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# Optimal design of permanent magnet brushless DC motor structure for power loss, volume and cost reduction using intelligent algorithm

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**Abstract**— As the rapid development of power electronic technology, control theory and permanent magnetic materials brushless DC (BLDC) motor developed a new kind of DC motor. Due to a series of advantages, its application was also more extensive than traditional motor, including high-precision electronic equipment, robot, aerospace, chemical mining etc many domains. In this paper an intelligent method based on imperialist competitive algorithm (ICA) is proposed to optimal design of slotless permanent magnet BLDC motor. The main specification of motor including loss, cost and volume are defined as functions of motor geometries parameters. The fitness function is a combination of losses, volume and cost to be minimized simultaneously. The real world BLDC motor is used to evaluate the performance of the proposed method. The simulation results show that the proposed method has a excellent performance.

**Index Terms**— BLDC, ICA, loss, cost, volume, optimization.

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## 1 INTRODUCTION

THERE are mainly two types of dc motors used in industry. The first one is the conventional dc motors where the flux is produced by the current through the field coil of the stationary pole structure. The second type is the brushless dc motor where the permanent magnet provides the necessary air gap flux instead of wire-wound filed poles. BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform shape. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated [1, 2].

The BLDC motor is becoming increasingly attractive in high performance variable speed drives since it can produce torque-speed characteristic similar to that of a conventional DC motor while avoiding the problems of failure of brushes and mechanical commutation. In addition to the reduction in maintenance needs, the BLDC motor has low mass or inertia, high efficiency, high dynamic response, long operation life, higher speed ranges, high torque density, large power to volume ratio, and significant reduction in friction and audible noise as compared with the induction motor or conventional DC servo motor at the same output rating [3, 4]. Applications where BLDC motors are being used include those requiring tough, dependable, reliable, continuous duty operations. A significant number of applications on extruders, wire drawers, winders, cranes, cable tensioners, conveyors, pullers, printing presses, roll formers, pump's motive part, computer's CD-ROM, robotic, propulsion system for aircraft and submarine or underwater remotely operated vehicles [5-10].

Yang et al. [11] have proposed a multiobjective optimal design of a low voltage high speed BLDC motor. A magnetic circuit model of motor has used as a preliminary design for optimization procedure. Multifunctional optimization method is applied to problem subject to constraints such as limited space, flux saturation, supply voltage, and current density. Then, results have used by finite element analysis for final modification. Eventually, a prototype BLDC motor have fabricated based on modified design for verification of the results. In [12], optimal design of a BLDC motor based on an experimental design method is presented, which the objective is to maximize the mean value of back electromotive force (EMF) and also, the optimization parameters are stator yoke and magnet thickness. In [13], a hybrid genetic algorithm (HGA) has been introduced for BLDC optimization to reduce cogging torque as electromagnetic topology optimization. A two-dimensional (2-D) encoding technique, which considers the geometrical topology and a 2-D geographic crossover which uses as the crossover operator have introduced. A novel local optimization algorithm, called the on/off sensitivity method, hybridized with the 2-D encoded GA, improves the convergence characteristics. In [14], a simplified analytical method to design a slotless BLDC motor has presented. This method consists of systems of equations with several approximations and in addition this method only can apply to small and two-pole motors. A comprehensive and comparative study of six stochastic optimization methods in designing optimal geometries of a universal electric motor has been proposed in [15], whereas the main goal is to minimize its power losses. The six applied methods are generational evolutionary algorithm (EA), steady-state EA, differential evolution (DE), particle swarm optimization (PSO), electromagnetism-like algorithm, and multilevel ant stigmergy algorithm. After design step, all results and geometrical parameters apply to finite element


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method and power losses of all designs are evaluated and compared to each other. Jang et al. [16] have used an analytical method to design and analysis of a high speed and high power density BLDC motor for centrifugal compressor. Then, the electromagnetic field, back EMF, and power losses are analyzed and the results are validated by finite element method. After that, the test machine has been manufactured and used for experimental tested for confirmation of the method. In [17], a detailed and comprehensive formulations necessity and needed in design of slotless BLDC motors with surface mounted magnet configuration have been presented considering both torque and speed as mechanical requirements. Then, GA has been used to find the optimal geometries of the motor. An objective function has been proposed covering the losses, cost and volume of the motor besides the mechanical and electrical requirements and constraints. In [18], a design method for a small-sized slotless BLDC motor with distributed hexagonal windings has employed and the objective is maximizing torque density. This new design method is semi-analytical whereas, numerical approaches based on finite element analysis with an analytic model are used to analyze the magnetic and output characteristics of the motor. The designed motor is fabricated, and the experimental results are compared with the results of the simulation. An analytical magnetic field distribution for slotless brushless machines with inset permanent magnets is presented in [19-21]. The induced back-electromotive force (EMF) is also presented for each magnetization pattern. The effects of iron inter-pole on the magnetic flux density and back-EMF have been considered. To verify the model, the results have been compared with finite element analyses results. In [22], a method for motor magnets design is proposed to optimize a BLDC motor based on design of experiment (DOE) method in order to reduce the cogging torque. The DOE methodology is used for a screening of the design space and for the generation of approximation models using response surface techniques. The experiments were performed based on the response surface methodology, as a statistical design of experiment approach, in order to investigate the effect of parameters on the response variations.

In most of the reviewed papers, the effect of required speed has been neglected in the optimization procedure and therefore power of the BLDC motor is not well defined. In this paper, a method for the optimal design of a slotless permanent magnet BLDC motor with surface mounted magnets using a ICA has been presented considering torque, maximum speed, voltage, losses and cost. An objective function has been proposed covering the power losses, material cost and volume of the motor simultaneously, besides the mechanical and electrical requirements. All of the effective parameters and constants have been considered in the optimization problem. ICA been used to find the optimal geometries of the assumed motor. Electrical and mechanical requirements such as voltage, torque and speed and other limitations e.g. upper and lower limits of the motor geometries are cast into constraints of the optimization problem. The results have been examined using sensitivity analysis and showed the efficacy of the proposed technique.

## 2 Slotless BLDC Motor Structure

The BLDC motors are categorized into two major groups from stator structure point of view; slotted and slotless. The preliminary BLDC motors have designed with slotted stator but newest ones have slotless configuration and the windings are wound into a cylindrical shape on the surface of the stator and are encapsulated in a high-temperature epoxy resin to maintain their orientation with respect to the stator laminations. Instead, the rotor is similar to that used in the conventional slotted BLDC motor. It has a number of magnet segments that define the motor poles and are affixed to a rotor core centered about and fixed to the motor shaft. The magnets are usually a high strength, rare-earth type, such as neodymium iron boron or samarium cobalt [23].

The preliminary advantage to be explored with the use of a slotless machine design is the reduction in manufacturing costs and its simplicity in production, compared to the manufacturing costs of a slotted BLDC machine. The production of a laminated stator is an expensive process, with steel laminations cut out from steel sheets, and these laminations are normally manually stacked together and affix. There also tends to be some material waste in this process, as there are an integer number of laminations that can be cut from a single sheet of steel. The slotless stator design originated with the goal to deliver smooth running performance and eliminate cogging and reduce slot harmonic effect. Mainly, the absence of cogging torque is the frequently cited reason for selecting a slotless BLDC motor. In order to minimize cogging torque in slotted configuration motors, techniques such as skewed stator slots or fractional slots can be employed and this makes design more complex and expensive. In addition, iron loss in a slotless motor is less than in an equivalent slotted design, inherently. Also, low magnetic saturation allows the motor to operate at several times its rated power for short intervals without perceptible torque roll-off at higher power levels. Several advantages of slotless BLDC are as follows, light weight, submersible, low winding inductance, high speed capability, lower vibration, lower audible noise, fast current response, high reliability, low electrical resistance, low static friction, Operates in hostile environment and no sparking, and high thermal efficiency [14, 18, 24].

The slotless BLDC motor mainly use as medical devices and factory automation, such as high speed medical drills, surgical robot systems, prosthetic limb drive systems, high speed miniature spindles, and etc [25- 28].

## 3 Imperialist Competitive Algorithm (ICA)

ICA is a population-based stochastic search algorithm. It has been introduced by Atashpaz and Lucas [29, 30]. Since then, it is used to solve some kinds of optimization problem. The algorithm is inspired by imperialistic competition. It attempts to present the social policy of imperialisms to control more countries and use their sources when colonies are dominated by some rules. If one empire loses its power, the rest of them will compete to take its possession. In ICA, this process is simulated by individuals that are known as countries.

This algorithm starts with a randomly initial population and

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objective function which is computed for them. The most powerful countries are selected as imperialists and the others are colonies of these imperialists .Then the competition between imperialists take place to get more colonies .The best imperialist has more chance to possess more colonies. Then one imperialist with its colonies makes an empire. Figure 1 shows the initial populations of each empire. If the empire is bigger, its colonies are greater and the weaker ones are less. In this figure Imperialist 1 is the most powerful and has the greatest number of colonies.

After dividing colonies between imperialists, these colonies approach their related imperialist countries. Figure 2 represents this movement. Based on this concept each colony moves toward the imperialist by a units and reaches its new position. Where a is a random variable with uniform (or any proper) distribution, b, a number greater than 1, causes colonies move toward their imperialists from different direction and S is the distance between colony and imperialist.

$$\alpha \approx U(0, \beta \times S) \tag{1}$$

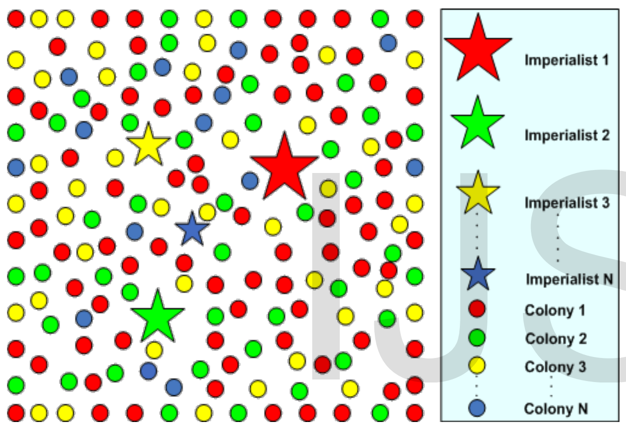


Fig. 1. Generating the initial empire

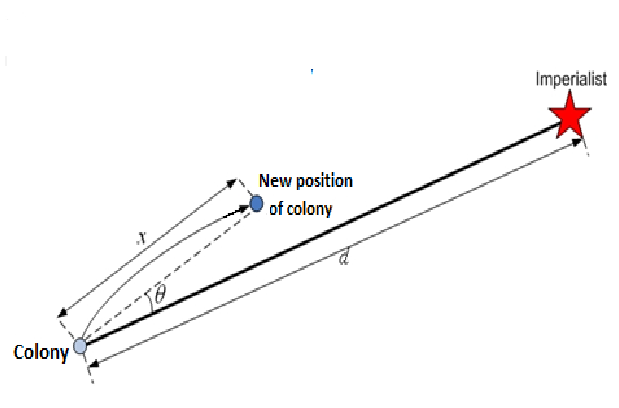


Fig. 2. Moving colonies toward their relevant Imperialist

If after this movement one of the colonies possess more power than its relevant imperialist, they will exchange their positions. To begin the competition between empires, total objective function of each empire should be calculated. It depends on objective function of both an imperialist and its colonies. Then the competition starts, the weakest empire loses its possession and powerful ones try to gain it. The empire that has lost all its colonies will collapse. At last the most powerful empire will take the possession of other empires and wins the competition [29, 30].

To apply the ICA for clustering, the following steps have to be taken:

Step 1: The initial population for each empire should be generated randomly.

Step 2: Move the colonies toward their relevant imperialist.

Step 3: Exchange the position of a colony and the imperialist if its cost is lower.

Step 4: Compute the objective function of all empires.

Step 5: Pick the weakest colony and give it to one of the best empires.

Step 6: Eliminate the powerless empires.

Step 7: If there is just one empire, stop, if not go to 2.

The last Imperialist is the solution of the problem.

## 4 Simulation Results and Discussions

### 4.1 Optimization Procedure

The main stage in the optimization of BLDC motor design is choosing objective function and setting constraints. First, the optimization variables, i.e. those motor parameters that need to be optimally found, should be represented as a vector, x:

$$x = [p \quad \beta \quad l_m \quad l_y \quad l_w \quad l_g \quad r_r \quad \lambda \quad A_c \quad J_{cu}]^T \tag{2}$$

The form of a proper objective function depends on the application and the required quantity of the motor. In this study the objective function consists of losses, cost and volume (mass) all of which should be minimized simultaneously. Three weighting factors are considered in order to bring all the objectives in a comparable scale and to control the importance of each individual objective. Therefore the objective function is written as:

$$f_0(x) = w_V V_t(x) + w_P P_{total}(x) + w_C C(x) \tag{3}$$

Where, wP, wV and wC are weighting factors, Ptotal is total power loss of motor, and C is the total cost of the materials used in the motor design. To solve the optimization problem one needs to initialize the constant parameters of the motor and the optimization technique parameters, see Table 1 and Table 2.

The upper and lower limits of the optimization variables and their obtained optimum values after optimization are listed in Table 3. Other characteristics of the optimized motor are listed in Table 4.

Table 1

List of constant parameters and their values

| | | | |
|---|---|---|---|
| $k_f$ | 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 | $\rho_m\,(kg\ m^{-3})$ | 7400 |
| $\delta$ | 5 | $\rho_w\,(kg\ m^{-3})$ | 8900 |
| $B_r(T)$ | 1 | $\rho_v\,(kg\ m^{-3})$ | 7700 |
| $B_{sy}^{knee}(T)$ | 1.5 | $c_{m1}(\Im\ kg^{-1})$ | 20 |
| $\kappa(A^2 m^{-3})$ | $10^{11}$ | $c_{m2}(\Im)$ | 1 |
| $n$ | $1.92^a$ | | 0.045 |
| $\gamma$ | 1 | $c_2(\Im\ kg^{-1})$ | 5.42 |
| $w_r^*(rad\ s^{-1})$ | 157 | $T_{em}^*(Nm)$ | 10 |
| $V^*(v)$ | 140 | | |

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TABLE 2
COEFFICIENT VALUES IN THE ICA

| Paramerer | Value |
|---|---|
| $N_{pop}$ | 50 |
| $N_{imp}$ | 12 |
| $\gamma$ | 0.4 |
| $\zeta$ | 0.1 |
| $\beta$ | 20 |
| Max iteration | 100 |

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TABLE 3
OPTIMIZATION VARIABLES

| Parameters | Min | Max | ICA-BLDC |
|---|---|---|---|
| $P$ | 1 | 6 | 5 |
| $\beta$ | 0.5 | 1 | 0.6912 |
| $l_m$ | 0.001 | 0.015 | 0.0120 |
| $l_y$ | 0.002 | 0.01 | 0.0081 |
| $l_w$ | 0.001 | 0.0055 | 0.0033 |
| $l_g$ | 0.001 | 0.004 | 0.0010 |
| $r_r$ | 0.005 | 0.1 | 0.0592 |
| $l_s$ | 0.006 | 0.6933 | 0.0730 |
| $A_c$ | 0.1 | 2 | 1.9951 |
| $J_{cu}$ | $3\times10^6$ | $6\times10^6$ | 5.8198 e+ 06 |

TABLE 4
CHARACTERISTICS OF THE OPTIMIZED MOTOR

| Specification | Vlaue |
|---|---|
| $V_t$ | 0.0011 |
| $Ptotal$ | 51.2446 |
| $P_{cu}$ | 42.1851 |
| $P_h$ | 4.4115 |
| $P_e$ | 2.4500 |
| $P_b$ | 2.1195 |
| $P_w$ | 0.0783 |
| $W_v V_t$ | 0.7891 |
| $W_c C$ | 0.8205 |
| $W_p P_l$ | 1.0248 |
| $W_v V_t + W_c C + W_p P_l$ | 2.6345 |
| $f_o$ | 2.59 |
| Efficiency | 0.9661 |
| Standard | $\pm 0.04$ |
| V (Volt) | 1.3034 e + 02 |
| I (Ampere) | 11.6115 |
| $P_{in}$ | 1513 |
| $P_{out}$ | 1462 |

The variation of each optimization parameters during ICA run is shown in Fig. 3. It can be observed that after 200 iterations, all the parameters are stables and reach to their optimum value. Therefore, it is shown that the ICA has a good speed for convergence. This fact can be seen from Fig. 4. This figure has shown the "Eligibility Criteria" in 5 different runs. In addition, it can be found that the proposed optimization procedure is stable and can solved the optimization problem satisfactory and without computational burden in each run.

### 4.2 Effects of the parameters of the ICA on the performance of the method

In this subsection we have analyzed the sensitivity of the proposed method with respect to the $N_{imp}, N_{pop}, \beta, \xi$ and $\gamma$, which control the behavior, and thus, the goodness of the ICA search process. The achieved results for 10 set of parameters are shown in Table 5. The average of best obtained value is depicted in table. It illustrates that this hybrid system have a little dependency on variation of the parameters.

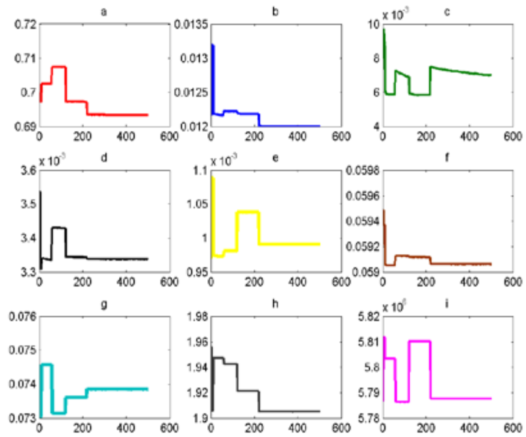


Fig 3. Variation of each optimization parameters during ICA run

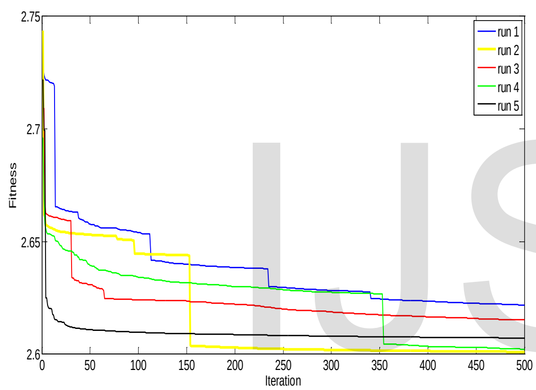


Fig 4. Eligibility Criteria in 5 different runs

TABLE 5
PERFORMANCE OF PROPOSED METHOD (ICA-BLDC) FOR DIFFERENT VALUES OF PARAMETERS

| $N_{imp}$ | $\beta$ | $\xi$ | $\gamma$ | $f_o$ |
|---|---|---|---|---|
| 12 | 25 | 0.5 | 0.6 | 2.71 |
| 10 | 25 | 0.1 | 0.4 | 2.69 |
| 8 | 25 | 0.05 | 0.2 | 2.74 |
| **12** | **20** | **0.1** | **0.4** | **2.59** |
| 10 | 20 | 0.5 | 0.8 | 2.66 |
| 8 | 20 | 0.05 | 0.6 | 2.68 |
| 10 | 15 | 0.5 | 0.8 | 2.67 |
| 8 | 15 | 0.05 | 0.4 | 2.65 |
| 10 | 10 | 0.1 | 0.8 | 2.62 |
| 8 | 10 | 0.05 | 0.6 | 2.65 |

### 4.3 Comparison with genetic algorithm

In order to compare the performance of ICA with another nature inspired algorithms, we have used genetic algorithm (GA) [17], to evolve the proposed method. According to results in Tables 6 and 7, the best performance obtained by ICA is 2.59. It can be seen that the success rates of ICA is higher than the performance of GA [17].

TABLE 6
OPTIMIZATION VARIABLES

| Parameters | Min | Max | GA-BLDC |
|---|---|---|---|
| $P$ | 1 | 6 | 5 |
| $\beta$ | 0.5 | 1 | 0.70 |
| $l_m$ | 0.001 | 0.015 | 0.013 |
| $l_y$ | 0.002 | 0.01 | 0.006 |
| $l_w$ | 0.001 | 0.0055 | 0.0035 |
| $l_g$ | 0.001 | 0.004 | 0.001 |
| $r_r$ | 0.005 | 0.1 | 0.0595 |
| $l_s$ | 0.006 | 0.6933 | 0.0756 |
| $A_c$ | 0.1 | 2 | 2 |
| $J_{cu}$ | $3\times10^6$ | $6\times10^6$ | 5800000 |

## 5 CONCLUSION

In this paper a new technique for the design optimization of slotless BLDC motors with surface magnet structure has been presented considering torque, maximum speed, voltage, losses and cost. An objective function has been proposed covering the power losses, material cost and volume of the motor besides the mechanical and electrical requirements. This method is based on capability of population-based optimization algorithms in finding the optimal solution. For this purpose we have considered GA and ICA. Unlike the GA, the ICA has no complicated evolutionary operators such as crossover, roulette wheel and mutation. After the design optimization of a given slotless BLDC motor using optimization algorithms, some conclusions can be drawn.

As well known, both exploration and exploitation are necessary for the population-based optimization algorithms. In practice, the exploration and exploitation contradict with each other, and in order to achieve good optimization performance, the two abilities should be well balanced. The superior performance of the ICA is due to its ability to simultaneously refine a local search, while still searching globally. It can do this because of the information exchange between the top eggs and the exploration globally due to the abandoning of nests and search via Immigration. Second, simulation results illustrate that ICA have a little dependency on variation of the parameters. Third concerning the computational efforts, ICA was very fast, requiring a few seconds to find the optimum. The results have been analyzed and showed the efficacy of the proposed technique for design of electrical machineries.

TABLE 7
COMPARISON BETWEEN ICA AND GA

| Parameters | GA | ICA | Is ICA better than GA? |
|---|---|---|---|
| $V_t$ | 0.00164 | 0.0011 | ✓ |
| $Ptotal$ | 56.71 | 51.2446 | ✓ |
| $P_{cu}$ | 44.81 | 42.1851 | ✓ |
| $P_h$ | 6.18 | 4.4115 | ✓ |
| $P_e$ | 3.52 | 2.4500 | ✓ |
| $P_b$ | 2.12 | 2.1195 | ✓ |
| $P_w$ | 0.08 | 0.0783 | ✓ |
| $W_v V_t$ | 0.776 | 0.7891 | ✓ |
| $W_c C$ | 0.861 | 0.8205 | ✓ |
| $W_p P_l$ | 1.136 | 1.0248 | ✓ |
| $W_v V_t + W_c C + W_p P_l$ | 2.773 | 2.6345 | ✓ |
| $f_o$ | 2.78 | 2.59 | ✓ |

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