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RESEARCH NOTE

Optimal Design of a Brushless DC Motor, by Cuckoo Optimization Algorithm

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ABSTRACT

This contribution deals with an optimal design of a brushless DC motor, using optimization algorithms, based on collective intelligence. For this purpose, the case study motor is perfectly explained and its significant specifications are obtained as functions of the motor geometric parameters. In fact, the geometric parameters of the motor are considered as optimization variables. Then, the objective function has been defined. This function consists of three terms i.e. losses, construction cost and the volume of the motor which should be minimized simultaneously. Three algorithms i.e. cuckoo, genetic and particle swarm have been studied in this paper. It is noteworthy that, cuckoo optimization algorithm has been used for the first time for brushless DC motor design optimization. A comparative study between the mentioned optimization approaches shows that, cuckoo optimization algorithm has been converged to optimal response in less than 250 iterations and its standard deviation is ± 0.03, while the convergence rate of the genetic and particle swarm algorithms are about 400 and 450 iterations with standard deviations of ± 0.07 and ± 0.06, respectively for the case study motor. The obtained results show the best performance for cuckoo optimization algorithm among all mentioned algorithms in brushless DC motor design optimization.

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1. INTRODUCTION

The use of DC motors has become common in industry, due to highlighted specifications such as vast speed control and high efficiency [1-3]. However, the presence of commutator and brushes can be considered as a major disadvantage of such motors due to constant erosion of the mentioned components which can finally lead to an increase in safety hazard and the maintenance cost. But this problem has been solved by the use of Brushless DC (BLDC) motors. In these motors electric circuits have been applied instead of commutator and brushes [2, 4].

So far, several investigations have been conducted on optimization of BLDC motor design. As stated in literature [5], a BLDC motor has been optimized by orthogonal multi-objective chemical reaction optimization algorithm (OMOCRO), in order to achieve maximum efficiency with minimal material cost. Consequently, a comparative experiment among non-dominated sorting genetic algorithm, multi-objective particle swarm and (OMOCRO) shows the best performance of (OMOCRO) for BLDC motor design optimization. Reference [6], has proposed a novel optimization method, search region management (SRM), in order to improve the efficiency of the local search algorithms. The mentioned method has been tested for optimal design of a BLDC motor with the help of FEA, in order to minimize the torque ripple. It has been stated in literature [7] a Multi-objective Krill Herd Algorithm (MOKH), using the beta distribution in the inertia weight tuning, has been proposed for electromagnetic optimization of a Brushless DC Motor with a promising performance.

Another investigation [8] has proposed the genetic algorithm for topology optimization of the stator teeth in a BLDC motor in order to reduce the torque ripple without decreasing the average torque. Son et al. [9] optimized BLDC motor through a population based algorithm called interstellar search method (ISM) with

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mesh adaptive direct search. Reduction of the torque ripple has been considered as the main objective of this paper. Another study [10] deals with the optimal design of an interior permanent magnet BLDC motor, using cost effective ferrite magnets in order to maximize the flux density and minimize the torque ripple. The genetic algorithm has been applied for flared shape rotor structure optimization. Kim et al. [11] have optimized the anisotropic ferrite magnet shape and magnetization direction of an interior Permanent Magnet BLDC Motor in order to maximize back-EMF of the mentioned motor with the help of (FEM). On the other hand, a 2-D analytical solution to predict the distribution of magnetic field and comparing the results with 2-D (FEM) in ironless BLDC motor, used in flywheel, has been raised by Liu et al. [12]. Investigation [13], discusses an outer rotor type motor design, used in the blower system of a vehicle in accordance to a BLDC and also BLAC motor with the help of finite element analysis.

In most of literatures mentioned that the influence of the required speed has been neglected in optimization and as a result, the motor power has not been well defined [5-10]. On the other hand, the applied optimization approaches are based on simple analysis with sensitivity to initial conditions which have been widely used in recent years. Therefore, employing a more up to date optimization algorithm seems to be vital. This investigation provides a detailed study in order to represent the essential equations for BLDC motor design, considering: Both speed and torque as mechanical required parameters and, using cuckoo optimization algorithm (COA) as a suitable approach for motor optimal design. To this end, the geometric parameters of the motor are considered as the optimization variables. Then the objective function is defined, based on minimization of losses, construction cost and the volume of the motor. Finally the obtained results of the three optimization approaches have been compared and the COA has been extracted as the best method.

2. MATERIALS OF A BLDC MOTOR AND THE APPLIED METHODS

2. 1. BLDC Motor Structure

Figure 1 depicts the structure of the studied motor in addition to its geometrical parameters [14]. Furthermore, the shown parameters, in Figure 1, have been introduced in Table 1.

TABLE 1. Parameters of BLDC motor

number of pole pairs	P	winding thickness	l_w (m)
cross sectional area of the winding	A_c (mm^2)	mechanical air gap	l_g (m)
pole–arc per pole–pitch ratio	β	rotor radius	r_r (m)
magnet thickness	l_m (m)	current density	$J_{cu}\,(\mathrm{Am}^{-2})$
stator/rotor core thickness	l_y (m)	wire gauge and stator/rotor axial length	l_s (m)

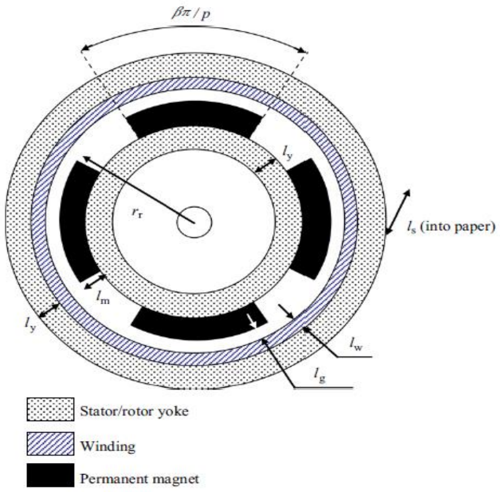

Figure 1. The structure of the studied BLDC motor

2. 2. Design Features

2. 2. 1. Electromagnetic Torque

For obtaining the total torque, the specifications which depend on the body material of the BLDC motor such as filling factor of the coil (k_f), permanent magnet and the stator and rotor core flux density (B_r), should be given in the knee point of the B-H curve.

Assuming the conductor and the magnetic field, are orthogonal to each other, the total torque can be obtained as follows [14, 15]:

$$T = A_w J_{cu} k_f k_c l B_r \tag{1}$$

$$A_w = \pi l_w (2r_r + 2l_g + l_w) \tag{2}$$

where, l and k_c represent the length of the conductor and the correction factor, respectively and A_w is the cross section of the coil.

Regardless of the armature reaction and also the reluctance of the stator and rotor core, the magnetic flux density will be as follows [14, 15]:

$$B_g = \frac{F_m}{A_g \Re} = \frac{B_r l_m}{(r_r + l_g)\ln\left(\frac{r_r + l_g + l_w}{r_r - l_m}\right)} \tag{3}$$

where, F_m , is the magneto-motive force and $\Re$ is the total reluctance of each winding. A_g can be obtained as:

$$A_g = l_s \frac{\beta\pi}{p}(r_r + l_g) \tag{4}$$

The electromagnetic torque of the BLDC motor based on its geometric parameters can be expressed in accordance to Equation (5).

$$T_{em} = \frac{\pi k_f k_c k_1 k_\beta B_r l_m l_s l_w (2r_r + 2l_g + l_w) J_{cu}}{\ln\left(\frac{r_r + l_g + l_w}{r_r - l_m}\right)} \tag{5}$$

The leakage component of the magnetic field (k_1) and also the active area of the auxiliary coil and magnet (k_β) are expressed with the help of Equation (6) and (7), respectively.

$$k_1 = 1 - \frac{1}{0.9[r_r / (\beta p (l_g + l_w))]^2 + 1} \tag{6}$$

$$k_\beta = \frac{\alpha(\beta, k_c)}{k_c} \tag{7}$$

α , indicates the span of the active coils, locating in the PM magnetic field, as shown in Figure 2. This parameter can be approximated by the following equation.

$$\alpha = \min(\beta, k_c)[k_s + (1 - k_s)\tanh(\delta \,|\, \beta - k_c \,|)] \tag{8}$$

It is noteworthy that, $k_s < 1$ and δ is obtained by experience and testing.

2. 2. 2. The Mechanical and Electrical Criteria

For making a relation between the motor geometry and the desired velocity, the electrical and also mechanical criteria should be defined in order to restrict the rotational velocity. From the mechanical aspect, the bearings are able to withstand high rotational speeds.

Therefore, they hardly impose any limitation on rotational velocity. But on the other hand, other rotating parts, specially permanent magnet can impose limitations on the maximum rotational velocity. As a result, a non-magnetic rotating sleeve is applied in order to enhance the mechanical robustness of the rotor.

From electrical point of view, the electrical time constant ($\tau = L / R$), can limit the maximum rotational velocity.

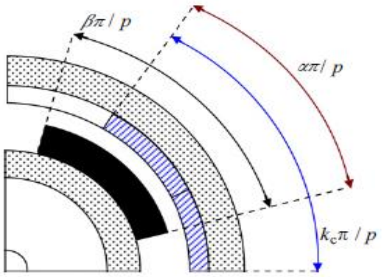

Figure 2. Concept of α

R and L represent the resistance and the inductance of each winding, respectively.

2. 2. 3. Cost of Materials

The volume of the applied materials which depend on the motor geometry have significant impacts on the motor cost as expressed in Equation (9).

$$C = C_m + C_w + C_y \tag{9}$$

where, C_m , C_w and C_y represent the costs of permanent magnet, winding and stator/rotor core, respectively. Each term of Equation (9), can be written in detail as follows.

$$C_m = c_{m1} \rho_m V_m + c_{m2} p \tag{10}$$

$$C_w = c_w A_g k_f \rho_w V_w \tag{11}$$

$$C_y = c_y \rho_y V_t \tag{12}$$

where, c_{m1} , c_w and c_y are the costs per unit mass of permanent magnet, winding and core materials, respectively. ρ_m , ρ_w and ρ_y represent the mass densities of permanent magnet, winding and rotor/stator core, respectively. Finally, V_m , V_w and V_t are the volumes of the permanent magnet, winding and rotor/stator core, respectively.

2. 2. 4. Losses in BLDC Motors

Losses in BLDC motors are divided into three categories i.e. electrical, magnetic and mechanical losses. The power loss due to resistance of windings can be obtained as follows.

$$P_{cu} = \rho k_f k_c k_{et} A_w l_s J_{cu}^2 \tag{13}$$

On the other hand, the eddy currents and hysteresis losses are considered as two major magnetic losses of a BLDC motor.

Assuming equal magnetic flux of the air-gap and the core, the maximum magnetic density of the stator is expressed as [14]

$$B_{sy} = \frac{\pi k_1 \beta B_r l_m}{2 p l_y \ln\left(\frac{r_r + l_g + l_w}{r_r - l_m}\right)} \tag{14}$$

Thus, the following equations are obtained for eddy current and hysteresis losses, respectively.

$$P_e = k_e' \rho_y V_{sy} B_{sy}^2 f^2 \tag{15}$$

$$P_h = k_h' \rho_y V_{sy} B_{sy}^n f \tag{16}$$

where, ρ_y is the density of the motor material and V_{sy} represents the stator volume. It should be noted that, the frequency in Equations (15) and (16) is calculated in accordance to Equation (17).

$$f = pw_r / 2\pi \tag{17}$$

On the other side, the mechanical losses in a BLDC motor can be divided into two categories including; friction and windage. The friction losses can be written as follows [14].

$$P_b = \frac{N_b}{2} \mu_f F_b d_i \omega_r \tag{18}$$

where, F_b and d_i are the load and the internal radius of the bearing. On the other hand, μ_f and N_b represent the bearing friction factor and the number of bearings respectively. The windage losses can be obtained as follows.

$$P_w = \pi k_r C_f \rho_{air} \omega_r^3 r_r^4 l_s \tag{19}$$

where, k_r and ρ_{air} represent the roughness factor of the rotor and the air density respectively and C_f is the friction factor which is obtained by Equation (20) in which *Re* is the Couette-Reynolds number.

$$C_f = \begin{cases} 0.5150 \dfrac{(l_g / r_r)^{0.3}}{\mathrm{Re}^{0.5}} & \textit{for} \quad 500 < \mathrm{Re} < 10^4 \\ 0.0325 \dfrac{(l_g / r_r)^{0.3}}{\mathrm{Re}^{0.2}} & \textit{for} \quad 10^4 < \mathrm{Re} \end{cases} \tag{20}$$

$$\mathrm{Re} = \rho_{air} w_r r_r l_g / \mu_{air}$$

$$T_{em} = \frac{\pi k_f k_c k_1 k_\beta B_r l_m l_s l_w (2r_r + 2l_g + l_w) J_{cu}}{\ln\left(\dfrac{r_r + l_g + l_w}{r_r - l_m}\right)} - \frac{P_e + P_h}{w_r} \tag{21}$$

$$T_{out} = T_{em} - (P_w + P_b) / \omega_r \tag{22}$$

In accordance to the obtained magnetic and mechanical losses, the modified formula of the electromagnetic and also the output torque can be modified as Equations (21) and (22). Also, the total losses of a BLDC motor can be expressed as:

$$P_{total} = P_{cu} + P_h + P_e + P_b + P_w \tag{23}$$

3. OPTIMIZATION METHODS

These paper apply three different evolutionary algorithms i.e. Cuckoo (COA) [16], genetic (GA) [17, 18] and particle swarm (PSO) [19-21], for optimal design of the BLDC motor. GA is a popular and applied algorithm because of several reasons such as, its high intuitiveness, ease of implementation, its high capability to solve highly nonlinear mixed integer optimization problems, large number of parameters and obtaining multiple local optima. On the other hand, PSO, has the same advantages as GA, but with better computational efficiency by applying statistical analysis and formal hypothesis testing. But this study has applied the COA for optimal design of BLDC motor for the first time. The cuckoo optimization algorithm has superiority to many other optimization algorithms i.e. GA and PSO, typically for multi-objective functions. In COA, the local search is performed with higher efficiency because there is only a single parameter apart from the population. In fact the only parameter which should be adjusted is the fraction of the nests needed to be abandoned (P_a). This issue improves the computing power and speed. GA and PSO are common algorithms and have been completely described in references [17-21]. But since, COA, has been used as the main algorithm for motor optimal design in this study, an initial understanding from the concept of these algorithms is presented as follows.

3. 1. Cuckoo Optimization Algorithm Cuckoo Optimization Algorithm (COA) has been inspired by the life of a bird, called cuckoo [16]. The initial population of COA which forms various societies, consists of cuckoos and eggs. Each cuckoo has some eggs and also an Egg Laying Radius (ELR). The cuckoos lay eggs inside their equivalent ELR and in the nests of other host birds. Among all the eggs, those ones, which are similar to the eggs of the host birds can grow up. The rate of grown eggs indicates the suitability of the area. The area with more remained eggs has higher profit. Cuckoos always search for areas with highest profit for egg laying. Therefore, selecting the best place is an important term which should be optimized by the cuckoos. The cuckoos which live in the worst habitats always are removed. Each cuckoo travels a specific percent of the whole path toward the ideal habitat with a clarified deviation which are known as λ and α respectively. These two parameters help the cuckoos to find the ideal habitat. The maximum number of cuckoos should be confined in the specific environment. In fact, cuckoos have been clustered and the best habitat is detected to achieve the objective point. Consequently, the new cuckoo population can travel to the objective habitat. Now, the survival of eggs in the nest are checked and the profit value is obtained. A suitable profit value can lead to stopping the process. Otherwise, the whole process should start from the beginning in accordance to the flowchart, presented by Amiri and Mahmoudi [16]. In fact, the survival process of cuckoos should finally converge to a condition with only one cuckoo society, containing the same profit values.

3. 2. Determination of the Effective Parameters for the Optimization Methods Accordance to literatures [16-21], the determinave parameters of the optimization algorithms are introuduced. This parameters are λ and α for COA; the cross over rate and also the percentage of mutation for GA and (C_1 & C_2) for PSO. (C_1 & C_2) determine the traveled distance of a particle in each iteration [19-21]. The amount of the aforementioned parameters of the optimization algorithms, are measured in 20 different conditions. Each measurement is implemented individually for about 50 times and finally, The effective parameters, mentioned in Table 2, are obtained from the eights, twentieth and fourth implementation of COA, GA and PSO respectively.

4. OPTIMIZATION PROBLEM DATA

4. 1. Design Variables and Constant Values The optimization variables are those parameters of the case study motor that should be optimized. These parameters are presented in the following vector.

$$x = [p \ \beta \ l_m \ l_y \ l_w \ l_g \ l_s \ r_r \ J_{cu} \ A_c]^T \tag{24}$$

Generally, there are 10 different design variables that should be optimized. Other quantities i.e. power losses, output torque, costs and volume of the motor can be calculated through them. The aforementioned design variables were defined in Table 1. while, the constant parameters of this motor is presented in Table 4.

In addition to these parameters, other adjustable coefficients of the COA are also presented in Table 3.

4. 2. Objective Function, with Considering the Constraints An appropriate definition of the objective function with consideration of the constraints is always known as the most significant issue in solving any optimization problem. The main concern in this investigation includes reduction of costs, volume and power loss of a BLDC motor. For this reason, the objective function will be as follows:

TABLE 2. The value of effective optimization parameters

COA		GA		PSO	
α	λ	Cross over rate	Mutation (%)	C_1	C_2
0.05	30	0.8	0.1	1.6	2

TABLE 3. Other COA coefficients

Number of Cuckoos	40	Max number of Cuckoos	200
Min number of eggs	2	α	30
Max number Of eggs	5	λ	0.05
Number of clusters	2	Max iteration	500

TABLE 4. Constant parameters of the BLDC motor

Quantity	Amount	Quantity	Amount
k_f	0.7	w_p	0.02
k_c	0.666	w_v	2000/3
k_s	0.95	w_c	0.0125
k_r	1	$\rho_m (kg\ \mathrm{m}^{-3})$	7400
δ	5	$\rho_w (kg\ \mathrm{m}^{-3})$	8900
$B_r (T)$	1	$\rho_y (kg\ \mathrm{m}^{-3})$	7700
$B_{sy}^{knee} (T)$	1.5	$c_{m1}(£\ \mathrm{kg}^{-1})$	20
$\kappa(A^2 m^{-3})$	10^{11}	$c_{m2}(£)$	1
$\rho(\Omega m)$	1.8×10^{-8}	$c_y (£\ \mathrm{kg}^{-1})$	3
$k_h^{'}(W\ s\ kg^{-1} T^{-n})$	0.018^a	$c_1(£\ \mathrm{mm}^2\ \mathrm{kg}^{-1})$	0.045
$k_e^{'}(W\ s^2\ kg^{-1} T^{-2})$	0.00008^a	$c_2(£\ \mathrm{kg}^{-1})$	5.42
n	1.92^a	$T_{em}^{*}(Nm)$	10
γ	1	$w_r^{*}(rad\ \mathrm{s}^{-1})$	157
$V^{*}(v)$	140		

[a] For M19 lamination with a thickness of 0.35mm

$$f_0(x) = w_V V_t(x) + w_P P_{total}(x) + w_C C(x) \tag{25}$$

where, $C(x)$, $P_{total}(x)$ and $V_t(x)$ represent, cost function, power loss function and volume function of the motor, respectively. On the other hand, w_C, w_P and w_V are the related weight of cost function, power loss function and volume function of the motor. In fact, these coefficients clarify the impact of each function.

In addition to electrical and mechanical constraints, some other limitations such as thermal, cost and manufacturing constraints are of great importance. The only electrical constraint is the voltage which can be obtained with appropriate selection of the winding diameter. Similarly, the mechanical constraints can be expressed as follows.

$$\begin{cases} T_{em} \geq T_{em}^{*} \\ \omega_r^{max} \geq \omega_r^{*} \end{cases} \tag{26}$$

where, T_{em}^{*} and ω_r^{*} are arbitrary torque and speed respectively. ω_r^{max} is considered as the maximum speed in the arbitrary torque. It should be noticed that, the manufacturing constraints contain some parameters i.e.

minimum air-gap (l_g^{min}) and the minimum area of the section (A_c^{min}).

Other constraints, caused by thermal limitations and saturation effect, are expressed as follows.

$$\begin{cases} B_{sy} \le B_{sy}^{knee} \\ k_f l_w j_{cu}^2 \le k \end{cases} \tag{27}$$

where, B_{sy}^{knee} represents, the magnetic flux density at the knee point of the B-H curve and k is the maximum permissible temperature of the windings.

After considering the impact of the electromagnetic torque, speed and magnetic flux density constraints, the objective function has been modified as follows.

$$f_0(x) = w_V V_t(x) + w_P P_{total}(x) + w_C C(x) + \frac{1}{\varepsilon}\left[f_u(1 - T_{em}/T_{em}^*) + f_u(1 - w_r^{\max}/w_r^*) + f_u(B_{sy}/B_{sy}^{knee} - 1) \right] \tag{28}$$

$$f_u(x) = \frac{1}{1 + e^{-\sigma x}}$$

where, ε is a tiny amount and σ is considered as a constant large number.

4. 3. Summary and Discussion For implementation of the BLDC motor optimization problem, the significant specifications of the motor are obtained as functions of the motor geometric parameters. The geometric parameters are mentioned in Table.1. In fact the mentioned parameters of the motor are considered as optimization variables and other quantities i.e. power losses, output torque, costs and volume of the motor can be calculated and optimized through them. The objective function consists of three terms including, losses, motor volume and manufacturing cost. The cost term is calculated by Equation (9), this Equation can be written in detail in accordance to Equations (10)-(12). Equations (3) and (4) are needed to define Equation (11). The total losses of a BLDC motor can be expressed as Equation (23). This equation has 5 terms including, Equations (13), (15), (16), (18) and (19). Equation (14) is essential for defining Equations (15) and (16) and also Equation (20) is necessary for defining Equation (19). For clarifying the impact of each function the related weight of cost function, power loss function and volume function of the motor is considered as in Equations (25). Equations (26) and (27) express the constraints of the objective function. By considering the constraints in Equation (25), the final objective function is shown as Equation (28). By means of optimization algorithms which are implemented on Equation (28), the geometric parameters and also the volume of the motor will be optimal in addition to losses and manufacturing cost simultaneously.

5. SIMULATION RESULTS AND DISCUSSION

5. 1. Technical Analysis of the Optimized Parameters After implementation of the algorithms according to the effective parameters, mentioned in subsection 3.2; design variables and constant values, mentioned in subsection 4.1 and also the modified objective function, presented in subsection 4.2, the optimal parameters of the case study motor are obtained. These values along with the minimum and maximum values of the parameters are given in Table 5. It should be noted that, GA and PSO results are validated with reference [14]. According to Table 5, when COA is applied, most of the geometrical optimized parameters i.e. β, l_m, l_w, l_g and l_s have the lowest values. Therefore, the motor has the lowest possible volume and lowest cost. On the other hand, the cross sectional area of the winding and the current density (A_c and J_{cu}) are also more applicable.

TABLE 5. The limitations and optimal value of the motor

No	Parameters	Min	Max	COA	GA	PS0
1	β	0.5	1	0.6912	0.7	0.6950
2	(m) l_m	0.001	0.015	0.0120	0.0130	0.0124
3	(m) l_y	0.002	0.01	0.0081	0.0060	0.0058
4	(m) l_w	0.001	0.0055	0.0033	0.0035	0.0034
5	(m) l_g	0.001	0.004	0.001	0.001	0.001
6	(m) r_r	0.005	0. 1	0.0592	0.0595	0.059
7	(m) l_s	0.006	0.6933	0.0730	0.0756	0.0732
8	(mm^2) A_c	0. 1	2	1.9551	2	1.9982
9	(Am^{-2}) J_{cu}	3×10^6	6×10^6	5819800	5800000	5784573

As a result, the objective function has the best value, using COA, as presented in Table 6. Another significant issue in any optimization approach is the convergence rate of the algorithm. The COA, converged after 250 iteration while the GA and PSO converge after 400 and 450 iterations, respectively. This issue indicates the suitable convergence rate of COA.

5. 2. The Impact of Motor Geometrical Parameters on the Objective Function Figure 3 shows the variation of the objective function, due to changing each geometrical parameter of the motor, while the rest of parameters remain constant. This figure is divided into 9 subfigures and is labeled from (a) to (i). Each subfigure depicts the impact of changing each geometrical parameter of the motor i.e. P , β , l_m , l_y , l_w , r_r, l_s, l_g and J_{cu} , on the objective function, respectively.

In all the subfigures, the red line, blue line and green point represent the proposed objective function variation, unconstrained objective function and the optimal point, respectively.

TABLE 6. Specifications of the optimized BLDC motor

No	Parameters	COA-Value	GA-Value	PSO-Value
1	$V_t (m^3)$	0.0011	0.00116	0.0012
2	C (£)	65.6417	68.86	64.51
3	(W) P_{total}	51.2446	56.71	52.3
4	(W) P_{cu}	42.1851	44.81	40.69
5	(W) P_h	4.4115	6.18	6.04
6	(W) P_e	2.4500	3.52	3.46
7	(W) P_b	2.1195	2.12	2.12
8	(W) P_w	0.0783	0.08	0.0697
9	$W_v V_t$	0.7891	0.776	0.75
10	$W_c C$	0.8205	0.861	0.804
11	$W_p P_l$	1.0248	1.136	1.043
12	f_o	2.59	2.78	2.71
13	Efficiency	96.61%	96.54%	96.46%
14	Standard	±0.03	±0.07	±0.06
15	V (Volt)	1.3034e+02	141.1	136
16	I (Ampere)	11.6115	11.6	11
17	(W) P_{out}	1462	1460	1461.31

In accordance to Figure 3a, the large number of poles causes an increment in the motor manufacturing cost and also a decrement in the magnetic losses due to low density of magnetic flux in stator and rotor core. It should be noted that, this issue has no impact on the volume of the motor. By considering the proposed objective function and Figure 3a, it is concluded that, applying higher number of poles can lead to a better design of the motor. However, this issue causes an increment in the leakage magnetic flux and a decrement in the output torque. According to Figure 3b, the value of β has no effect on the volume of the motor. But it is noteworthy that, a lower value of β can lead to a reduction in the cost, magnetic leakage flux, magnetic losses and also the output torque. On the other hand, a large value of β can lead to a decrement in the output torque due to its effect on increasing the magnetic leakage flux.

Figure 3c shows that, reduction of l_m leads to improvement of manufacturing cost, volume and losses of the BLDC motor. But on the other hand, the output torque and the maximum speed of the motor still keep decreasing as before. As shown in Figure 3d, an increment in l_y will lead to a reduction in the magnetic losses and causes an increment in the cost and volume of the motor. It should be noted that, considering a very small value for l_y , may lead to saturation. Figure 3e, shows that, the existence of high space for winding has different impacts on the cost and volume of the motor. But in general, it can lead to improvement of the efficiency. It is noteworthy that, l_w should not be lower than a permissible amount.

Otherwise, the motor will not be able to produce a suitable torque. The radius of the rotor (r_r) is considered as one of the most significant parameters in a BLDC motor design. As shown in Figure 3f, by reducing the r_r value, all the three items in the objective function will be reduced simultaneously. But it should be noted that, a very small r_r value has negative effect on producing the necessary output torque and on the other hand, a very large r_r value has inverse effect on the maximum speed of the motor. Figure 3g depicts that, a small value of l_s is favorable, but unfortunately, this small amount can lead to an adverse impact on the output torque of the motor.

This issue is not desirable. As shown in Figure 3h, l_g which shows the air-gap amount, is considered to have its minimum value.

Figure 3i indicates that, the output torque and the copper losses are proportional to the current density and the square of current respectively.

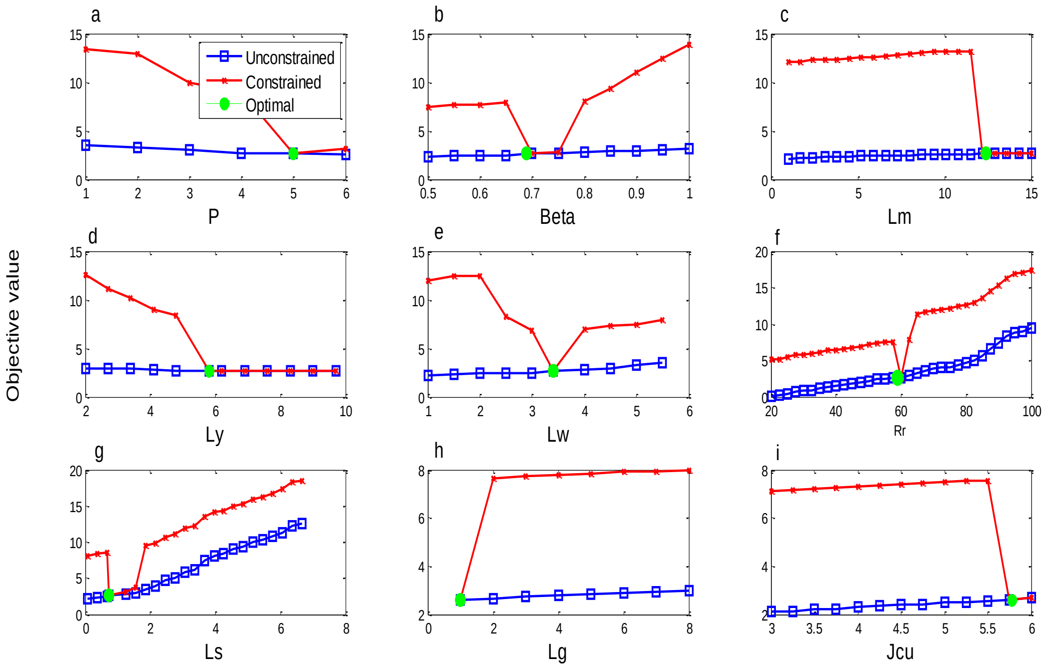

Figure 3. Objective function variation, due to changing each geometrical parameter of the BLDC motor

Although, increasing the current density can lead to an improvement in the cost and volume of the motor, but it is noteworthy that, the impact of an increment in the copper losses is able to overcome the two aforementioned advantages.

5. 3. The Comparison of COA Performance with GA and PSO

Figure 4 and Table 7 show the convergence rate, fitness and also the standard deviation of COA, GA and PSO algorithms.

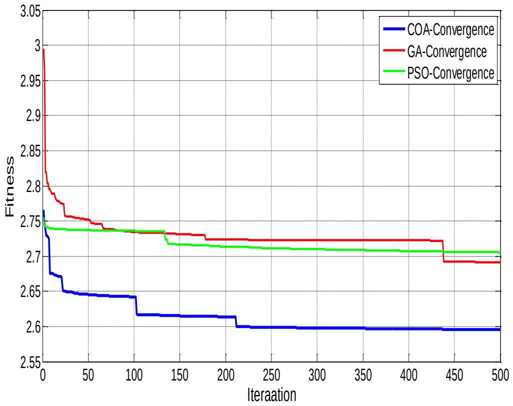

Figure 4. The convergence waveform comparison of COA, GA and PSO

TABLE 7. The comparison of applied methods

Algorithm	Fitness	Standard deviation	Convergence rate
COA	2.59	±0.03	250
GA	2.78	±0.07	400
PSO	2.71	±0.06	450

By considering, Table 7 and Figure 4, it is concluded that, COA algorithm has the best performance among all the described algorithms for optimal design of a BLDC motor.

6. CONCLUSION

In this paper, an optimal design of a BLDC motor, using three optimization approaches i.e. COA, GA and PSO has been studied. The priorities of parameters optimization in design of a motor are different in various applications. Therefore, the importance of this problem has become more obvious due to simultaneous parameter optimization. This investigation firstly clarifies significant specifications of the motor as functions of the motor geometric parameters. Then, the objective function has been defined in order to minimize the losses, construction cost and the volume of the motor simultaneously. Three different optimization approaches i.e. COA, GA and PSO have been applied for the case study motor optimal design. It is noteworthy that, COA has been used for the first time for this purpose. The obtained results of three optimization methods have been compared together and finally it is concluded that, COA can converge to an optimal response in less than 250 iterations, while this value is 400 and 450 iterations for GA and PSO, respectively. As a result, the proposed method has an acceptable convergence rate. On the other hand, the obtained fitness value and the standard deviation of COA is more applicable, compared with GA and PSO.

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Optimal Design of a Brushless DC Motor, by Cuckoo Optimization Algorithm

RESEARCH NOTE

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چکیده

این مقاله به بررسی طراحی بهینه از یک موتور بدون جاروبک جریان مستقیم با استفاده از الگوریتم‌های بهینه‌سازی که بر پایه هوش جمعی هستند می‌پردازد. برای این منظور، ابتدا موتور مورد مطالعه کاملاً توضیح داده شده و مشخصه‌های مهم آن به شکل توابعی از پارامترهای هندسی موتور به دست آورده شده است. در حقیقت، پارامترهای هندسی موتور به عنوان متغیرهای بهینه‌سازی در نظر گرفته شده‌اند. سپس تابع هدف تعریف گشته است. این تابع متشکل از سه بخش می‌باشد که شامل تلفات، هزینه ساخت و حجم موتور می‌گردند که می‌بایست به شکل هم‌زمان مینیمم گردند. در این مقاله سه الگوریتم بهینه‌سازی شامل الگوریتم‌های فاخته، ژنتیک و اجتماع ذرات مورد مطالعه قرار گرفته‌اند. شایان ذکر است که، الگوریتم فاخته برای اولین بار برای بهینه‌سازی طراحی موتور بدون جاروبک مورد استفاده قرار گرفته است. یک مطالعه مقایسه‌ای ما بین الگوریتم‌های یاد شده نشان می‌دهد که، الگوریتم فاخته در کمتر از ۲۵۰ تکرار و با انحراف استانداردی معادل ۰,۰۳ ± به همگرایی می‌رسد. در حالیکه نرخ همگرایی الگوریتم ژنتیک و اجتماع ذرات به ترتیب ۴۰۰ و ۴۵۰ با انحراف استانداردی معادل۰,۰۷ ± و۰,۰۶ ± می‌باشد. نتایج به دست آمده نشان‌دهنده بهترین عملکرد الگوریتم فاخته مابین الگوریتم‌های یاد شده به منظور بهینه‌سازی طراحی موتور بدون جاروبک جریان مستقیم می‌باشد.

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