

Azimuth Thruster PMSM Optimization using Symbiotic Organisms Search Algorithm

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Abstract -- The azimuth thruster is widely used in electric propulsion ships due to its excellent performance in contrast to their mechanical counterparts which present an inherent drawback regarding to maintenance needs, high costs and overall system deficiency. At the same time, according to up-to-date manufacturers' reports, permanent magnet motors make azimuth thrusters more compact, lighter and more efficient compared to other types of motors. Thus, the replacement of a conventional drive with a properly designed low-speed permanent magnet synchronous motor (PMSM) directly coupled to the thruster propeller, provides an attractive alternative. This paper, based on authors' previous work on low-speed surface mounted PMSM design for azimuth thruster application, presents and proposes here an optimization procedure using a meta-heuristic population based technique namely the symbiotic organism search (SOS) algorithm. The results obtained reveal that the SOS algorithm provides effectively the required design solutions and performance.

Index Terms—Azimuth thruster, electrical machine design, meta-heuristics, optimization, permanent magnet synchronous motor, symbiotic organisms search algorithm

I. INTRODUCTION

DUE to the breakthrough in efficiency, maneuverability, reliability and flexibility of operations, the application of electric propulsion is widespread [1]. The azimuth thruster can make a 360-degree revolution around the axis and achieve maximum thrust in any direction. It can make the ship rotate, move laterally, and retreat in a special driving operation. Azimuth thrusters are installed on various engineering vessels, such as tugboats, floating crane vessels, dredgers, ferries, and working pontoons [2], [3]. In order to improve the maneuverability, efficiency and system dependability of engineering vessels, more than two propellers might be employed. For example, tugs are equipped with multiple propellers at the stern, midship and bow [4]. This kind of propulsion systems is becoming widely used, since it exhibits high efficiency and reliability, especially when it is combined with permanent magnet synchronous motors (PMSMs). Except from high efficiency, the high power density and the increased fault-tolerance capability are also main requirements for a motor in order to be used in such an application. Generally, PMSMs present high power density in high-speed operation. However, in

low-speed applications, the achievement of increased power density and low torque ripple is not an easy task [5].

Through the literature review, there are numerous optimization methods which have been employed and applied to problems related to PMSM design and/or their drives. Moreover, after the development of the “no free lunch theorem” [6], scientists and engineers have focused their efforts towards the design of tailored optimization algorithms as, for example, in [7], [8]. Additionally, recent trends indicate more and more a potential shift from conventional methods to the use of population based meta-heuristic algorithms [9], [10]. In [11] one of the first examples for the PMSM torque ripple minimization employing a standard genetic algorithm (GA) was proposed. Non-dominated sorting GA (NSGA-II), bees algorithm (BA), grey wolf optimizer (GWO), particle swarm optimization (PSO), harmony search (HS) algorithms etc., have also been reported e.g. in [12]–[16]. The main drawback of these methods however is the need for selecting appropriate values for their tuning parameters.

In [17], Cheng and Prayogo proposed a very promising meta-heuristic algorithm, called the symbiotic organisms search (SOS) algorithm that is based on cooperating behavior among organisms in the nature. The SOS algorithm mimics symbiotic communication strategies that organisms use to stay alive in the ecosystem. The SOS algorithm is a population-based algorithm, where the organisms of the ecosystem are considered as a population. The SOS algorithm prerequisites only common governing parameters such as population size and maximum number of function evaluations for its operation, unlike for example: a) the GA which requires mutation, crossover, selection rate, etc., b) the PSO algorithm which needs inertia weight, social, and cognitive parameters and c) the HS algorithm which requires harmony memory rate, pitch adjusting rate, and improvisation rate [18]. In other words, the SOS algorithm does not require algorithm-specific controlling parameters, which makes the algorithm robust and able to generalize.

It is also to be emphasized that although the specific algorithm has been utilized in the last few years in several engineering problems (e.g. [19]), this is the first time that is being applied in electrical machine design optimization. The paper is organized as follows: In Section II a brief informative description of the azimuth thruster technology is given and also the adopted PMSM topology characteristics for such a system based on authors' previous work are presented. The details of the SOS algorithm implemented and used here are described in Section III. Section IV justifies the solution approach and presents the obtained results along with a discussion. Finally, Section V concludes the work.

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II. BRIEF DESCRIPTION OF AZIMUTH THRUSTER TECHNOLOGY AND THE PMSM UNDER STUDY

A. Types of Azimuth Thrusters & Advantages

Azimuth thruster is the configuration, which is used in marine vessels to provide necessary thrust in desired direction which give ships better maneuverability than fixed propellers and rudder systems. Electric ship propulsion system technology is changing rapidly and so is the propulsion mechanism system. These thrusters are primarily used in dynamic positioning of vessels to maintain the position by counteracting environmental obstacles such as wind and waves. Nowadays however, these are also used for main propulsion. The technology of azimuth thrusters has led so far into two major variants, based on the location of the driving motor [20]:

a) *Mechanical transmission type*. The motor is installed inside the ship and is connected to the outboard unit by gearing. The motor may be diesel or diesel-electric. Depending on the shaft arrangement, mechanical azimuth thrusters are divided into L-drive and Z-drive. An L-drive thruster has a vertical input shaft and a horizontal output shaft with one right-angle gear (Fig. 1a). A Z-drive thruster has a horizontal input shaft, a vertical shaft in the rotating column and a horizontal output shaft, with two right-angle gears.

b) *Electrical transmission type*. This type is more commonly called “pod”, where an electric motor is fitted in the pod itself, connected directly to the propeller without gears (Fig. 1b). The electricity is produced by an onboard engine, usually diesel or gas turbine. Invented in 1955 by Friedrich W. Pleuger and Friedrich Busmann (Pleuger Unter-wasserpumpen GmbH), ABB Group's Azipod was the first product using this technology. The most powerful podded thrusters in use today are the four 21.5 MW Rolls-Royce Mermaid units fitted to RMS Queen Mary 2.

Mechanical azimuth thrusters can be fixed installed, retractable or underwater-mountable. They may have fixed pitch propellers or controllable pitch propellers. Fixed installed thrusters are used for tugboats, ferries and supply-boats. Retractable thrusters are used as auxiliary propulsion for dynamically positioned vessels and take-home propulsion for military vessels. Underwater-mountable thrusters are used as dynamic positioning propulsion for very large vessels such as semi-submersible drilling rigs and drill ships.

The current study focus on PM motor optimization for potential use into the second type. Some of the advantages of this thruster combination are: improved propulsion efficiency, improved fuel efficiency, reduced noise and vibration both airborne and structural, reduced hydro acoustic noise, reduced or no cavitation, reduced hull space demand, no inboard cooling system, no hydraulic pumps/powerpacks, environmentally friendly, less maintenance onboard, reduced maintenance at docking intervals, reduced steering gear torque.

B. Previous Work on PMSM Topology used in this Study

A generic multi-criteria design approach towards high power density and fault-tolerant low-speed PMSM for podded applications has been presented recently by the authors [5].

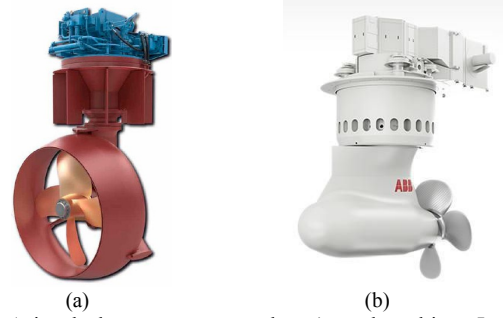


Fig. 1. Azimuth thruster type examples, a) gearbox driven L-drive type (courtesy of Rolls Royce, b) direct-driven Azipod (courtesy of ABB).

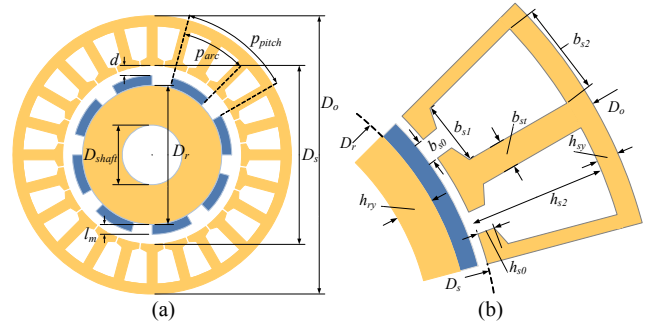


Fig. 2. Typical geometrical representation for the examined PMSM design, a) cross section of the whole motor, b) detailed view of the stator slots.

TABLE I
OPTIMIZATION PROBLEM CONSTRAINTS AND DESIGN VARIABLES RANGE

Quantity	Symbol	Value
Efficiency	η	$\geq 95\%$
Power factor	$\cos\phi$	≥ 0.95
Max. supply voltage	V_{LL}	690
Nominal frequency	f	≤ 150 Hz
Number of poles	$2p$	20-90
Peak phase current *	I	≤ 6.0 kA
Current density	J_s	≤ 3.5 A/mm ²
Stator outer diameter	D_o	$1.52 \text{ m} \leq D_o \leq 2.16 \text{ m}$
Motor's axial length	L	≤ 2.60 m
Slot opening width*	b_{s0}	≥ 6 mm
Stator yoke height	h_{sy}	$h_{sy} \geq 2h_{s2}/3$
Slot width at the top	b_{s2}	$0.15h_{s2} \leq b_{s2} \leq 0.80h_{s2}$
Stator tooth shoe height *	h_{s0}	$h_{s0} \geq 3.0$ mm
Pole arc / pole pitch ratio *	$embrace$	50 % - 90 %
Magnet thickness*	l_m	5-20 mm
Airgap length	d	3-10 mm
Flux density in cores yoke	B_y	≤ 1.8 T
Flux density in stator teeth	B_{st}	≤ 1.9 T
Flux density in airgap	B_δ	≤ 1.0 T

(*) the search variables selected for this study.

Based on this work, under the problem constraints and requirements shown in Table 1, only few candidate PMSM topologies were found suitable for the specific azimuth thruster studied, in terms of slot/poles combination, power density, efficiency, fault tolerance, manufacturing aspects and many more. Thus, if any of them might be chosen, then it could (and should) be optimized further with regard to torque ripple, losses and current density minimization. Here, a 60/72 poles/stator slots configuration has been chosen as a candidate motor. Its basic dimensions (i.e. the motor's diameters, axial length, etc.) and winding characteristics will be considered here constant and as determined in [5], since these parameters have to comply to strict constraints. The typical surface-mounted PMSM topology is shown in Fig. 2a, while Fig. 2b provides a detailed view of the stator slot.

III. SYMBIOTIC ORGANISMS CONCEPT AND SOS ALGORITHM

A. Concept fundamentals

The word ‘symbiosis’ is originated from Greek literature meaning ‘to live with each other’. Symbiotic relationships are generally classified in two types: mandatory and voluntary relations. In mandatory relations’ type, both organisms are completely mutually dependent in terms of durability, while in voluntary (arbitrary) type, they can be mutually dependent following non-mandatory relations. The most favorite natural symbiotic relations are *mutualism*, *commensalism*, and *parasitism*. The mutualism represents a symbiotic relationship between two different species where both profit. The commensalism is also another symbiotic relationship where one of species derives benefits and the other is unprofitable. Besides, the parasitism indicates a symbiotic relationship between two different species where one gains advantages and the other is unfairly damaged. The SOS algorithm essentially implements the above concept to provide an effective optimization technique.

B. The SOS algorithm

The SOS algorithm initiates with a randomly generated population, where the system has n number of organisms (i.e. population size) in the ecosystem. In the next stage, the population is updated in each generation g by the *mutualism*, *commensalism* and the *parasitism* phase respectively. Moreover, the updated solution in the each phase is accepted only if it has a better functional value. The course of optimization is repeated until it satisfies the termination criterion. In this optimization method, the better solution can be achieved by the symbiotic relations between the current solution and either of other random solution and the best solution from the population. Resemble to other population-based algorithms, the SOS algorithm also exploits a number of candidate solutions in the required regions in the search space when it is searching the global optimum solution. Hence, it starts taking an initial population into account known as primary ecosystem, where a group of organisms are randomly generated in the search space. Each organism has one candidate solution. These processes mentioned above are repeated for all organisms in a given ecosystem until achieve final criteria. Fig. 3 summarizes the computational method of the algorithm. Furthermore, Fig. 4 explains the SOS algorithm flowchart used here.

1) Mutualism phase

In this phase X_i , X_j ($i \neq j$) are the two random organisms, which interact with in themselves so as to enhance their chances of survival. The new candidate solutions for X_i and X_j are given in Eqs. (1) and (2),

$$X_{i_new} = X_i + rand(0,1) \cdot (X_{best} - Mutual_Vector \cdot BF_1) \quad (1)$$

$$X_{j_new} = X_j + rand(0,1) \cdot (X_{best} - Mutual_Vector \cdot BF_2) \quad (2)$$

$$\text{where} \quad Mutual_Vector = \frac{X_i + X_j}{2} \quad (3)$$

$$\text{and} \quad BF_1, BF_2 = 1 + round(r) \quad , \quad r \in [1,2] \quad (4)$$

The $rand(0,1)$ is a vector of random numbers. The organism can be partially or fully benefited from the interaction and the benefit factor BF_1 and BF_2 are random numbers, either 1 or 2. Equation (3) represents the “mutuality” vector, giving the relationship between X_i and X_j . The value $(X_{best} - Mutual_Vector)$ reflects the efforts by the organism to increase survival. All the better values, replace the original solutions (Fig. 3).

2) Commensalism phase

Similar to mutualism phase, two random organisms X_i and X_j ($i \neq j$) from the ecosystem are allowed to interact in commensalism phase. In this interaction organism X_i benefits from the interaction, but organism X_j neither benefit nor suffers from the relationship. The new candidate solution of X_i is calculated, which is modeled as,

$$X_{i_new} = X_i + rand(-1,1) \cdot (X_{best} - X_j) \quad (5)$$

The benefit advantage in this case is provided by $(X_{best} - X_j)$ in which the organism X_j provides maximum benefit to organism X_i in terms of survival. Finally, if the new fitness value is greater than the previous value the organism X_i would be updated.

3) Parasitism phase

In parasitism phase, one of the randomly selected organisms from the ecosystem X_i acts as a “parasite”. The duplicating organism X_i creates the *parasite_vector* and is modified by a random number. The newly formed parasite fights for survival with the organism X_j which is randomly chosen from the ecosystem so as that it can treat as a host against the parasite. If the fitness value of the parasite-vector is larger than that of X_j , then it will damage X_j and occupy its place in the ecosystem. On the other hand, if X_j has a greater fitness value, it can overcome the parasite-vector leading to preventing the durability of parasite in the ecosystem.

```
% d is dimension of the problem
- Define objective function f(x) where x=(x1, x2, x3, ..., xd)
- Initialize an ecosystem of organisms with random solutions
While (t < Max iterations)
  for i = 1: eco_size % for all the organisms
    - Find the best organism X_best in the ecosystem
    % Mutualism phase
    - Randomly select one organism X_j, where X_j ≠ X_i
    - Determine mutual relationship vector (Mutual_Vector)
      and benefit vectors (BF) using Eqs. (3) and (4)
    - Modify organisms X_i and X_j using Eqs. (1) and (2)
    - If modified organisms give better fitness evaluation
      than previous, then update them in ecosystem
    % Commensalism phase
    - Randomly select one organism X_j, where X_j ≠ X_i
    - Modify organism X_i with the help of X_j using Eq. (5)
    - If the modified organism gives better fitness evaluation,
      then update it in ecosystem
    % Parasitism phase
    - Randomly select one organism X_j, where X_j ≠ X_i
    - Generate parasite_vector from organism X_i
    - If parasite_vector gives better fitness value than X_j,
      then replace it with parasite_vector
  end for
- The global best solution is saved as optimal solution
end while
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Fig. 3. Pseudo code of SOS algorithm.

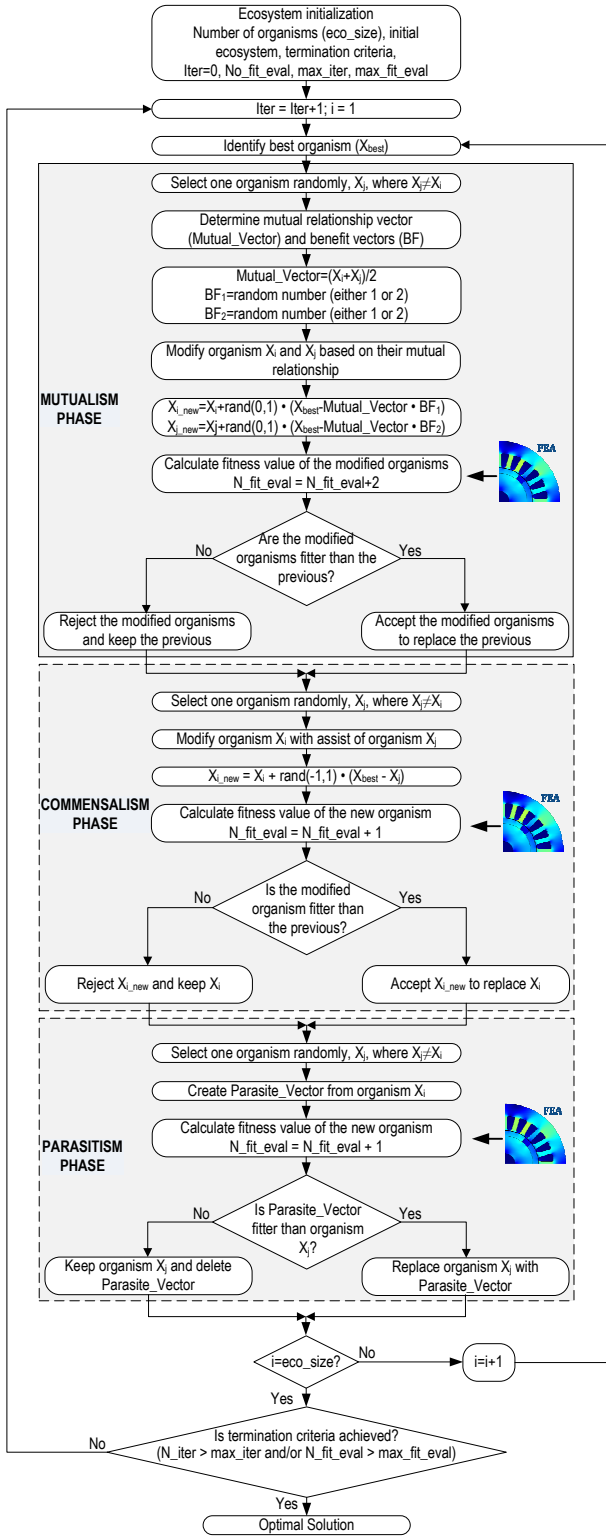


Fig. 4. Detailed flowchart of the SOS algorithm implemented and utilized in this study combined with FEA for azimuth thruster PMSM optimization.

C. Benefits and Limitations of SOS Algorithm

SOS compared to other population based algorithms are similar in many characteristics, with their iterative performance on a collection of candidate solutions to achieve the global solution. However, SOS algorithm does not procreate (e.g. unlike in GA, PSO), but adapts through

individual interactions. Also, SOS differs to other algorithms by using three different strategies mentioned before (mutualism, commensalism and parasitism).

The first strategy in SOS actually modifies candidate solution, after taking the difference between best and average solution. The advantage of exploring new search space is utilized, when the organisms are separated by a wide space. The values of the interacting individuals are updated simultaneously. The second strategy in SOS utilizes the best solution as the point of reference and exploits points nearer to it. The speed of convergence is thus enhanced. Finally, the third strategy performs actually as a mutation operator (unique to SOS) where the trial mutation vector, competes randomly with other excepting its parent. This competition has the following advantages: a) complete solution is modified, b) the modified dimensions represent the characteristics of local search, c) because of randomization, the solutions are widely spread in the solution space.

Of course, there are not many limitations in this algorithm, like other meta-heuristic algorithms, because all the meta-heuristic algorithms start with to work on a primary setting and try to provide optimal solutions in several repetitions.

IV. PROBLEM STATEMENT, RESULTS AND DISCUSSION

The effectiveness of the SOS method to solve the optimization problem of the azimuth thruster PMSM is demonstrated in this Section. A software program has been developed in the MATLAB environment which was interacted with a FEA software and ran on a computer with 6 core/12 threads processor with clock speed at 3.3 GHz and 16 GB RAM. Moreover, 10 trial runs were performed aiming to test the robustness of the SOS algorithm. The results of these runs revealed that the optimal search variables values obtained by the algorithm for all the runs were always almost identical between them (disregarding the convergence time), showing the robustness and superiority of the SOS method for the electrical machine design problems.

With respect to Fig. 2, the five selected design variables were: a) the magnets' pole arc to pole pitch ratio (*embrace*) as a percentage, b) the magnets' thickness (l_m) in mm, c) the slot opening width (b_{s0}) in mm, d) the stator tooth shoe height (h_{s0}) in mm and e) the peak phase current in kA. The upper and lower search variables limits were set to $ub=[90, 16, 30, 9, 6]$ and $lb=[50, 8, 10, 3, 4]$ respectively.

Regarding the optimization function, it is a fact that in optimization problems its formulation is of crucial importance. Equation (6) was employed here as a minimization objective,

$$\min F_{obj} = \left(\alpha \frac{T_{calc}}{T_{des}} + \beta \frac{R_{des}}{R_{calc}} + \gamma \frac{P_{C,des}}{P_{C,calc}} \right)^{-1} + \delta \underbrace{\left| \frac{T_{calc}}{T_{des}} - 1 \right|}_{penalty} \quad (6)$$

where T_{calc} and T_{des} are the calculated and the desired PMSM torque respectively, $P_{C,calc}$, $P_{C,des}$ are the calculated and the desired core losses respectively and R_{calc} , R_{des} are the calculated and the desired torque ripple respectively. The desired values were set at $T_{des}=193.5$ kNm, $R_{des}=2\%$ and

$P_{C,des}=10$ kW. The first one is mandatory to be satisfied. The second and third one, are set to almost unfeasible values to be obtained, in order for the algorithm to be forced to find solutions towards them. Also, for the sake of the algorithm's convergence speed, a varying penalty was introduced for the calculated torque which is represented from the second term of Eq. (6). Coefficients α , β , γ and δ may be used as weights to "calibrate" the objective function value according to different objective priorities. Equal weight values chosen here i.e. $\alpha=1$, $\beta=1$, $\gamma=1$, while for the penalty term $\delta=10$.

Regarding the SOS algorithm, the number of ecosystem organisms was selected as $eco_size=50$. The maximum number of function evaluations was set at $max_fit_eval=400 \cdot d$, where $d=5$ is the number of problem search variables (or else the problem dimension). Since four function evaluations are performed in each iteration, the resulting maximum number of iterations is $max_iter=500$.

The adopted algorithm succeeded to converge to an optimal design satisfying all the applied constraints. Figure 5, depicts the obtained convergence curve of the algorithm, while Fig. 6 shows the search variables variation (through their universe of discourse) during the iterations. From these figures it can be easily seen that: a) the algorithm succeeded to converge quickly and b) the exploitation and exploration potential of the algorithm is effective.

The optimum "organism" found corresponds to $embrace=0.789$, magnet thickness $l_m=11.48$ mm, slot opening width $b_{s0}=16.52$ mm, tooth shoe height $h_{s0}=5.37$ mm and peak phase current=5.025 kA. The resulting torque obtained with the above solution was $T=193.5$ kNm, while the corresponding core losses $P_C=35.80$ kW and the respective torque ripple $R=3.28$ %. Fig. 7 illustrates the torque variation through the optimization process. It should be noted that the x-axis does not refer to iterations but to "alterations" i.e. the number of consecutive variations of calculated torque value towards the desired one. Moreover, the motor's output torque versus time curve is depicted in Fig. 8. After an intense torque fluctuation for a small time period, the steady-state is reached at 100 msec. Under this condition, the average torque value is indicated also. Considering the above, it can be seen that the set requirements are met by the proposed solution. Additionally, comparing the derived results with the corresponding ones obtained in [5] for the PMSM topology under study, it can be said that a reduction of 12.5% and almost 60% has been achieved regarding to core losses and torque ripple respectively.

Aiming to determine further whether the proposed PMSM topology performance is acceptable, more operational characteristics were examined. The magnetic flux density distribution of the PMSM is depicted in Fig. 9 for different magnet position relative to the stator tooth. The value of the magnetic flux density over the various motor parts has been found within the acceptable limits. Regarding to the stator teeth no severe saturation is observed. Furthermore, the motor's airgap flux density and its phase back-electromotive force (back-emf) (shown in Fig. 10) present a quite sinusoidal form and very low harmonic content. The absence of odd harmonics with great amplitude in the phase back-emf

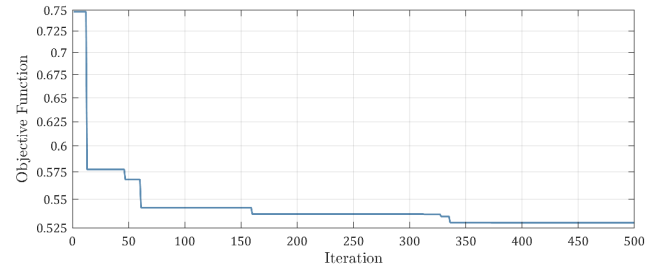


Fig. 5. Variation of the objective function value (algorithm convergence) through the optimization process.

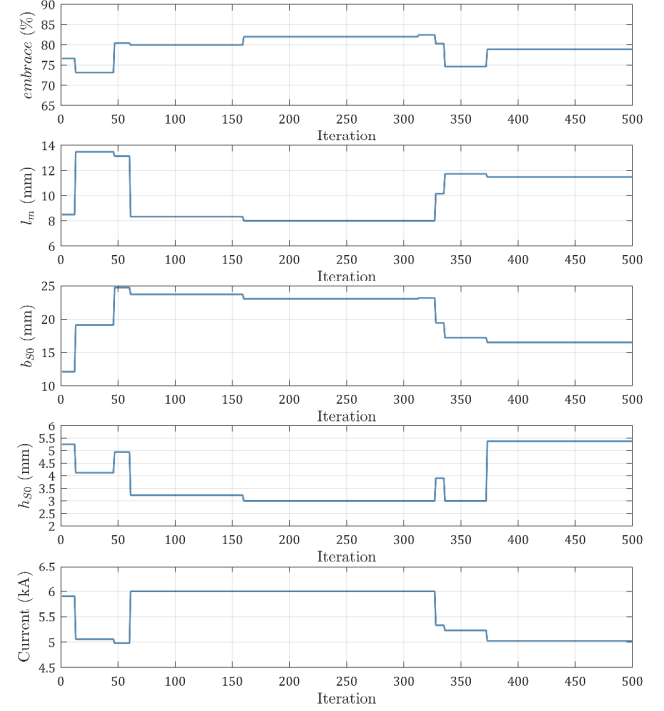


Fig. 6. Variation of the search variables through the optimization process.

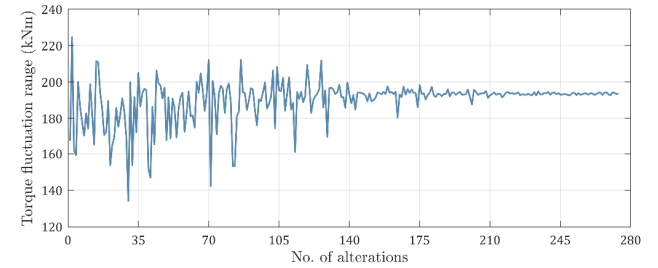


Fig. 7. Variation of the torque toward the desired value.

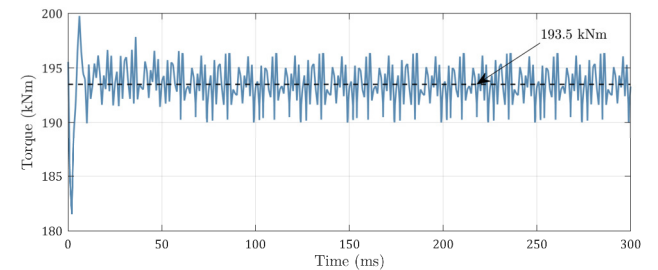


Fig. 8. Motor's output torque variation versus time.

can justify the low torque ripple of the derived PMSM topology. The PMSM's design variables and performance features are summarized in Table II and Table III respectively.

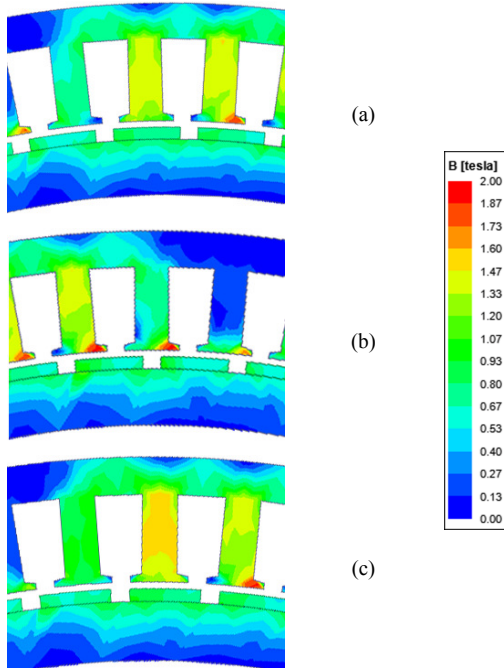


Fig. 9. Magnetic flux density distribution of the PMSM when a) magnet center is aligned with the stator's tooth, b) stator's tooth center is between two adjacent magnets and c) magnets edge is aligned with the tooth's tip.

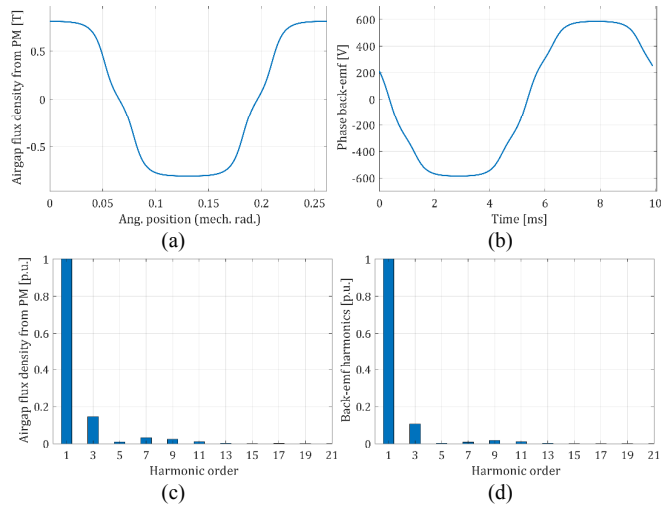


Fig. 10. Results of the optimized azimuth thruster PMSM, a) airgap flux density, b) phase back-emf and c), d) their corresponding harmonics.

V. CONCLUSIONS

The symbiotic organisms search (SOS) algorithm has been successfully implemented for the first time in an electrical machine problem. The application chosen was the optimization of an azimuth thruster PMSM topology. The derived results indicated satisfactory convergence characteristics, computational efficiency and robustness of the specific algorithm. Therefore, it could be utilized aiming to provide reliable optimization solutions to electrical machine design related problems. The obtained through optimization process PMSM configuration satisfied all the set requirements and constraints. Moreover, the motor's performance was considered as acceptable by taking into consideration several operational characteristics, such as the magnetic flux density distribution, the back-emf quality, etc.

TABLE II
FINAL TOPOLOGY DESIGN VARIABLES

Quantity	Symbol	Value
Stator outer diameter	D_o	1.793 m
Stator inner diameter	D_s	1.568 m
Rotor outer diameter	D_r	1.556 m
Motor axial length	L	1.850 m
Shaft diameter	D_{shaft}	1.427 m
Number of poles	$2p$	60
Number of slots	Q_s	72
Airgap length	d	6 mm
Slot opening width	b_{s0}	16.52 mm
Slot width at the base	b_{s1}	37.07 mm
Slot width at the top	b_{s2}	43.26 mm
Stator tooth shoe height	h_{s0}	5.37 mm
Slot total height	h_{s2}	78.38 mm
Magnet thickness	l_m	11.48 mm
Pole arc/pole pitch ratio	$embrace$	0.789
Number of turns per phase	n_c	12
Winding factor	k_w	0.966

TABLE III
FINAL TOPOLOGY PERFORMANCE CHARACTERISTICS

Quantity	Symbol	Value
Nominal output power	P_{out}	4.05 MW
Nominal speed	n	200 rpm
Nominal output torque	T	193.5 kNm
Peak phase current	I	5.025 kA
Current density	J_s	2.53 A/mm ²
Copper losses	P_{cu}	33.74 kW
Core losses	P_c	35.80 kW
Torque ripple	R	3.28 %
Power density	P_d	0.336 kW/kg
Torque density	P_T	54.46 Nm/A

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