Cuckoo Search as a Tool for Optimal Design of PM Brushless DC Motor

Goga Cvetkovski, Lidija Petkovska, Paul Lefley

Structured Abstract:

Purpose – The purpose of this paper is to provide an optimal design of a single-phase permanent magnet brushless DC motor (SPBLDCM) using the efficiency of the motor as an objective function. In the design procedure of the motor, a Cuckoo Search (CS) algorithm as an optimization tool was used.

Design/methodology/approach – For the purpose of this research work a computer program for the optimal design of electrical machines based on the Cuckoo Search optimization has been developed. Based on the design characteristics of SPBLDCM, some of the motor parameters are chosen to be constant and others variable. A comparative analysis of the initial motor model and the CS model based on the value of the objective function, as well as the values of the optimization parameters, was performed and is presented.

Findings – Based on the comparative data analysis of both motor models, it can be concluded that the main objective of the optimization is realized, and it is achieved by an improvement in the efficiency of the motor.

Practical implications – The optimal design approach realized on SPBLDCM and presented in this research work can be also implemented on other electrical machines and devices using the same or even other objective functions.

Originality/value – An optimization technique using CS as an optimization tool has been developed and applied in the design procedure of SPBLDCM. According to the results it can be concluded that the CS algorithm is a very suitable tool for design optimization of SPBLDCM and electromagnetic devices in general. The quality of the CS model has been proved through the data analysis of the initial and optimized solution. The quality of the CS solution has been proved by comparative analysis of the two motor models using FEM as a performance analysis tool.

Keywords: Design optimisation; Finite element analysis; Optimal design; Cuckoo search; Permanent magnet machine.

Article Classification: Research paper

Running Heads:

I. Introduction

Efficiency improvement in general, as well as efficiency improvement of electrical machines has become of wide interest to researchers and designers, due to the issues of electricity prices in a very competitive market. During the past few years, many different techniques, approaches and optimisation algorithms have been implemented in the design procedures for a wide variety of electrical machines. The optimisation process of an electric motor can be realized by implementing a wide range of objective functions that are known in the research community. The objective function can be a specific property of the machine that can be optimised, for example efficiency, torque, volume, weight or cost (Lee *et al.*, 2009), (Kwack *et al.,* 2010), (Yamazaki and Ishigami *et al.,* 2010),(Yang and Chuang, 2007) There is also a possibility that the objective function of the optimal design can be defined as a multi-objective function (Nabeta *et al.*, 2008), (Le Besnerias *et al.,* 2008), (Ashabani and Mohamed *et al.*, 2011), (Luizzi *et al.*, 2003), (Jannot *et al.* 2011), (Parasiliti *et al.,* 2012). The research work in this paper is focused on the optimal design of a motor using efficiency as the objective function.

Generally speaking, the optimal design of electrical machines can be defined as a constrained maximization or minimization problem with a significant number of optimization parameters and a variety of constraints. Therefore, the optimal design of an electrical machine becomes a difficult problem to be solved using deterministic methods. On the other hand it can be quite an easy task for the stochastic methods such as: Genetic Algorithms (GA) (Zhao *et al.,* 2014), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO) and other swarm inspired optimization methods. Recently another method has been drawing attention to the research and optimization community. This method is known as Cuckoo Search (CS). Described in this paper, this method was implemented in an optimal design algorithm of a single-phase permanent magnet brushless DC motor (PMBDCM) using efficiency as the objective function. Comparative analysis of the optimal motor solution based on the objective function value, as well as the values of other important parameters in relation to the initial model is presented.

II. Cuckoo Search Optimization of PMBDCM

A. Cuckoo Search Introduction

The Cuckoo Search is a metaheuristic search algorithm which has been proposed recently by (Yang and Deb, 2010). The algorithm is inspired by the reproduction strategy of the cuckoo birds. As mentioned previously at the most basic level, cuckoos (Payne *et al.*, 2005) lay their eggs in the nests of other host birds, which may be of a different species. The host bird may discover that the eggs are not their own and either destroy the egg or abandon the nest all together. This has resulted in the evolution of the cuckoo eggs which mimic the eggs of local host birds.

The authors defined the CS algorithm by setting three rules that idealize the behaviour of cuckoo birds in order to become appropriate for implementation as a computer algorithm:

- Each cuckoo lays one egg at a time, and places it in a randomly chosen nest.
- The best nests with high-quality eggs will be carried over to the next generations.
- The number of available host nests is fixed and the egg laid by a cuckoo may be discovered by the host bird with a probability $p_s \in (0, 1)$. In this case, the host bird can either get rid of the egg, or simply abandon the nest and build a completely new nest at some other location.

Based on the rules presented previously, the CS can be implemented in practice as follows. Each egg in a nest represents a possible solution to the investigated problem. Therefore, each cuckoo bird can lay only one egg into a nest in the original form although each nest can have multiple eggs representing a set of solutions, in general. The main millstone of CS is to generate new and potentially better solutions that will replace the worse solutions in the current nest population. The quality of solutions is evaluated with the objective function that is defined for each problem separately.

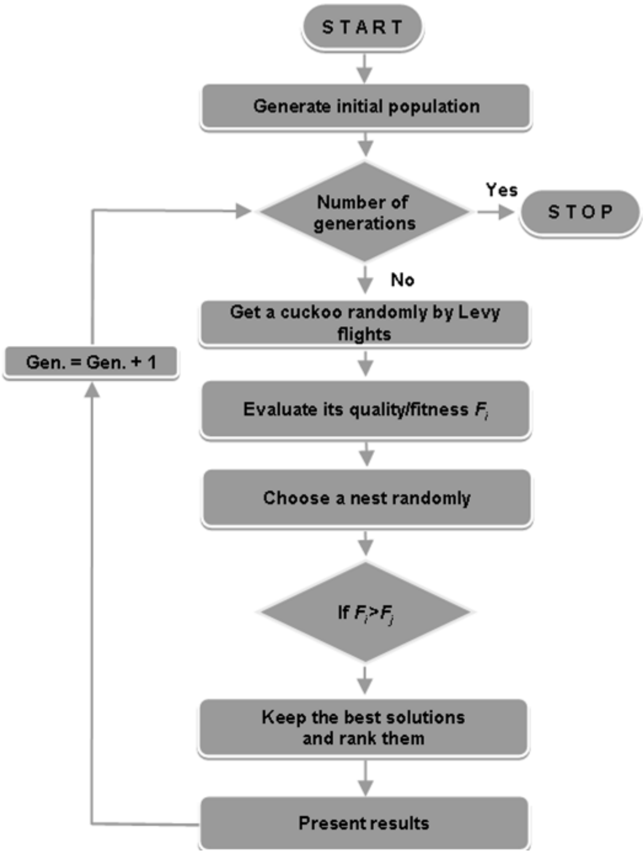

Fig. 1. Main steps of the CS-ODEM computer program

Furthermore, the last rule is approximated by an additional parameter p_s named the switching probability that determines when the worst of the n host nests is replaced by a new randomly generated nest. In fact, this parameter balances two components of the CS process, i.e., exploration and exploitation. This means that while the *exploration* process succeeds in enabling the algorithm to reach the best local solutions within the search space, the *exploitation* process expresses the ability to reach the global optimum solution which is likely to exist around the local solutions obtained. A metaheuristic algorithm must be able to rapidly converge to the global optimum solution of the related objective function. A flow chart representation of the CS-ODEM programme, used for the optimal design of the single-phase brushless DC motor, is presented in Fig. 1.

B. Permanent Magnet Brushless DC Motor Description

The goal of the optimal design of a single phase brushless DC motor is to obtain a motor with maximised efficiency while satisfying certain performance, magnetic and geometric constraints. The optimal design of the motor is performed on a previously defined topology of the single-phase brushless DC motor (Ahmed and Lefley, 2011) with rated voltage, 300 V, and speed, 1500 rpm. The single phase brushless DC motor is a four-pole motor with concentrated windings mounted on each asymmetrical stator pole. The motor also has 4 symmetrical permanent magnets with B_r=1.13 T mounted on the rotor. A cross-section representation of the motor is shown in Fig. 2. It should be mentioned that the motor has an asymmetrical air gap, which is made by reshaping the small stator poles, and the permanent magnets that are mounted on the surface of the rotor core.

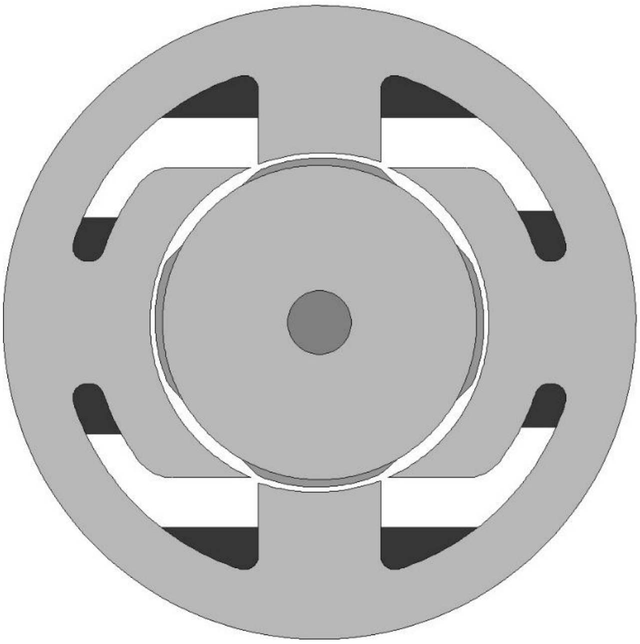

Fig. 2. Permanent magnet brushless DC motor representation

C. PMBDCM Optimization

Due to the specific geometry of the motor for this optimal design procedure, the following geometrical parameters of the motor are selected as design variables: outside radius of the rotor iron core **R_{ro}**, permanent magnet radial length **l_m**, air-gap between the rotor PM and stator poles **g**, opening between the stator poles **b_{so}**, axial length of the motor **L**, and radius of the stator winding single wire **r_{cu}**. Some of these parameters are presented in Figure 3. The rest of the geometrical parameters are determined as functions of the optimization parameters. The values of the Cuckoo Search parameters that are assigned to all of them are user and problem dependent. The values for this optimal design problem are: number of nests 300, number of variables 6 and number of generations 100.

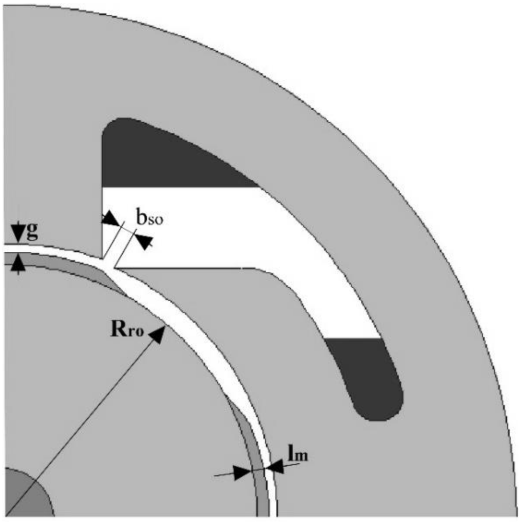

Fig. 3. Optimization motor parameters presentation

Since the Cuckoo Search algorithm is defined as a minimization process, the inverse value of the efficiency of the motor, is defined as an objective function of the optimization and can be presented with the following equation:

$$objective\ function = \frac{1}{efficiency} = \frac{T \cdot \omega_m + P_{Cu} + P_{Fe} + P_s}{T \cdot \omega_m} \tag{1}$$

where: ω_m-synchronous speed, T-rated torque, P_{Cu}-ohmic power loss, P_{Fe}-stator iron core power loss and P_s-other constant losses.

TABLE I. OPTIMISATION CONSTRAINTS

Description	**Parameters**	**Value**
Torque	T (Nm)	6.366
Phase voltage	U_{ph} (V)	300
Number of phases	N_{ph}	1
PM residual flux density	B_r (T)	1.13
Number of permanent magnets	N_m	4
Number of stator slots	Z	4
Stator back iron flux density	B_{mbi} (T)	≤ 1.0
Stator teeth flux density	B_{mst} (T)	≤ 1.0
Stator and rotor steel core specific loss	G_{Fe} (W/kg)	6
Stator conductor resistivity	ρ_{Cu} (Ω m)	$1.75\ 10^{-8}$
Stator steel mass density	ρ_{st} (kg/m^3)	7300
Permanent magnets mass density	ρ_{PM} (kg/m^3)	7400
Rotor steel mass density	ρ_{rot} (kg/m^3)	7850
Copper mass density	ρ_{Cu} (kg/m^3)	8930

Some of the design constraints used in the optimal design of the single-phase brushless DC motor are geometrical, and the other constraints take into account the motor performance and material characteristics. The choice of these constraints has been carefully selected to reduce the number of independent design variables. Some of them are presented in Table I. This is obtained by a steady-state analysis of the motor, which allows the main electrical, magnetic and mechanical quantities, including the set of motor specifications, to be expressed as functions of its dimensions and working conditions.

TABLE II. BOUNDARIES OF OPTIMISATION PARAMETERS

Variables	**Lower boundary**	**Upper boundary**	**Initial model**
R_{ro} (m)	0.0342	0.0418	0.038
l_m (m)	0.0018	0.0022	0.002
g (m)	0.0009	0.0011	0.001
b_{so} (m)	0.002	0.003	0.0023
L (m)	0.0972	0.1188	0.108
r_{cu} (m)	0.0003	0.0005	0.0004

TABLE III. OPTIMISATION COMPARATIVE DATA

Variables	**Units**	**Initial model**	**CS Solution**
R_{ro}	(m)	0.038	0.0418
l_m	(m)	0.002	0.00185
g	(m)	0.001	0.0009
b_{so}	(m)	0.0023	0.00299
L	(m)	0.108	0.1009
r_{cu}	(m)	0.0004	0.0005
Objective function	(/)	1.1334	1.1051
Efficiency	(/)	0.8823	0.9049

The design variables during the optimization process are varied between their predefined lower and upper boundaries that are presented in Table II. The value of each optimization variable is generated randomly within the variable bounds. These values are problem dependent and should be carefully defined before the optimization process. In the case of the optimal design of PMBDCM the prescribed values of the lower and upper boundaries are taken to be 10% less and more than the initial value of each parameter. The values of the optimization parameters, the objective function and the efficiency of the initial model and the Cuckoo Search optimized model are presented in Table III.

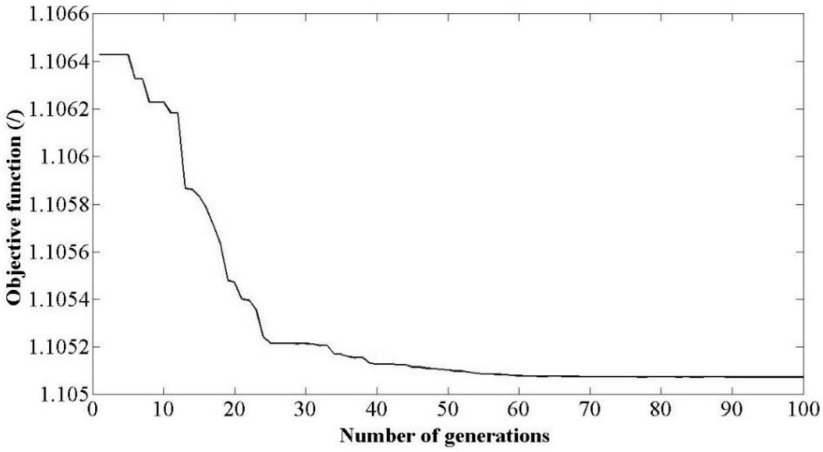

Fig. 4. Objective function change during generations of the CS

TABLE IV. DATA COMPARISON OF PMBDCM INITIAL MODEL AND CUCKOO SEARCH SOLUTION

Parameters	Description	Initial model	CS Solution
Efficiency (/)	Efficiency	0.8823	0.9049
N (/)	No. of turns/coil	648	656
X_n (m)	Gap between the pole shoe and the stator inner radius	0.00757	0.0103
X_c (m)	Stator pole shoe thickness stator back iron thickness	0.014	0.016
X_p (m)	Stator pole width	0.028	0.032
B_g (T)	Air gap flux density	0.3501	0.3122
I_{ph} (A)	Phase current	3.27995	3.4722
R_{ph} (ohm)	Phase resistance	6.9873	5.5742
P_{Cu} (W)	Ohmic losses	91.3825	67.2030
P_{Fe} (W)	Iron losses	32.0648	30.7083

From the presented data, it can be concluded that the efficiency of the CS solution in comparison with the initial model is improved by little more than 2%. The improvement of the value of the motor efficiency from the CS solution in relation to the initial prototype model is as a result of the decrease of the total ohmic power losses in the stator windings of about 26 %. As a result of the reduction of the flux density in all the cross sections of the motor the iron loss in the stator was reduced from 32.0648 W to 30.7083 W and contributed in the improvement of the overall efficiency of the motor. The influence of the change of the stator winding single wire radius on the efficiency of the motor is significant. Also, the change of the PM radial length l_m, as well as the air gap *g* also have an important influence on the change of the other parameters and the efficiency of the motor. It is interesting to notice that some of the parameters change as a result of the variation of some other parameters in order to compensate their change and influence on the efficiency improvement. It can also be noticed that by reducing the radial length of the PMs the number of turns increases and the air gap decreases in order to maintain the rated torque.

An additional investigation of the two models was performed by using Finite Element Analysis (FEA). The Finite Element Analysis in the research work was performed separately on the prototype (initial model) and on the final CS solution for comparison.

III. Finite Element Analysis of PMBDCM

In addition to the two PMBDCM models' analysis, a calculation of the magnetic field of the two models for different loads and rotor positions have been performed (Belahcen, A. *et al.,* 2015). The proposed quasi 3D analysis (Cvetkovski *et al.*, 2000) is very suitable for this type of geometry and has a lot of advantages over the standard 3D calculation, such as lower memory storage and reduced computation time. The quasi 3D calculation consists of standard 2D calculation of the magnetic field, but where the axial length of the motor is also taken into consideration. For the analysis of the two motor models an FE analysis has been performed for different rotor positions and for a certain number of loads. The software used for this performance analysis is called Finite Element Method Magnetics-FEMM (Meeker, 2010). For each segment of the motor an accurate materials library was used in the model. An example of the stator magnetic material magnetization characteristic used for the construction of the prototype of the PMBDCM is presented in Figure 5. Due to a lack of space in this paper only the representations of the magnetic field distribution for the initial and CS models are shown in Fig. 6 and Fig. 7, respectively. The distribution of the magnetic field for both models is presented for only one rotor position where the permanent magnets are aligned with the stator poles.

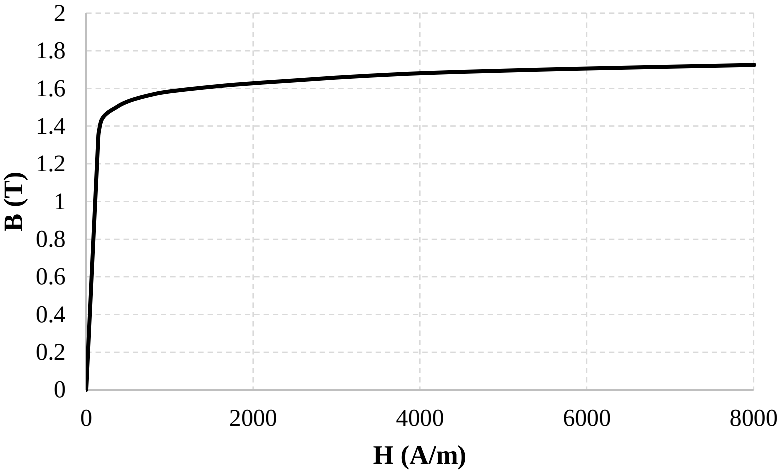

Fig. 5. Objective function change during generations of the CS

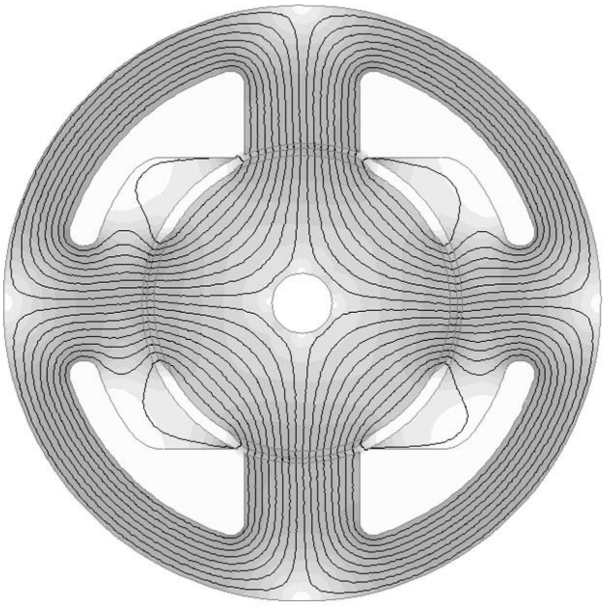

Fig. 6. Magnetic field distribution at no load for the initial model

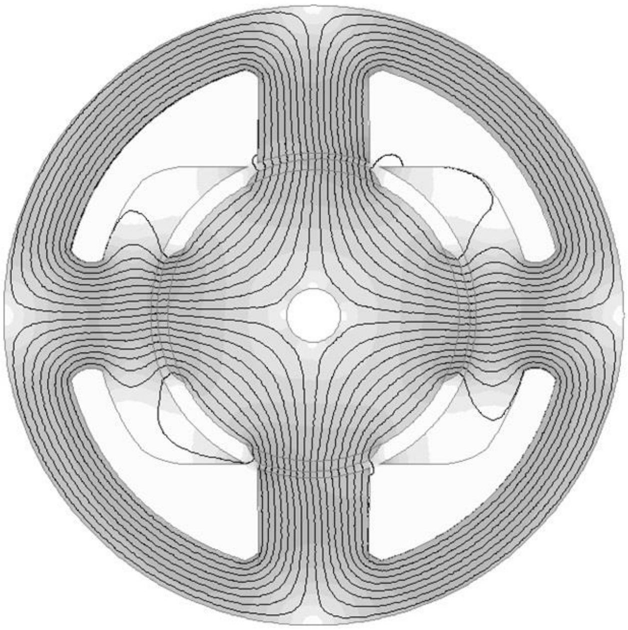

Fig. 7. Magnetic field distribution at no load for the CS model

Air gap Flux Density

In the postprocessor mode of the program using the data from the magnetic field calculation, the value of the air gap flux density in the middle of the air gap can be calculated by using equation (2) and solving it numerically.

$$\mathbf{B} = \text{curl } \mathbf{A} \tag{2}$$

The value of the air gap flux density for the single-phase BLDC motor was calculated for different load currents. As an example, the air gap flux density distribution for the initial and optimized CS model has been determined and presented in Fig. 8 and Fig. 9. respectively.

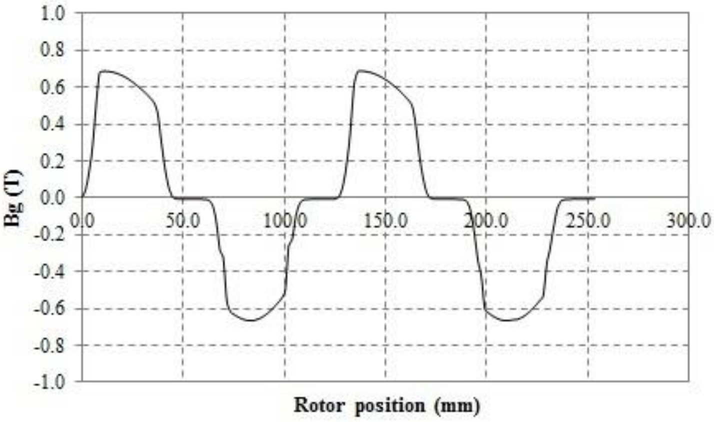

Fig. 8. Air gap flux density distribution at no load for the initial model

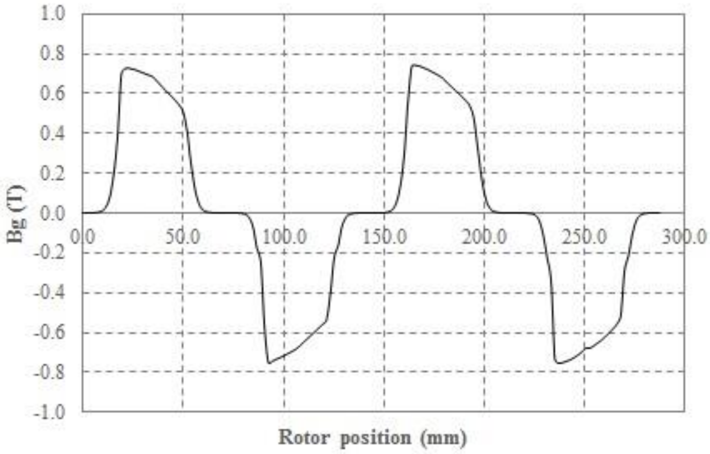

Fig. 9. Air gap flux density distribution at no load for the CS model

Based on the magnetic field analysis of the two motor solutions and the air gap flux density distribution, it is noticeable that the optimized solution has a much better utilization of the magnetic materials in the motor, which is one of the benefits from the optimization. It can be also noticed that the values of the flux density in certain parts of the motor are in good agreement with the predefined values as constraints in the optimization process. This proves that the mathematical model of the motor for the optimization fully describes the physical model of the motor and is in good agreement with the FEMM model. Further investigation will be realized in future concerning the electromechanical characteristics of the motor such as electromagnetic and cogging torques.

Electromagnetic Torque

The electromagnetic torque of the initial and CS solution of the motor was solved in the FEM post processor using an additional Laplace equation, and the *weighting function* computed. The stress tensor was then evaluated as a volume integration and the results displayed. The static electromagnetic torque of the initial motor was calculated at a rated current of 3.28 A, and is presented in Fig. 10. Also, the static electromagnetic torque of the CS solution was calculated at a rated current of 3.47 A, and is presented in Fig. 11. The torque characteristic was evaluated for one half of a rotation, i.e. 180° mechanical or 360° electrical.

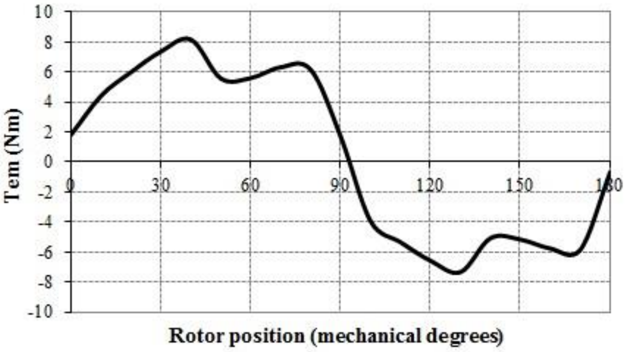

Fig. 10. Electromagnetic torque spanned over a pair of poles (initial model)

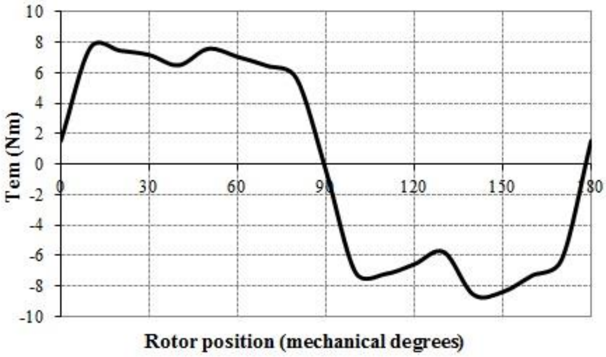

Fig. 11. Electromagnetic torque spanned over a pair of poles (GS model)

The above presented electromagnetic torque distribution for both models shows that not only the efficiency of the motor has been improved, but also the peak value of the torque for the CS model has been increased.

Furthermore, an additional investigation of the whole optimal design process and FE analysis can be realized through a definition of a tentative cost function. The cost function for a certain constraint is a function that, when evaluated on a configuration, returns a measure of how well that constraint is satisfied. This measure is a scalar value that expresses the amount of constraint violation. When we compare two designs and say that one design is better than the other, we are weighing various factors to reach a judgement. The development of cost functions is an attempt to quantify these assessments. The constraints in the cost function can be geometric, indirect geometric and non-geometric. In this sense the cost function for this analysis is defined as:

$$Cost\ function = n_t * n_u * n_f * n_v \tag{3}$$

where: n_t-CS number of iterations, n_u-number of unknown nodes of the finite-element mesh, n_f-number of field simulations for evaluating the values for the torque-angle curve and n_v-number of design variables. The goal of this cost function analysis was to achieve an optimal solution in which besides the increase of the efficiency will also give an optimal computational time that is not hardware dependent (Di Barba P. *et al.,* 2001). The values of the optimized parameters in the tentative cost function for the proposed CS solution are: n_t=100, n_u≈81500, n_f=19 and n_v=7. Based on these values the value of the cost function is 1.08395*10^9. From the presented values it is evident that the parameter n_u will have the largest influence on the value of the cost function. On the other hand, the quality of the result gained from the FE analysis is directly proportional to the number of nodes and finite elements involved in the calculation of the magnetic field for a predefined rotor position. The presented value for this parameter has been previously carefully determined based on the convergence of the calculated value of the torque, based on a predefined accuracy value. Therefore, the value of the cost function can be decreased by a decrease of the number of CS iterations, as well as by a decrease in the number of variables and number of field simulations for evaluating the values for the torque-angle curve. Based on the results presented in Fig. 4 it can be concluded that the number of iterations can be decreased from 100 to 90 without influencing the values of the efficiency of the solution and the values of the optimized parameters. Based on the change of the value of this parameter, the value of the cost function decreased to 9.75555*10^8. A further decrease of the value of the cost function, due to the symmetry of the electromagnetic torque can be achieved by a reduction of the number of field calculations from 19 to 10. With this change the cost function can be further decreased to 5.1345*10^8. In our future work we will also investigate the possibilities to reduce the number of variables in the search for a more efficient solution regarding the objective and cost functions.

IV. Conclusion

In this paper a novel technique for optimal design of electrical machines, called Cuckoo Search, has been introduced and implemented. Based on this methodology a new solution for the design of a single phase permanent magnet brushless DC motor is reached. The new solution has better motor parameters and efficiency. The efficiency of the motor has been selected as an objective function in the optimal design. Finally, the two motor solutions, the initial and optimized solution, have been analysed using the Finite Element Analysis approach. In order to have a full picture of the optimized model a detailed analysis of the electromagnetic characteristics of the two motor models will be performed and presented in some near future work.

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