cogging torque, researchers have investigated various techniques such as skewing, choosing proper number of slots and poles, and notch design methods [4].

In this study, a new robust optimization method to reduce cogging torque of a permanent magnet synchronous motor (PMSM) is proposed. By combining the worst function value (WFV) approach and a type of stochastic optimization algorithm, the immune algorithm (IA) in this case, a new WFV based IA (WFV-IA) is developed and validated by mathematical test. We subsequently applied the robust cogging torque optimization method to the design of an IPMSM. Prior to the direct application to the practical problem, we propose an effective strategy which is the static analysis assisted (SAA) technique to reduce the computational cost of practical design problems. The proposed method significantly reduces the computational burden of the optimization problem in this study.

II. Development of the Proposed Algorithm

A. *WFV based robust optimization*

Fig. 1 shows original optimum and the robust optimum taking uncertainty Δ into consideration. In the figure, Point x* is the global optimum, and Point x_r is a local peak from a conventional optimization viewpoint. However, assuming that there exists some uncertainty Δ, Point x* can no longer be considered as superior to Point x_r. In other words, Point x_r is the optimum in the robust optimization problem.

A simple method to measure the robustness of a solution is to define the uncertainty set and to evaluate the worst function value in the set. For convenience, we assumed that variations in the design parameters could occur with equal probability such, the uncertainty set is modeled with a rectangular shape as shown in Fig. 2. In the figure, Δ_1 and Δ_2 represent possible variations of design variables x_1, and x_2 respectively. The optimization problem and the uncertainty set can be represented as (1) and (2), respectively [2].

$$\begin{aligned}&\min\{f(x)\}\\ &s.t.\ \ g_i(x)\le 0,\ \mathrm{i}=1,\ldots,\mathrm{m}\end{aligned} \tag{1}$$

$$U(x_n)=\{\xi\in R^n : x_n-\Delta\le\xi\le x_n+\Delta\} \tag{2}$$

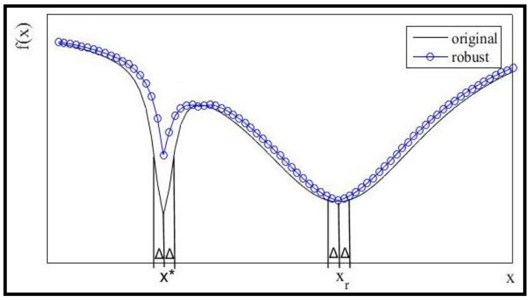

Fig. 1. Example of a robust optimum.

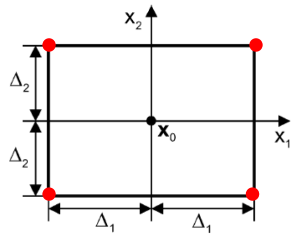

Fig. 2. Rectangular uncertainty set.

B. *WFV-IA and numerical verification*

In this study, a type of stochastic optimization algorithm, IA, is used to develop a new robust optimization algorithm. IA conducts optimization given the expectations and affinities between antigens and antibodies which act in the immune system of the human body. The whole flow of IA is well described in [5]. Contrary to the typical IA, we applied the WFV concept considering uncertainty Δ at the affinity calculation stage between the antibodies and antigens. The modified IA, WFV-IA, is verified by the mathematical function shown in Fig. 3. The test function has a global peak with high steepness, represented by point A and another robust peak denoted as Point B, as shown in Fig. 3. The average value of ten test trials in Table 1 shows that the developed algorithm can find the robust optimum, point B, with large function calls compared to the conventional IA. The large number of function calls could be a big problem when we apply to the practical electric machine design with FEA. The issue will be dealt with in Section Ⅲ.

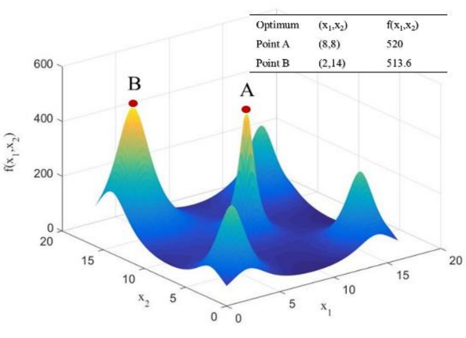

Fig. 3. Test function for the developed algorithm.

TABLE I
COMPARISON OF OPTIMIZATION RESULTS

Item	IA	WFV-IA
Variables1 x_1	7.981	1.982
Variables2 x_2	8.002	13.986
Function value	518.903	513.001
Worst value with uncertainty	507.383	511.044
Number of function calls	1838	6364.5

III. COGGING TORQUE OPTIMIZATION STRATEGY

In this section, the WFV-IA is applied to the robust optimal design of an IPMSM, where the objective is cogging torque minimization. However, as shown in previous section, it requires quite large number of function calls for uncertainty set evaluations and it is heavy burden to designers due to the increasing time for FEA. In this regard, we propose the SAA technique in the WFV algorithm which consists of several steps to reduce the calculation burden significantly. The detailed process is as follows.

Step 1— Function evaluation of the nominal point:

One period of cogging torque is fully analyzed by a FEA at the nominal point rather than conducting evaluations of uncertainty set. This step is identical to that used in the typical optimization process.

Step 2— Extraction of the rotor position generating peak:

From step 1, we can extract the information of the rotor position which generates peak value of the cogging torque.

Step 3— Static analyses of the uncertainty set evaluation:

At this stage, we implement static analyses of an uncertainty set using the information of rotor position in step 2. In a two-dimensional problem, four corner points of the uncertainty set are the targets for the static analyses.

Step 4— WFV verification:

As a result of step 3, we can obtain the WFV of uncertainty set at the nominal point. This value is utilized in mainly leading optimization algorithm.

IV. DESIGN RESULT AND REVIEW

Using the developed process, the optimal design for cogging torque reduction of IPMSM is implemented. The detailed design results and review will be included in the full paper.

V. CONCLUSION

In this paper, a robust optimization algorithm based on the IA with the WFV concept and the SAA technique for reducing the computational cost is proposed. The validity is verified mathematically and applied to the optimal design of IPMSM.

VI. ACKNOWLEDGMENT

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