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Minimization of a Cogging Torque for an Interior Permanent Magnet Synchronous Machine using a Novel Hybrid Optimization Algorithm

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Abstract – Optimization of an electric machine is mainly a nonlinear multi-modal problem. For the optimization of the multi-modal problem, many function calls are required with much consumption of time. To address this problem, this paper proposes a novel hybrid algorithm in which function calls are less than conventional methods. Specifically, the proposed method uses the kriging meta-model and the fill-blank technique to find an approximated solution in a whole problem region. To increase the convergence speed in local peaks, a parallel gradient assisted simplex method is proposed and combined with the kriging meta-model. The correctness and usefulness of the proposed hybrid algorithm is verified through a mathematical test function and applied into the practical optimization as the cogging torque minimization for an interior permanent magnet synchronous machine.

Keywords: Hybrid optimization algorithm, Kriging, Motor, Optimization, Permanent magnet machine, Simplex

1. Introduction

An objective function for the optimization of an electromagnetic machine is mostly nonlinear function and has many peaks. For these optimizations of the nonlinear multi-modal function, many researchers have proposed several techniques such as the auto tuning niching genetic algorithm(ATNGA), and the climb method [1-8].

Ecosystem-inspired optimizations have been widely used for the optimization of the electromagnetic machine [4-15]. These algorithms can find a number of optima, which include the global solution through a large number of function evaluations.

Optimization methods can be categorized into two types, the stochastic method and the deterministic method. In the stochastic method, which is a probabilistic optimization method, the genetic algorithm (GA) has been commonly used. Although probabilistic optimization methods such as GA show high performance for searching optima over an entire problem region, the speed of convergence to the optimal point is slow. On the other hand, the deterministic optimization methods like the pattern search or the simplex method cannot search the optima over the entire problem region and the optimal point converges on a local peak rapidly.

To compensate for the weakness of each stochastic method and deterministic method and to combine their strengths, the hybrid algorithm, which combines the interpolation method and the deterministic optimization method, is proposed in this paper. To search the global optima effectively over an entire problem region, the interpolation method is used in this research instead of using the stochastic method. This is because the interpolation method is more efficient and useful than the general stochastic methods for the combination with the deterministic method. Hence, the proposed algorithm can search the global optima. The kriging method, which is widely used for the interpolation, is used in this research [16]. To enhance the convergence speed to a local-optimal point, a novel parallel gradient assisted simplex method is combined with the interpolation method. Hence, this research refers to the proposed hybrid algorithm as kriging combined with the parallel gradient assisted simplex method (KSM).

The correctness and usefulness of the proposed KSM is verified through the application into a mathematical test function and a practical electric machine. Via the mathematical test function, the performance of the propose KSM is compared with that of conventional multi-modal optimization algorithms such as an ATNGA and a climbing method. Furthermore, to verify the possibility of the application into the practical electrical machine, the interior permanent magnet synchronous machine (IPMSM) is designed optimally to minimize the cogging torque.

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2. The Proposed Algorithm, KSM

Specification of the KSM according to the step is as follows based on Fig. 1.

1) Step 0 – Initialization

Initialize parameters such as the problem region and the number of initial population for optimization process.

2) Step 1 – Create initial population

The initial population should be generated and distributed in the problem region evenly and properly to reflect the tendency of the problem region at the initial stage. If the number of initial samples is k^2, the problem region is divided into k by k matrix and one sample is generated randomly in each small region of divided matrix as shown in Fig. 2.

3) Step 2 – Construction of an approximated model

The KSM employs kriging to build an approximated meta-model of the real objective function.

4) Step 3 – Simplex operation

Although the optima can be found from the meta-model of objective function, which is constructed in the previous step, they are not the exact solution. To approach to the exact solution, the parallel gradient assisted simplex method (GASM) is adopted in this research. In the conventional simplex method, a simplex geometry searches the optimal solution using data of the previous simplex geometry until its termination topology is satisfied. However, in the proposed KSM, several simplex geometry search local peaks in parallel, not by using data of the previous simplex geometry like the conventional simplex method but by using the meta-model, which is updated from the previous simplex geometry.

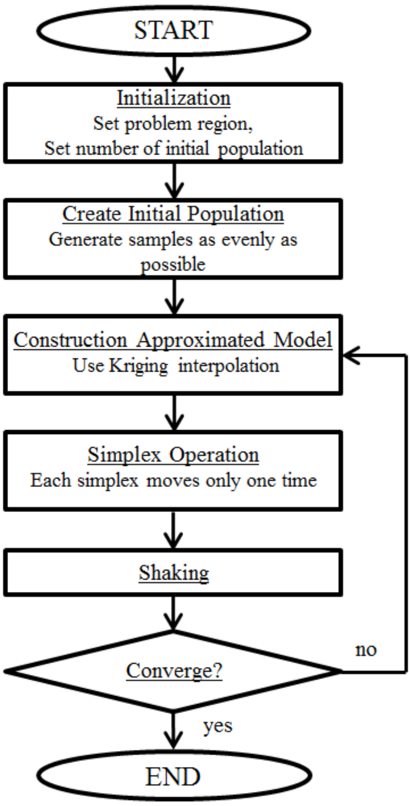


Fig. 1. Flow chart of the proposed KSM.

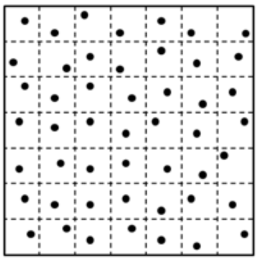


Fig. 2. Initial samples generated randomly (49 samples)

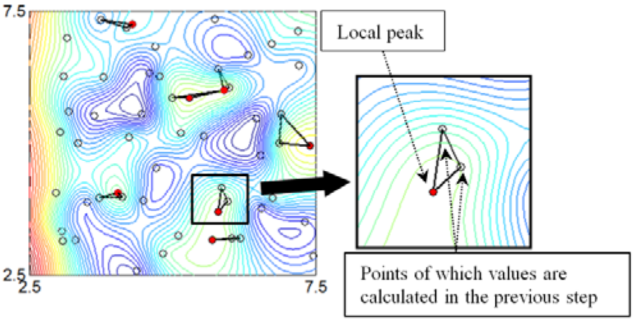


Fig. 3. Construction of the KSM.

Specifically, each simplex geometry for the KSM is constructed in every iteration step by using each local peak and previously calculated points as shown in Fig. 3. The local peak is updated in every iteration step. The previously calculated points of each simplex geometry are points which are calculated in the previous step and located near from each local peak. Hence, points of simplex geometry in the KSM do not always consist of points of the previous simplex geometry as is the case for the conventional method but by the updated local peak and points which area previously calculated and near the local peak.

5) Step 4 – Shaking

To increase the diversity of the solution and prevent converging into the local peak, shaking is conducted in this step. As a result of the shaking, some samples are generated in the region where number of samples are fewer compared to the other regions.

In this process, the ‘fill-blank’ technique is suggested for the shaking. The fill-blank technique generates samples randomly in whole problem regions and then their distance from other points, of which function values are calculated in the previous step, are estimated without any additional function call. Specifically, the distances from a generated sample to previously calculated points are calculated. Among them, the shortest distance is selected as a minimum distance for the generated sample. This process is carried out for all of generated samples. By comparing each minimum distance of the generated samples, the largest value of minimum distance can be identified. This means that this point is the furthest from previously calculated points among the generated samples. Hence, this sample is selected as a final point to be added in the meta-model via the calculation of the function call. This routine is repeated at every iteration to fill out the area of which population is low.

6) Step 5 – Convergence check

Step 2-Step 4 are repeated until most peaks are not improved any further.

3. Verification of the KSM

The performance of the proposed algorithm was verified via a mathematical problem and applied to a practical optimization problem, which is the optimization of the magnet shape of the rotor and the slot opening of the stator for the IPMSM.

3.1 Verification of KSM via mathematical test function

The formula for the test function is (1), where $2.5 \leq x_1, x_2 \leq 7.5$, and its shape is illustrated in Fig. 4.

$$f = 50 + \sum_{k=1}^{2} (-1)^k (x_k - 5)^2 + 5\cos[2\pi(x_k - 5)] \qquad (1)$$

As shown in Fig. 5, low population regions A, B, and C are filled out with dot a, b, and c, respectively, by using fill-blank technique and the surrogate model approaches to the shape of the actual test function as the iteration is increased. Briefly, in the proposed KSM, local peaks are roughly estimated by using the kriging and the fill-blank technique and the gradient assisted simplex method finds each local peak in parallel delicately.

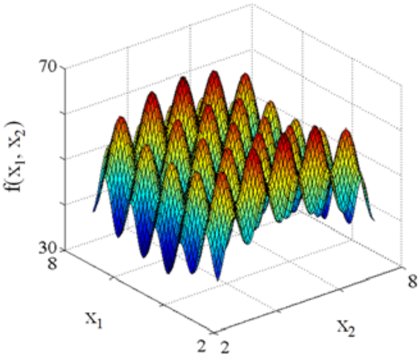
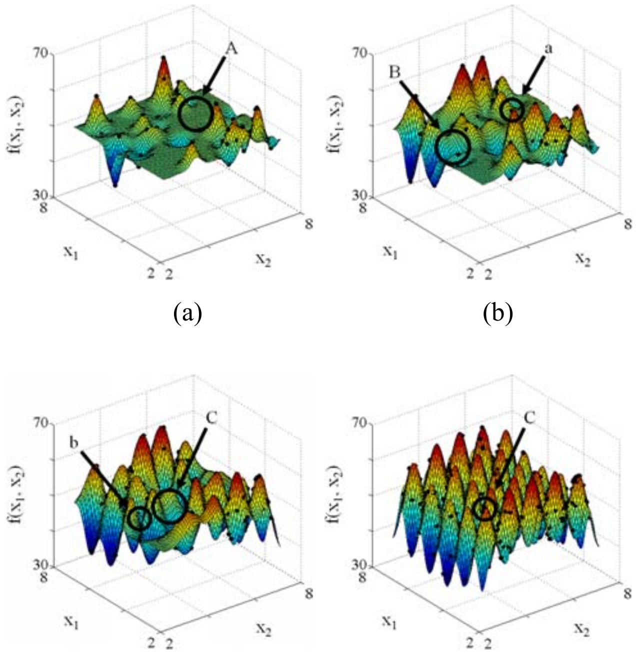


Fig. 4. Test function for the verification of usefulness of the proposed KSM algorithm.



(a) (b)

(c) (d)

Fig. 5. Optimization process by using the KSM: (a) initial state; (b) iteration 2; (c) iteration 4; (d) iteration 10.

Table 1. Comparison of the algorithm performance by using the test function between the proposed KSM and conventional methods

	ATNGA	Climb	Proposed
Number of peaks	25	25	25
Number of found peaks	25	25	25
Number of function	4961	294	261

Average value for 50 times

The performance criteria are identifying exact number of peaks and function calls. Using this criterion, the performance of the KSM is compared with other multi-modal optimization methods, which are ATNGA and climb method. As tabulated in Table 1, the proposed KSM shows superior performance compared to other conventional multi-modal optimization algorithms.

3.2. Verification of the KSM via optimization of the IPMSM

By using the proposed KSM, of which performance is verified via the test function in the part 3.1, the feasibility of the application into the practical machine design is testified as follows.

Recently, IPMSM has received much attention, because the saliency of rotor core makes IPMSM possible to have high-power and high-speed performance by using field weakening control algorithm [17, 18]. Hence, the IPMSM is selected for the practical application of the KSM in this research.

Cogging torque of IPMSM is reduced in this research by using the proposed KSM. A lot of techniques are proposed for the reduction of cogging torque of the IPMSM, the surface mounted permanent magnet synchronous machine, and the axial flux permanent magnet machine [19-30]. These approaches indicate that the pole-arc to pole-pitch ratio strongly effects on the cogging torque. Furthermore, the cogging torque is sensitive to the variation of the slot opening. Thus, these variables are considered as design variables for the cogging torque minimization of the IPMSM as illustrated in Fig. 6. Specifically, the design variables for the reduction of the cogging torque of IPMSM are the slot opening and the pole-arc to pole-pitch ratio. The range of the slot opening is 1.44-4.3 mm and the pole-arc to pole-pitch ratio is 0.425-0.9.

The reference model of the IPMSM is tabulated in Table 2. The 3rd harmonic EMF of the reference model is large as shown in Fig. 7. Further, as shown in Fig. 8(a), the upper part of the EMF wave for the reference model is suppressed compared to the optimized results, which are Candidate 1 and Candidate 2 shown in Figs. 8(b) and Fig. 8(c). These results occurred by the THD, which is caused by the large pole-arc to pole-pitch ratio 0.8.

At the end of the optimization by using KSM, the final meta-model for the cogging torque is obtained as shown in Fig. 9. From this optimization result, Candidate 1 and Candidate 2, of which cogging torque values are small, were selected for candidates. The characteristics of the

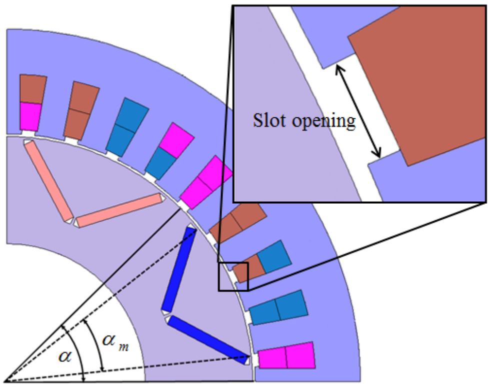


Fig. 6. Design variables: the pole-arc to pole-pitch ratio and the slot opening.

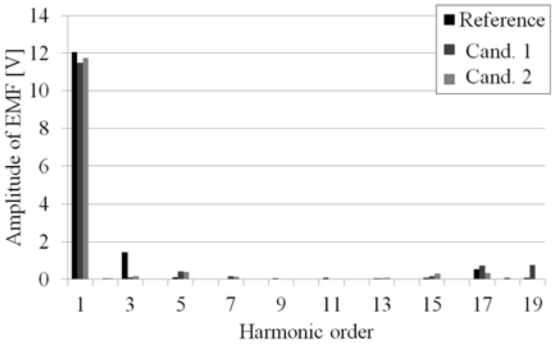
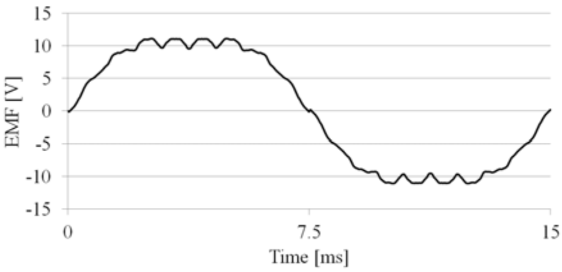
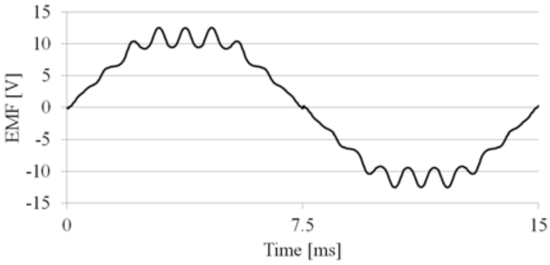


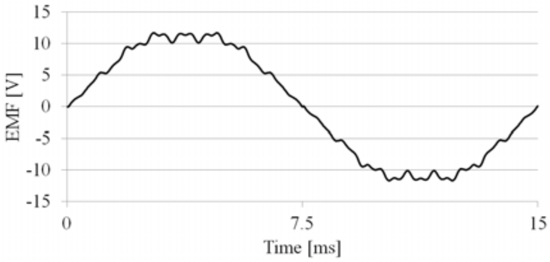
Fig. 7. Comparison of harmonic of back-EMF for the IPMSM.



(a) Reference model



(b) Candidate 1



(c) Candidate 2

Fig. 8. Comparison of back-EMF waveform of the IPMSM at 1000 rpm.

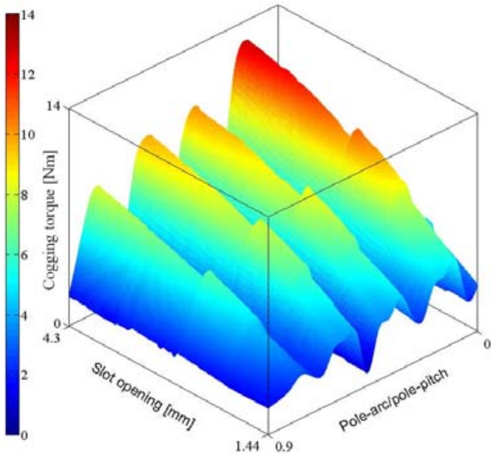


Fig. 9. Calculated meta-model of the cogging torque for IPMSM through the proposed KSM.

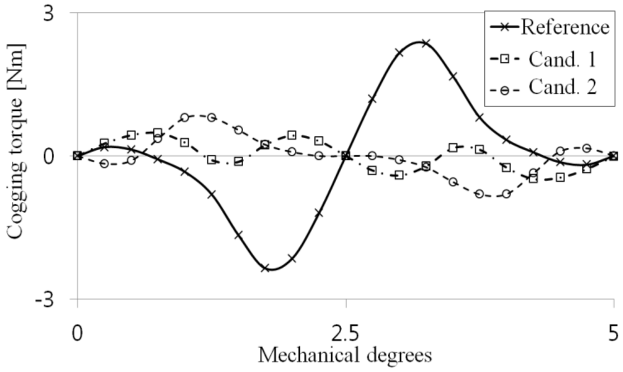


Fig. 10. Comparison of the cogging torque waveform.

Table 2. Specification of a reference model for the IPMSM

Parameter	Value
Rated power	20 kW
Permanent magnet	Nd-Fe-B (Br=1.2T)
Stator diameter	230 mm
Pole number	8
Air-gap	0.8 mm
Number of slots	36
Stator slot opening	1.44 mm
Magnet pole-arc/pole-pitch ratio	0.8

Table 3. Comparison of the IPMSM characteristics of the reference model and the optimized candidates

Parameter	Reference	Candidate 1	Candidate 2
$\alpha m/\alpha$	0.800	0.676	0.681
Slot opening	1.44 mm	4.014 mm	1.454 mm
THD	12.78 %	10.26 %	5.47 %
Cogging torque	2.36 Nm	0.48 Nm	0.81 Nm
Amplitude of EMF of 1^{st} order harmonic @ 1000 rpm	12.04 V	11.47 V	11.72 V

reference model and the two candidate solutions are compared in Table 3. According to Table 3 and Fig. 10, Candidate 1 seems the best solution from the point of view of the cogging torque. However, Candidate 2 has lower THD and higher amplitude of EMF than that of Candidate 1. These characteristics can guarantee low noise and high performance. Thus, Candidate 2 is selected as the final optimal solution.

As shown in Fig. 9, the cogging torque is more sensitive to the variation of αm/α compared to the slot opening. The αm/α of the reference model is larger than that of Candidate 2. The slot opening value of reference model and Candidate 2 is similar. From these data, it can be found out that αm/α has main effect on the THD and cogging torque. This finding also can be verified via data shown in Table 3.

Although the amount of the magnet of the Candidate 2 is lower than that of the reference model, the amplitude of 1st order harmonic of EMF for Candidate 2 is slightly small compared to the reference model and the THD of Candidate 2 is better than the reference model.

In other words, Candidate 2 can generate similar output using less amount of magnet. Furthermore, the noise and torque ripple of Candidate 2 are lower than the reference model due to its lower THD.

4. Conclusion

The optimal design of the electric machine is mostly a nonlinear multi-modal problem, which requires many function calls and much time consumption to search for the optimum. Hence, this paper has a significant meaning in the sense that the proposed novel hybrid algorithm can mitigate the function call and time consumption compared to conventional multi-modal optimization methods for the optimization of the electric machine.

The proposed novel hybrid method combines the kriging meta-model, the fill-blank technique, and the novel parallel gradient assisted simplex method, which is named as KSM in this paper.

The feasibility of the application of the proposed KSM into an optimal design of the practical electric machine is confirmed through the cogging torque minimization of the IPMSM.

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