Optimal Design for Cogging Torque Reduction of an IPMSM Using PSO with Anti-Submarine Operation Concept

Sung-Yeong Yoon[1], Jae-Gil Lee[1], Jong-Suk Ro[2], and Hyun-Kyo Jung[1], *Senior Member, IEEE*

[1]Department of Electrical and Computer Engineering, Seoul National University, Seoul 08826, Korea
[2]School of Electrical and Electronics Engineering, Chung-Ang University, Seoul 06974, Korea

The Anti-Submarine Operation Particle Swarm Optimization (ASOPSO) refers to an algorithm that simulates an anti-submarine operation, a type of naval operation. It is an algorithm that finds the optimal solution by dividing particles into three groups with different velocities, providing diversity to how the optimal solution is found using behaviors of particles appearing at specific iterations. Using test functions, we found that the proposed algorithm has better convergence characteristics with regard to reaching the optimal solution and that it improves the search time and number of required iterations in the exploration search area. By applying the proposed algorithm to design of an interior permanent-magnet synchronous motor (IPMSM) for cogging torque reduction, we verified its effectiveness.

***Index Terms*—Particle Swarm Optimization, Optimal Design, Interior permanent magnet synchronous motor, Cogging torque.**

I. Introduction

The conventional Particle Swarm Optimization, first introduced by Kennedy and Everhart, is a stochastic optimization method based on the behavior and intelligence of swarms such as bees and birds [1]. The mechanism of the PSO relies on the fact that particles move when determining the optimal solution in a problem space using the optimum experience of individuals (P_{best}) and the entire population (G_{best}) simultaneously [2]. Because process of the algorithm is simple, the PSO is one of the algorithms widely used for various optimization problems. [3]-[5]. However, for the optimization of higher order functions with many local optimal solutions, the PSO tends easily to fall to the local optimal solution rather than finding the global optimum with even longer searching time.

Therefore, in this paper, we propose a new modified PSO algorithm that mimics an anti-submarine operation to overcome the weaknesses of the PSO. An anti-submarine operation is a naval operation that searches for and attacks enemy submarines. The modified PSO is termed the Anti-Submarine Operation PSO (ASOPSO). ASOPSO is the algorithm that imitates the searching of a sea area using aircraft, surface vessels and submarines to find enemy submarines. In other words, it is an algorithm that finds the optimal solution by dividing particles into three groups with different velocities.

This method helps to search for new areas when the particles find the optimal solution in a problem area. In addition, it provides diversity in how the solution is found, and it can find the solution more rapidly and more accurately than the PSO.

Before directly applying the proposed algorithm to design application, we verified its performance using test functions. Subsequently, by applying the proposed optimization algorithm to an interior permanent-magnet synchronous motor (IPMSM), we prove its effectiveness and find the optimal topology for an electric machine.

II. Proposed Algorithm

A. *Basic theory of ASOPSO*

ASOPSO is the algorithm using three different groups which operate at different speeds to find the optimal solution; these groups represent aircraft, surface vessels and submarines. Table 1 shows the characteristics of them. The proposed algorithm is designed based on the assumption that all groups are engaged in anti-submarine operation when enemy submarines invade certain territorial waters.

TABLE I
Characteristics of Groups

Group	Pros	Cons
Aircraft	Excellent mobility to explore large areas in a short period of time.	Bad covertness.
Surface Vessels	Good mobility.	Bad covertness.
Submarines	Excellent covertness.	Bad mobility due to low speed.

The ASOPSO modifies the velocity equation of the ith particle, which determines its velocity and position vectors as follows:

$$v_i^{t+1} = w_g \cdot v_i^t + c_1 \cdot r_1 \cdot \frac{(P_i - x_i^t)}{\Delta t} + c_2 \cdot r_2 \cdot \frac{(P_g - x_i^t)}{\Delta t} \qquad (1)$$

Here, c_1 and, c_2 are acceleration constants, and r_1 and r_2 are two uniformly distributed random numbers generated within [0,1]. P_i is the personal best point (P_{best}) for the i_{th} particle and P_g is the group best point (Gr_{best}). Unlike the PSO, particles are divided into three groups of different velocities by specific ratios. Groups A, B, and C respectively consist of submarines with the lowest velocity, surface vessels with medium velocity, and aircraft with the highest velocity. In other words, all groups become particles with different velocities. The velocity of each group is controlled by the inertia weight w_g . w_g for each respective group denoted as w_A, w_B, and w_C. w_g is randomly determined within the range. (w_A = 0.4~0.55, w_B= 0.55~0.75, w_C= 0.75~0.9) It ensures diversity to search for wider areas even in the final iteration. Essentially, particles search for problem area using the P_{best} and Gr_{best} from the group to which they belong.

B. *Detailed strategies of ASOPSO*

As mentioned earlier, basically, particles search for the optimal solution by maneuvering of each group. In addition, all groups have special behaviors at specific iterations. These behaviors impart diversity with regard to the search for the optimal solution. The detailed strategies of the proposed algorithm are as follows.

Strategy 1- Collaborative maneuvering to find enemy submarines: All groups have an operational meeting to find an enemy submarine at specific iterations. As a result of this meeting, all particles search in the direction of the best point among the Gr_{best}s in all groups, that is, the global best point.

Strategy 2 – Exploring problem area by evasive maneuvering: All groups maneuver to guarantee survivability to avoid attack and to prevent enemy submarines from guessing their behavior patterns. Particles search for in the direction of Gr_{best} of another group at specific iterations. (A→B, B→C, C→A)

Strategy 3 – Reset a searching area of each group: When the searching time is long, the submarines with good covertness and low possibility to be attacked by enemy submarines searches around the expected position of the enemy submarine. And the surface vessels that are more likely to be attacked by enemy submarines navigate in the middle area.

Lastly, the aircraft with excellent mobility navigates the outermost of the expected enemy submarine location for wide-area search. To simulate this situation, we divide the particles by specific ratios in order of the nearest distance from the best Gr_{best} of all groups (Global best) and distribute them to each group, A, B, and C at specific iterations.

As results of Strategy 1 and 2, particles can search the problem area much wider than the PSO, and by strategy 3, particles search around the Global best more minutely to obtain more accurate solution. Fig. 2 shows a flowchart of ASOPSO.

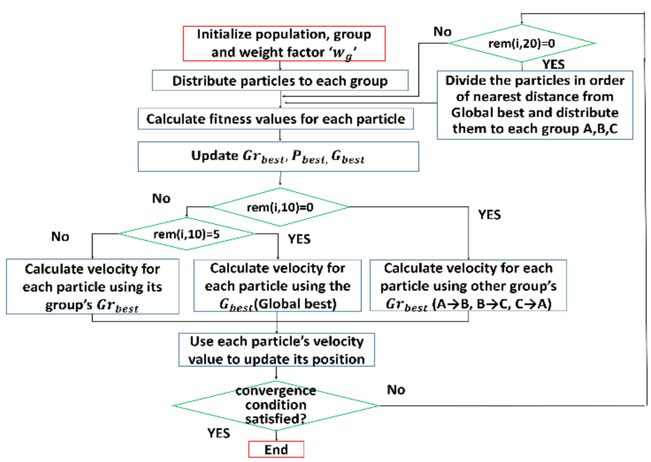
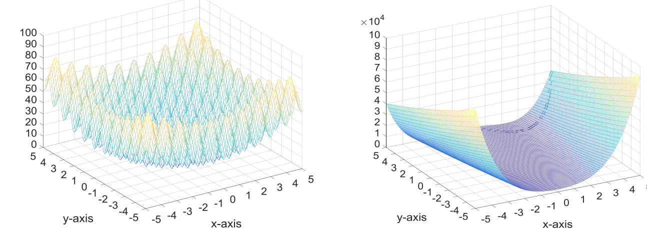


Fig. 2. Flowchart of ASO-PSO Algorithm

III. Numerical Comparison of The Proposed Algorithm

To validate the performance of the proposed algorithm, Rastrigin and Rosenbrock function as shown in Fig. 3 are used to compare the performance of the PSO, Immune Algorithm, Bird Mating Optimization, Social Spider Optimization and proposed algorithm. From Table II, the global optimal solutions according to the Rastrigin and Rosenbrock function are located at (0, 0) and (1, 1), respectively. The independent run is performed 100 times and the population size is set to 50. And particles are divided into three groups of different velocities at a 1:1:1 ratio. Those methods will stop their iterative process when the improvement rate is less than 0.1% by comparing the average position of the top 20% particles in order of good fitness value to that of the previous generation. These results are shown in Table III.

Table III presents results which demonstrate that the performance of the proposed algorithm is much better than those from other algorithms. Thus, ASOPSO can find the global optimum accurately and quickly compared to other algorithms.



$f_1 = 21 + [x_1 - 10\cos(2\pi x_1)] + [x_2 - 10\cos(2\pi x_2)]$ $\quad f_2 = 1 + 100(x_2 - x_1^2)^2 + (x_1 - 1)^2$

(a) Rastrigin function (b) Rosenbrock function

Fig. 3. Test functions to verify the proposed algorithm.

TABLE II
Searching Area, Optimal Solution and Function Value of Test Functions

Function	Searching Area	Optimal Solution	Optimal Function Value
f_1	$-5 \le x_i \le 5, (i = 1,2)$	(0, 0)	1
f_2	$-5 \le x_i \le 5, (i = 1,2)$	(1, 1)	1

TABLE III
Performance Comparison Result

	Function	ASOPSO	PSO	IA	BMO	SSO
Average Function value	f_1	1.01	1.0656	1.0328	1.0856	1.0748
	f_2	1.0002	1.0205	1.0314	1.0085	1.0094
Average Function call	f_1	1785	4746	1826.4	1996.2	2264.5
	f_2	2181	5049	4524	2468.4	2785.2

IV. Conclusion

Although the PSO is a useful method for finding global optimum, it takes a long time to converge and too many function calls. Therefore, in order to overcome these drawbacks, we propose ASOPSO, an improved PSO algorithm. Using test functions, it is confirmed that proposed has better performance than conventional PSO and other algorithms. In the full paper, proposed algorithm is applied to the design of an IPMSM for cogging torque reduction.

References

[1] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. IEEE Int. Conf. Neural Netw.*, 1995, vol.4, pp. 1942-1948.

[2] S. Sumathi and P. Surekha, *Computational Intelligence Paradigms Theory and Applications Using Matlab.* Boca Raton, FL: CRC Press, 2010, pp. 656-671.

[3] J. H. Seo, C. H. Im, S. Y. Kwak, C. G. Lee, and H. K. Jung, "An improved particle swarm optimization algorithm mimicking territorial dispute between groups for multimodal function optimization problems," *IEEE Trans. Magn.*, vol. 44, no. 6, pp. 1046-1049, Jun. 2008.

[4] C. Venkaiah and D.M.V. Kumar, "Fuzzy PSO congestion management using sensitivity-based optimal active power rescheduling of generators," *J.Electr. Eng. Technol.*, vol. 6, no. 1, pp. 32-41, 2011.

[5] J. H. Lee, J. W. Kim, J. Y. Song, Y. J. Kim and S. Y. Jung. "A novel memetic Algorithm using modified particle swarm optimization and mesh adaptive direct search for PMSM design," *IEEE Trans. Magn.*, vol. 52, No 3, pp. 1-4, March. 2016.