Computational Research Progress in Applied Science & Engineering

ISSN 2423-4591

CRPASE Vol. 03(03), 109-114, September 2017

A New Method for Optimal Design of Slotless Permanent Magnet BLDC Motor with Surface Mounted Magnets Using Modified Social Spider Algorithm

Abotaleb Noori*, Naser Noruzi

Department of Electrical Engineering, Minoodasht Branch, Isalmic Azad University, Minoodasht, Iran

Keywords

BLDC motor,
Modified social spider algorithm,
Power losses,
Evolutionary algorithms.

Abstract

In this paper, a new method based on the evolutionary algorithms is proposed for optimal design of a slotless permanent magnet brushless DC (BLDC) motor with surface mounted magnets. BLDC motor is the ideal choice for applications that require high reliability, high efficiency, and high power-to-volume ratio. These motors are widely used in sensitive applications such as medical instruments, space crafts and submarines. In these applications having high efficiency, minimum volume and cost are very important. So, in this paper, the objective function of design is presented considering efficiency, volume and cost, simultaneously. The modified social spider algorithm (MSSA) is one of the newest evolutionary algorithms whose capabilities have been proved in solving complicated optimization problems. The MSSO algorithm must find the optimal value of geometric parameter of motor including number of pole pairs, cross sectional area of wire, pole–arc per pole–pitch ratio, magnet thickness, stator/rotor core thickness, winding thickness, mechanical air gap, rotor radius, current density, wire gauge and stator/rotor axial length to minimize the power losses, volume and cost. The simulation results show that the proposed method has excellent performance in slotless permanent magnet BLDC design.

1. Introduction

BLDC motors are coming of age due to continuous improvement in high energy permanent magnet materials, power semiconductor and digital integrated circuits. In any application requiring an electric motor where the space and weight are at a premium, the BLDC motors becomes the ideal choice. A BLDC motor has high power to mass ratio, good dissipation characteristics and high speed capabilities. Limitations of brushed DC motors overcome by BLDC motors include lower efficiency, susceptibility of the commutator assembly to mechanical wear, consequent need for servicing, less ruggedness and requirement for more expensive control electronics. Due to their favorable electrical and mechanical properties, BLDC motors are widely used in servo applications such as automotive, aerospace, medical field, instrumentation areas, electromechanical actuation systems and industrial automation requirements [1-4].

Considering the application filed of BLDC motor, it is very important that this type of motor has maximum efficiency or minimum power loss, minimum volume and minimum cost. The optimal design of BLDC motor is a nonlinear and complicated optimization problem with numerous variables and limitations. Furthermore, it is a non-differential problem, so classical methods that use gradient information could not be used. During the recent years, various evolutionary algorithms such as genetic algorithm (GA) inspired by the Darwinian law of survival of the fittest, particle swarm optimization (PSO) inspired by the social behavior of bird flocking or fish schooling, bee's algorithm (BA) inspired by the foraging behavior of bee's, and Biogeography-Based Optimization (BBO) inspired by the migration behavior of island species have been presented for solving the nonlinear-non-differential optimization problem.

In recent years, several researchers have used evolutionary algorithms in optimal design of electrical machines [5-11]. Upadhyay and Rajagopal [5] have proposed a GA-based optimal design of a permanent magnet BLDC motor considering efficiency as the objective function and motor weight and temperature rise as the constraints [5]. Rahideh et al. [6] have used genetic algorithm for the optimal design of BLDC motor considering power loss, volume and cost. Cvetkovski et al. [7] have proposed a new method to single phase permanent magnet brushless DC motor optimal design by using a genetic algorithm. The objective function

* Corresponding Author:
E-mail address: abtlb.noori@gmail.com – Tel, (+98) 9155475732

Received: 12 June 2017; Accepted: 10 September 2017

of the optimization search is selected to be the efficiency of the motor and the design process is defined as a maximization problem. Based on the values of some specific motor parameters, a comparative analysis of the improved motor and the initial motor design is performed. As an addition to the comparative analysis, a Finite Element Method modeling and analysis of both models is also performed. Rao and Othman [8] have investigated the application of GA and simulated annealing techniques for optimal design and analysis of a brushless DC motor is investigated.

Umadevi et al. [9] have depicted an enhanced particle swarm optimization (PSO) algorithm for the design of BLDC motor. The algorithm is applied to shape optimization of a 120W BLDC motor using a multi objective optimization problem. The objectives have been the maximization of average torque and minimization of cogging torque in the BLDC motor, magnet length, air gap and stator slot opening are considered as the design variables. The results obtained using the PSO algorithm have indicated that it is capable of giving better design solutions when compared and investigated with those obtained from GA and finite element analysis. Fang et al. [10] have used an improved magnetic equivalent circuit (MEC) to calculate the nonlinear magnetic field in an interior-type permanent-magnet (IPM) BLDC motor. The PSO algorithm is then employed to refine the design for optimal structural parameters that result in the lowest cost and highest performance [10]. Shabanian et al. [11] have applied BA for the optimal design of BLDC motor and the performance of proposed method is compared with other algorithms such as bat algorithm [11].

It is well known that both exploration and exploitation are necessary for the population-based optimization algorithms, such as GA, PSO, and so on. In these optimization algorithms, the exploration refers to the ability of investigating various unknown regions in the solution space to discover the global optimum. While, the exploitation refers to the ability of applying the knowledge of the previous good solutions to find the better solutions [12]. 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 results presented in [13, 14] show that the SSA is capable of providing superior results compared to many previously proposed metaheuristic techniques.

MSSA is one of the most powerful optimization algorithms having the exploration and exploitation capabilities simultaneously [15]. So, in this paper, we proposed the application of MSSA for the optimal design of slotless permanent magnet BLDC motor. The rest of paper is organized as follow. The second section briefly describe the optimization algorithm and introduce the proposed method. Section three present some simulation results and finally section four concludes the paper.

2. Proposed Method

In this paper, a new method for the optimal design of a slotless permanent magnet BLDC motor with surface mounted magnets using SSO has been presented considering torque, power, maximum speed, voltage, losses and cost. The proposed objective function is formed by a set of geometrical variables such as, number of pole pairs (p), cross sectional area of the winding (A_c), pole–arc per pole–pitch ratio (β), magnet thickness (l_m), stator/rotor core thickness (l_y), winding thickness (l_w), mechanical air gap (l_g), rotor radius (r_r), current density (J_{cu}), wire gauge and stator/rotor axial length (l_s), which is usually represented by the machine form factor (λ). More details regarding the BLDC motor geometrical variables can be found in Rahideh et al. [6].

The SSA algorithm is based on the simulation of cooperative behavior of social-spiders. In the SSO algorithm, individuals emulate a group of spiders which interact to each other based on the biological laws of the cooperative colony. The algorithm considers two different search agents (spiders): males and females. Depending on gender, each individual is conducted by a set of different evolutionary operators which mimic different cooperative behaviors that are typically found in the colony. The MSSA is the same as the original SSA except that the binary mask based random walk used to generate new solutions for the next iteration has been replaced with the new mutation process, after which a selection process is applied. More details about MSSA algorithm can be found in [15].

An objective function has been proposed covering the power losses, material cost and volume of the motor simultaneously, besides the mechanical and electrical requirements. In addition to these criteria, other objectives may be considered such as cogging torque minimization, vibration reduction, magnetic flux leakage and leakage inductance minimization. Generally, inclusion some of these criteria in the formulas is not convenient and a structural modification to the motor is required. For instance, cogging torque is almost eliminated in the slotless configuration against slotted structure of BLDC motors. Also, an increment in the accuracy of fabrication procedure reduces the vibration. Therefore, the most important and common criteria are loss, cost and mass which are considered in the present work.

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 needed to be optimally found, should be represented as a vector as

$$Spider = \left[P \ \beta \ l_m \ l_y \ l_w \ l_g \ r_r \ \lambda \ A_c \ J_{cu}\right] \quad (1)$$

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

$$f_o(x) = \omega_V V_t(x) + \omega_P P_{total}(x) + \omega_C C(x) \quad (2)$$

where, ω_P, ω_V and ω_P are weighting factors, V_t is the volume of motor, P_{total} is the total power loss of motor and C is the total cost of the materials used in the motor design.

The electrical requirement is the level of voltage source for the motor, V^*. This constraint is satisfied by a proper choice of the wire gauge for the BLDC motor windings.

Besides, the mechanical specifications can be represented by a set of inequality constraints, such as

$$T_{em} > T_{em}^{*} \tag{3}$$

$$\omega_r^{max} \geq \omega_r^{*} \tag{4}$$

where, T_{em}^{*}, ω_r^{*} and ω_r^{max} are required torque, required rotational speed, and the maximum speed at the required torque, respectively.

4. Simulation Results

4.1. Motor Constant

In this section, we evaluate the performance of proposed method. The computational experiments for this section were done on Intel core i7 Duo with 16 GB RAM using ASUS computer. The computer program was performed on MATLAB (version 8.5.0.197613 [R2015a], Massachusetts, USA) environment. To solve the optimization problem, one needs to initialize the constant parameters of the motor and the optimization technique parameters (see Table 1).

Table 1. Motor constants [6]

k_f	0.7	ω_P	0.02
k_c	0.666	ω_V	666
k_s	0.95	ω_C	0.0125
k_r	1	$\rho_m(kg\ m^{-3})$	7400
δ	5	$\rho_w(kg\ m^{-3})$	8900
$B_r(T)$	1	$\rho_y(kg\ m^{-3})$	7700
$B_{sy}^{knee}(T)$	1.5	$T_{em}^{*}(Nm)$	10
ρ(Ωm)	1.8×10^{-8}	$\omega_r^{*}(rad\ s^{-1})$	157
$V^{*}(v)$	140	γ	1
n	1.92^{a}	$\kappa(A^2m^{-3})$	10^{11}

4.2. Performance of the proposed method

In this section the performance of proposed method is investigated. In each optimization algorithm, control parameters have important role on its performance. In MSSA algorithm, parameters such as number of spiders, number of male spiders, number of female spiders etc. must be determined carefully. The parameters of MSSA are listed in Table 2. This values are selected after extensive simulation and based on the best answer.

Table 2. MSSA parameters

Parameter	Value
Spider number (N)	70
N_f	55
N_m	15
α_0	2.5
β_0	2
δ_0	3
Max iteration	100

The obtained optimum values after optimization are listed in Table 3. Other characteristics of the motor are listed in Table 4, where P_{out} is the output power of the motor.

Table 3. Optimum value of the motor geometric parameters

Parameters	Optimal value
P	5
β	0.6926
l_m	0.0121
l_y	0.0082
l_w	0.0033
l_g	0.0010
r_r	0.0592
$1/\lambda\ or\ l_s$	0.073
A_c	1.9954
J_{cu}	5.8132×10^{6}

Table 4. Characteristics of the optimized motor using SSO

V_t	0.0011
C	65.64
P_{total}	51.052
P_{cu}	42.1821
P_h	4.4114
P_e	2.4500
P_b	2.1195
P_w	0.0782
$\omega_V V_t$	0.789
$\omega_C C$	0.8205
$\omega_P P_{total}$	1.0233
$\omega_V V_t + \omega_P P_{total} + \omega_C C$	2.6211
Efficiency	96.67
standard	±0.01
V (Volt)	130.34
I (Ampere)	11.6115
Input power	1513
Output power	1463

The convergence of MSSA is shown in Figure 1. Also, the variation of each optimization parameter during MSSA run is shown in Figures 2 and 3. It can be observed that after 47 iterations, all the parameters are stables and reach to their optimum value. Therefore, it is shown that the MSSA has a excellent speed for convergence. In Figure 4, the performance of MSSA is shown in different runs. It can be seen that MSSA has robust performance in different runs.

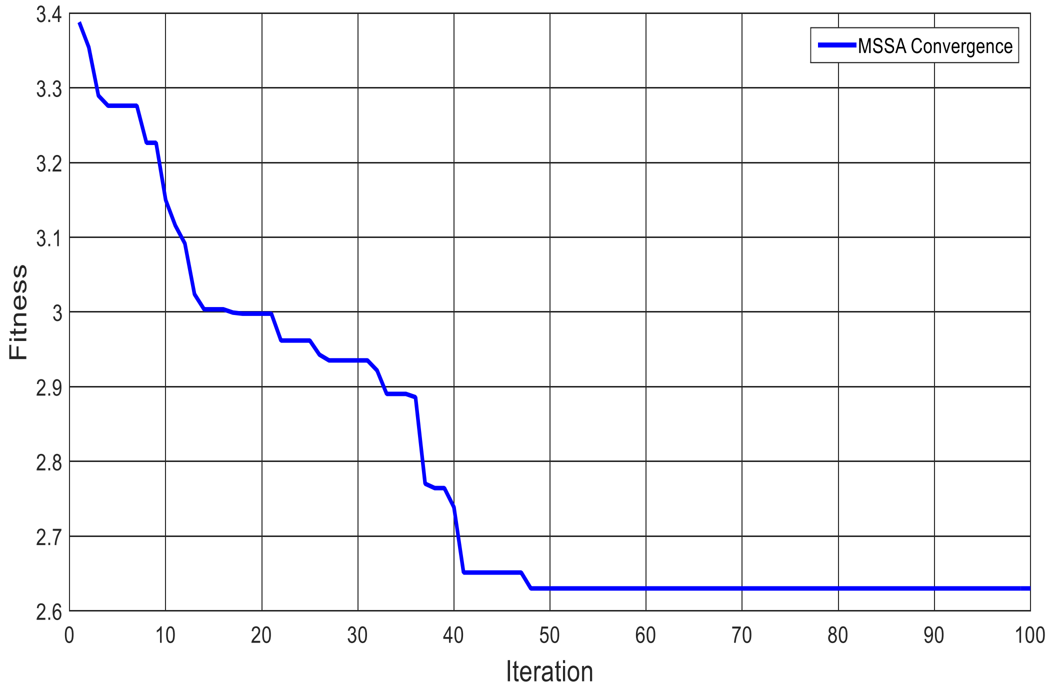

Figure 1. Convergence of MSSA

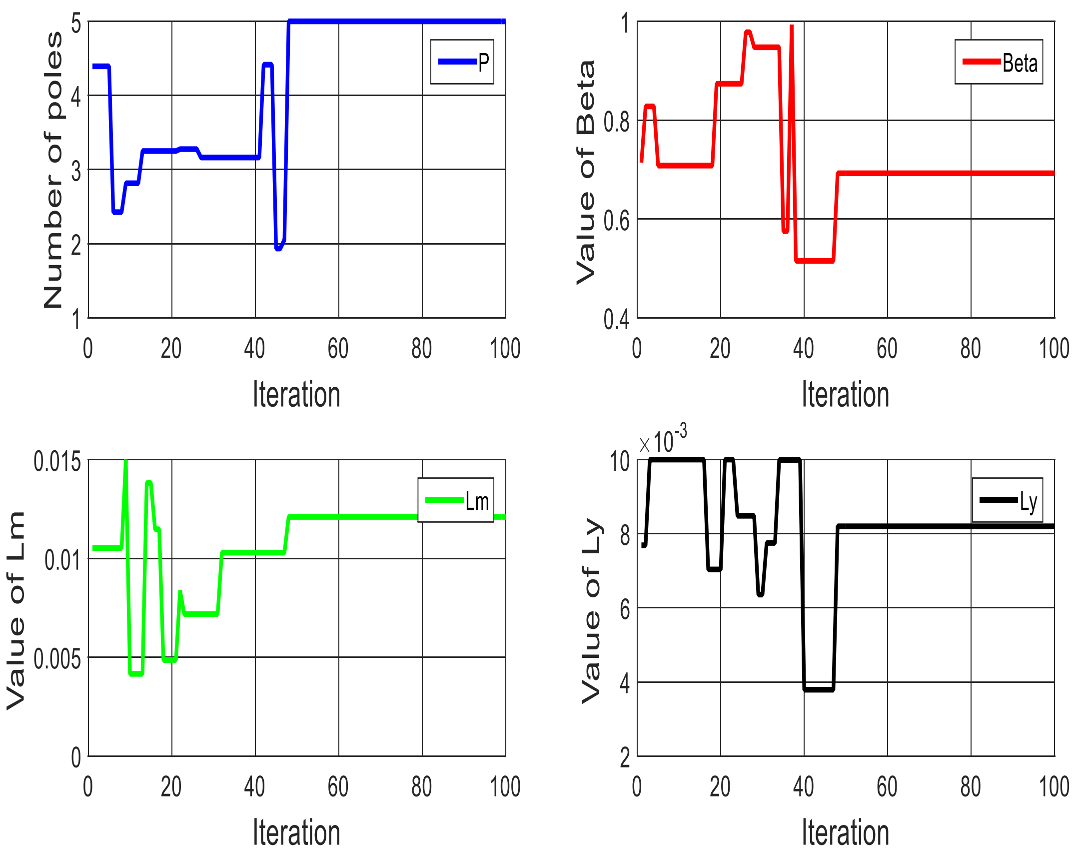

Figure 2. Convergence of 1st,2nd, 3rd and 4th geometric parameter during optimization

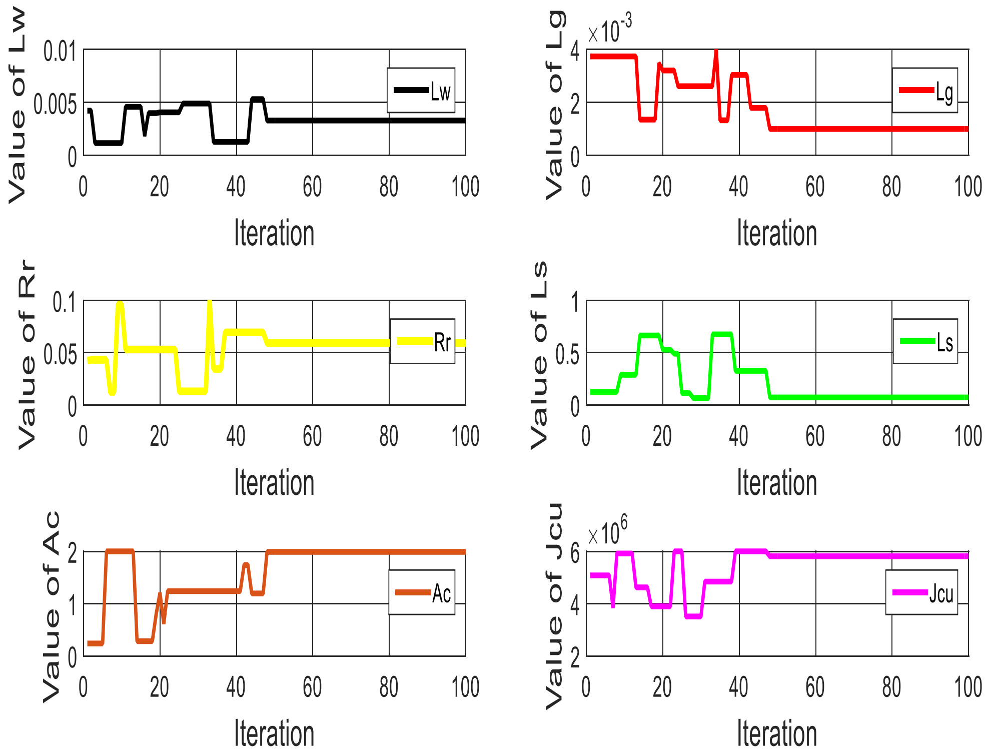

Figure 3. Convergence of 5th, 6th, 7th, 8th, 9th and 10th geometric parameter during optimization

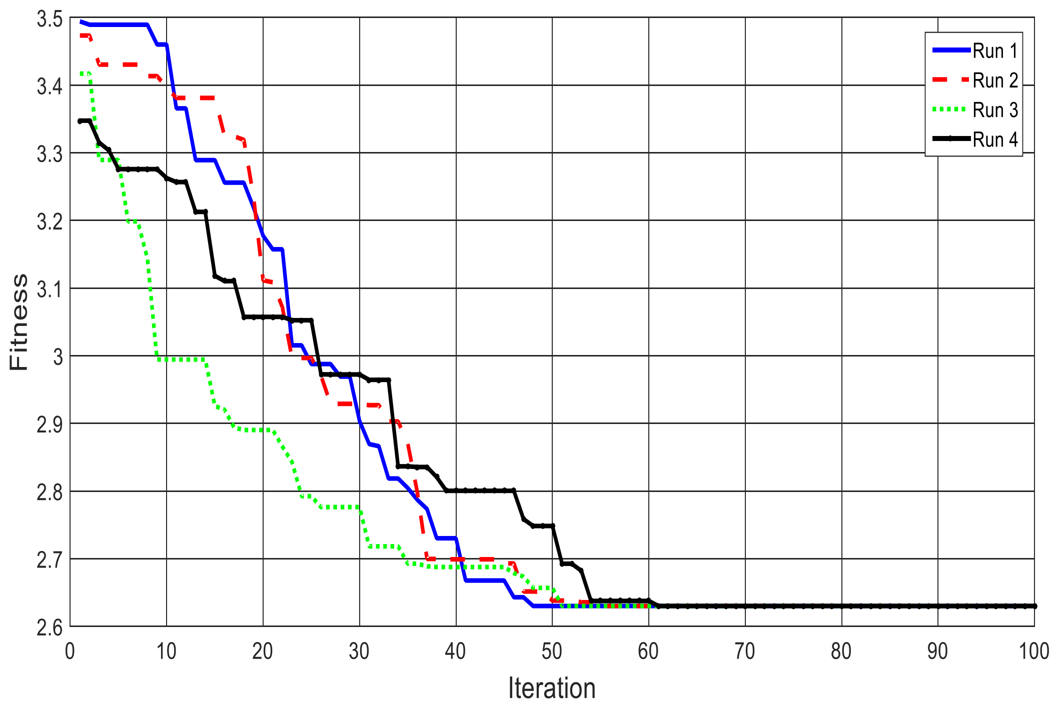

Figure 4. The performance of MSSA in different runs

4.3. Comparison with Other Methods

In order to compare the performance of MSSA with another nature inspired algorithms, we have used SSA, genetic algorithm (GA) [6], chaotic bat algorithm (CBA) [11] and bees algorithm [11] to evolve the proposed method. The SSA, GA, CBA and BA results have been shown in Table 5. In this table, the value of fitness function, standard deviation nad the needed iteration to obtain the optimal value are listed. The standard deviation is calculated for 50 different runs. According to results in Table 5, the best performance obtained by MSSA-BLDC is 2.6211. It can be seen that the success rates of MSSA is higher than the performance of other methods.

Table 5. Performance of different method for BLDC motor design

Method	f_o	Standard deviation	Needed iteration
SSA	2.6902	±0.04	128
GA	2.773	±0.1	250
CBA	2.6942	±0.07	179
BA	2.6345	±0.03	90
MSSA	**2.6211**	±0.01	**47**

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 nature based optimization algorithms in finding the optimal solution. For this purpose we have considered MSSA, SSA, GA, CBA and BA. Unlike the other nature based optimization algorithms, the MSSA 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 SSO 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 MSSA have a little dependency on variation of the parameters. Third concerning the computational efforts, MSSA 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.

References

[1] K. Premkumar, B.V. Manikandan, Adaptive Neuro-Fuzzy Inference System based speed controller for brushless DC motor, Neurocomputing 138 (2014) 260–270.

[2] Y. He, S. Zheng, J. Fang, Start-up current adaptive control for sensorless high-speed brushless DC motors based on inverse system method and internal mode controller, Chinese Journal of Aeronautics 30 (2017) 358–367.

[3] H. Liu, H. Zhang, A novel direct torque control method for brushless DC motors based on duty ratio control, Journal of the Franklin Institute 354 (2017) 4055–4072.

[4] M. Bahreini, M. Maghfoori Farsangi, K. Lee, Output Feedback Stabilization of Networked Brushless DC Motor with Random Delay via Markovian Jump Systems. IFAC-PapersOnLine 48 (2015) 55–60.

[5] P.R. Upadhyay, K.R. Rajagopal, Genetic algorithm based design optimization of a permanent magnet brushless DC motor, Journal of Applied Physics 97 (2005)

[6] A. Rahideh, T. Korakianitis, P. Ruiz, T.Keeble, M.T. Rothman, Optimal brushless DC motor design using genetic algorithms, Journal of Magnetism and Magnetic Materials 322 (2010) 3680–3687

[7] G. Cvetkovski, P. Lefley, L. Petkovska, S. Ahmed, Optimal design of a novel single phase PM BLDC motor using Genetic Algorithm. 15th International Power Electronics and Motion Control Conference (EPE/PEMC) (2012).

[8] K. Rao, A. Othman, Design optimization of a BLDC motor by Genetic Algorithm and Simulated Annealing. International Conference on Intelligent and Advanced Systems (2007).

[9] N. Umadevi, M. Balaji, V. Kamaraj, Design optimization of brushless DC motor using Particle Swarm Optimization. IEEE 2nd International Conference on Electrical Energy Systems (ICEES) (2014).

[10] X. Fang, S. Wang, J. Qiu. J. Guo Zhu, Y. Guo, X. Yang, J. H. Ha, Z. W. Yingke Sun, J. Zhang, Design optimization of an interior-type permanent magnet BLDC motor using PSO and improved MEC. International Conference on Electrical Machines and Systems (ICEMS) (2007).

[11] A. Shabanian, A. Amini Poustchi Tousiwas, M. Pourmandi, A. Khormali, A. Ataei, Optimization of brushless direct current motor design using an intelligent technique, ISA Transactions 57 (2015) 311–321.

[12] G. Zhu, S. Kwong, Gbest-guided artificial bee colony algorithm for numerical function optimization, Applied Mathematics and Computation 217 (2010) 3166–3173

[13] J.J.Q. Yu, V.O.K. Li, A social spider algorithm for solving the non-convex economic load dispatch problem, Neurocomputing 171 (2016) 955–965.

[14] E. Cuevas, M. Cienfuegos, D. Zaldvar, M. Pérez-Cisneros, A swarm optimization algorithm inspired in the behavior of the social-spider, Expert Systems with Applications 40 (2013) 6374–6384.

[15] W.T. Elsayed, Y.G. Hegazy, F.M. Bendary, M.S. El-bages, Modified social spider algorithm for solving the economic dispatch problem, Engineering Science and Technology, an International Journal 19 (2016) 1672–1681.