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Optimal design of axial flux permanent magnet motor using Cuckoo search

***Abstract**. In this paper a cuckoo search based optimal design of axial flux permanent magnet motor (AFPMM) is proposed. This approach employs a Cuckoo search (CS) technique as a search tool for optimal design solution of a AFPMM based on the value of the objective function. Several optimisation solutions are analysed and a best solution is proposed based on the values of the optimisation parameters and the efficiency, as well as other important motor parameters. An overall comparison of the optimal solution and the prototype model of the motor is presented.*

***Streszczenie.** W niniejszej pracy zaproponowano projekt optymalnej konstrukcji osiowego strumienia silnika z magnesami trwałymi (AFPMM) oparty o wykorzystanie algorytmu kukułki. Projekt wykorzystuje algorytm kukułki (CS) jako narzędzie do wyszukiwania optymalnego rozwiązania projektowego AFPMM w oparciu o wartości funkcji celu. Autorzy przeanalizowali kilka rozwiązań optymalizacyjnych i zaproponowali najlepsze rozwiązanie oparte o wartości parametrów optymalizacji oraz wydajności, jak również innych ważnych parametrów silnika. Przedstawiono porównanie optymalnego rozwiązania projektowego z wynikami uzyskanymi dla prototypowego modelu silnika. (**Optymalne projektowanie silnika z magnesem trwałym i osiowym strumieniem z wykorzystaniem algorytmu kukułki**).*

Keywords: optimal design, cuckoo search, axial flux permanent magnet motor, finite element method.
Słowa kluczowe: projekt optymalizacyjny, algorytm kukułki, silnik z magnesem trwałym i osiowym strumieniem, metoda elementów skończonych.

Introduction

The practical application of gradient based optimisation techniques has been reduced by the difficulty of generating automatically objective functions and their derivatives for highly non-linear engineering problems. During the 1950s and 1960s, computer scientists investigated the possibility of applying the concepts of evolution as an optimisation tool for engineers and this gave birth to a subclass of gradient free methods called genetic algorithms (GA) [1]. Since then many other algorithms have been developed that have been inspired by nature, for example particle swarm optimisation (PSO) [2], differential evolution (DE) [3] and, more recently, the cuckoo search (CS) [4]. These are heuristic techniques which make use of a large population of possible designs at each iteration. For each member of the population, the objective function is evaluated and a fitness value is assigned. A set of rules is then used to move the population towards the optimum solution. Although this results in a global search without the need to calculate objective function gradients, the large number of objective function evaluations means the computational efficiency of these procedures is often inferior to classical gradient-based methods.

Formatting of the text

Cuckoo are fascinating birds, not only because of the beautiful sounds they can make, but also because of their aggressive reproduction strategy. Some species such as the *ani* and *Guira* cuckoos lay their eggs in communal nests, though they may remove others' eggs to increase the hatching probability of their own eggs [5]. Quite a number of species engage the obligate brood parasitism by laying their eggs in the nests of other host birds (often other species). There are three basic types of brood parasitism: intraspecific brood parasitism, cooperative breeding, and nest takeover. Some host birds can engage direct conflict with the intruding cuckoos. If a host bird discovers the eggs are not its owns, it will either throw these alien eggs away or simply abandons its nest and builds a new nest elsewhere. Some cuckoo species such as the New World brood-parasitic *Tapera* have evolved in such a way that female parasitic cuckoos are often very specialized in the mimicry in colour and pattern of the eggs of a few chosen host species [5]. This reduces the probability of their eggs being abandoned and thus increases their reproduction. Furthermore, the timing of egg-laying of some species is also amazing. Parasitic cuckoos often choose a nest where the host bird just laid its own eggs. In general, the cuckoo eggs hatch slightly earlier than their host eggs. Once the first cuckoo chick is hatched, the first instinct action it will take is to evict the host eggs by blindly propelling the eggs out of the nest, which increases the cuckoo chick's share of food provided by its host bird. Studies also show that a cuckoo chick can also mimic the call of host chicks to gain access to more feeding opportunity. Subsequently, such behaviour has been applied to optimization and optimal search based on the behaviour of the cuckoo bird.

From mathematical point of view the Cuckoo Search is a metaheuristic search algorithm which has been proposed recently by Yang and Deb [4]. The algorithm is inspired by the reproduction strategy of the cuckoo birds. As mentioned previously at the most basic level, cuckoos lay their eggs in the nests of other host birds, which may be of 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 cuckoo eggs which mimic the eggs of local host birds. To apply this as an optimisation tool, Yang and Deb used three idealised rules:

- Each cuckoo lays one egg, which represents a set of solution co-ordinates, at a time and dumps it in a random nest;
- A fraction of the nests containing the best eggs, or solutions, will carry over to the next generation;
- The number of nests is fixed and there is a probability that a host can discover an alien egg. If this happens, the host can both discard the egg or the nest, and use these results in building a new nest in a new location.

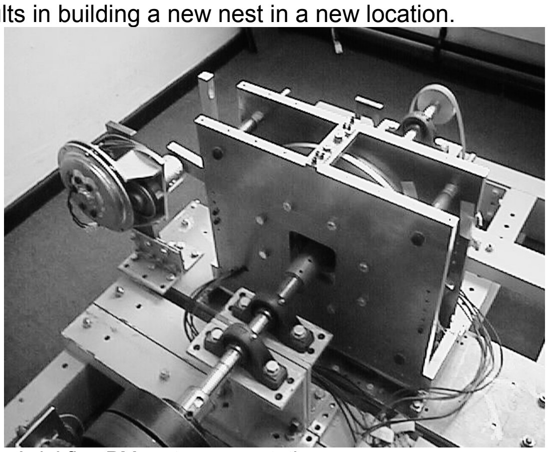


Fig.1. Axial flux PM motor presentation

Axial flux PM motor Description

The motor used in the optimisation process is a brushless three phase synchronous permanent magnet axial flux motor, with rated torque 54 Nm at 750 rpm@50 Hz, fed by a pulse width modulated (PWM) inverter. The AFPMM is a double sided disc motor with two laminated stators having 36 slots and a centred rotor with 8 skewed neodymium-iron-boron permanent magnets that have a remanent flux density of B_r=1.17 T and coercitive filed of H_c=-883 kA/m. A presentation of the motor is shown in Figure 1.

Cuckoo search design of AFPMM

The optimisation of the efficiency of the optimised motor is performed by an optimal design programme CS-ODEM (Cuckoo Search for Optimal Design of Electrical Machines), in which the Cuckoo Search (CS) is used as an optimisation tool. A block diagram presentation of the CS-ODEM programme for the efficiency optimisation of the AFPMM is presented in Figure 2. 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 150, number of variables 7 and number of generations 100.

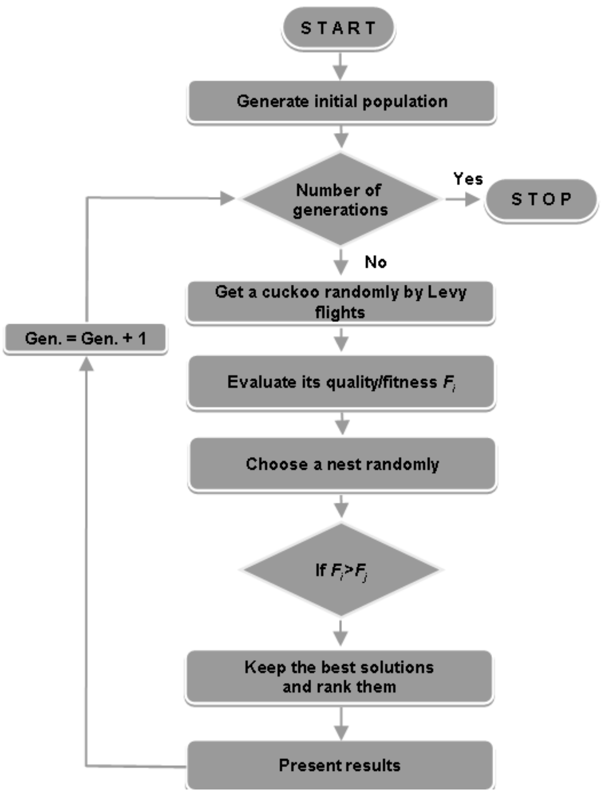


Fig.2. Main steps of the CS-ODEM programme

In the case of this design optimisation the following motor parameters are chosen to be variable: inside radius of the stator cores and PM R_i, outside radius of the stator cores and PM R_o, permanent magnet fraction α_m, permanent magnet axial length l_m, air-gap g, single wire diameter d_w, and stator sloth width b_s. The objective function of this optimal design process of the AFPMM is selected to be the efficiency of the motor. The target of the optimal design is to get a solution of the motor with increased efficiency. As it is known the Cuckoo Search is in general a minimisation algorithm and therefore the objective function of the search will be an inverse function of the efficiency of the motor. The objective function for the axial flux permanent magnet motor optimisation can be presented with the following equation:

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

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

The optimization variables have been carefully determined, based on the influence of those variables on the optimization process and the quality of the solution. The upper and lower bounds of the CS optimization parameters are presented in Table 1.

Table 1. Upper and lower bounds of CS optimization parameters

Parameters	Lower bound	Upper bound	Prototype
R_i (m)	0.070	0.074	0.072
R_o (m)	0.128	0.138	0.133
α_m(/)	0.6	0.730	0.6646
l_m (m)	0.009	0.0110	0.010
g (m)	0.0018	0.0022	0.002
d_w (m)	0.0006	0.0014	0.001
b_s (m)	0.0070	0.0090	0.008

Table 2. Cuckoo search optimization results

Optimisation parameters	Prototype model	Cuckoo Serach AFPMM Solution
R_i (m)	0.072	0.070725
R_o (m)	0.6646	0.712905
α_m (/)	0.01	0.01068
l_m (m)	0.002	0.001827
g (m)	0.133	0.139438
d_w (m)	0.001	0.0014
b_s (m)	0.008	0.008364
Objective function F_o (/)	1.2019	1.5567
Efficiency (/)	**0.8325**	0.8653

The comparative parameters data of the initial and the optimized model are presented in Table 2. The convergence of the objective function of the motor during the Cuckoo optimization search for 100 generations is shown in Fig. 3.

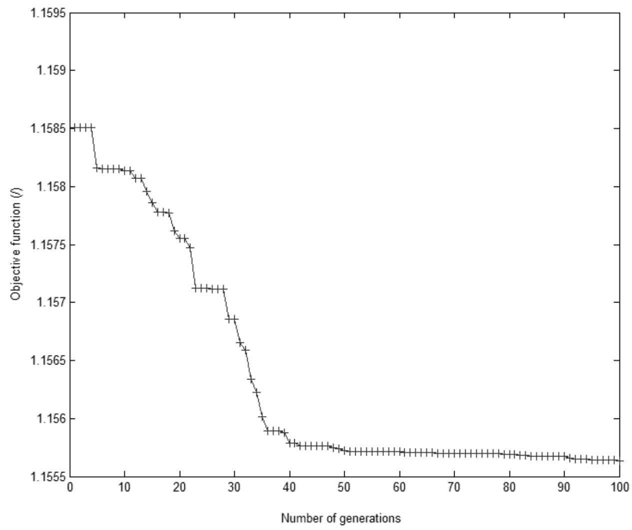


Fig.3. Objective function change during generations

Comparative analysis of the prototype and GS solution

Some specific parameters values for the prototype and the CS optimal solution are shown in Table 3. The objective CS solution has its own advantages and disadvantages in relation to the values of the prototype parameters. It is evident that the CS solution in comparison to the prototype has decreased mass of the permanent magnets. This is very important because with this improvement the overall mass of the rotor is also decreased which leads to an EV performance improvement, due to the fact that the rotor is directly mounted on the shaft of the vehicle. Also, the efficiency of the CS solution is slightly higher than the efficiency of the prototype. The improvement of the efficiency of the CS solution in relation to the prototype is due to the significant decrease of the total ohmic power losses of the stator windings. This decrease of the losses is as a result of the decrease of the stator windings phase resistance and also decrease of the phase rated current load. On the other hand, due to the increase of the total stator core mass the total iron losses are also increased. Finite Element Method (FEM) analysis of electric motors over the years has become a well established tool for analysis of electric motors. This approach will be used to analyze in more detail the CS solution and the prototype.

Table 3. Cuckoo search optimization results

Parameters	Description	Initial Motor	CS Solution
N (turns)	number of turns per section	13	11
B_g (T)	average air gap flux density	0.695	0.745
$m_{stator\ iron}$ (kg)	total mass of the two stators iron	7.766	12.279
m_{Cu} (kg)	total mass of the two stators copper	4.70	8.26
m_{pm} (kg)	total mass of the PMs	3.71	2.55
I_{ph} (A)	phase current	8.723	8.33
R_{ph} (ohm)	phase resistance	1.245	0.570
P_{Cu} (W)	ohmic losses	345.43	144.27
P_{Fe} (W)	iron losses	15.03	19.35
η (/)	efficiency	0.8319	0.8653

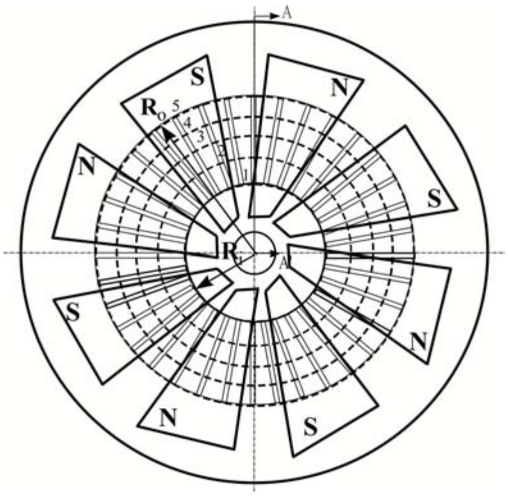
AFPMM FEM modelling and magnetic field analysis

In order to get the necessary data for the PM axial field motor, a calculation of the magnetic field has to be performed. The 2D analysis is very suitable for this type of geometry and has a lot of advantages over the 3D calculation, such as lower memory storage and reduced computation time. The quasi-3D method [6] which is adopted for this analysis consists of 2D FEM calculations of the magnetic field in a three dimensional radial domain of the axial field motor.

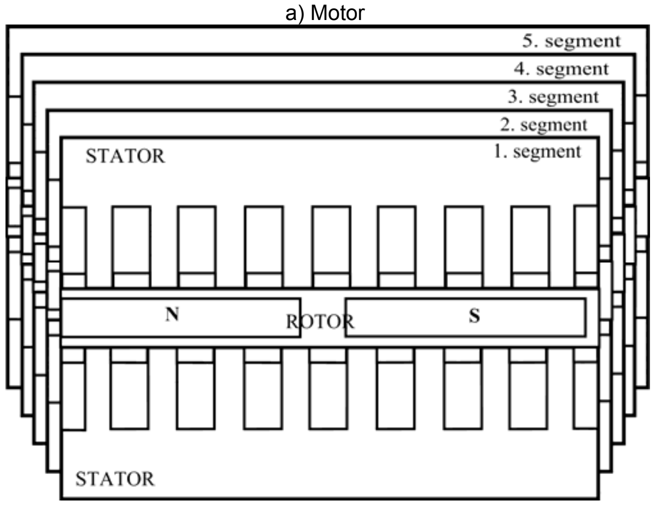
For this purpose, a notional radial cut through the two stators and the rotor of the motor is performed and then opened out into linear form, as shown in Fig. 4.

By using this linear quasi three-dimensional model of the disc motor, which is divided into five segments, it is possible to model not only the skewing of the magnets, but also to simulate the vertical displacement and rotation of the rotor. Due to the symmetry of the machine the calculation of the motor is performed for one quarter of the permanent magnet disc motor, i.e. for one pair of permanent magnets.

After the proper modelling of the AFPMM an adequate mesh size refinement, especially in the air gap, is performed. The magnetic field calculations are performed for different current loads and different rotor displacements for each segment separately. As an example, the magnetic field distribution of the motor at no load and one rotor position for the 3rd middle segment, of the prototype and the CS solution is presented in Fig 5(a) and Fig. 5(b), respectively.

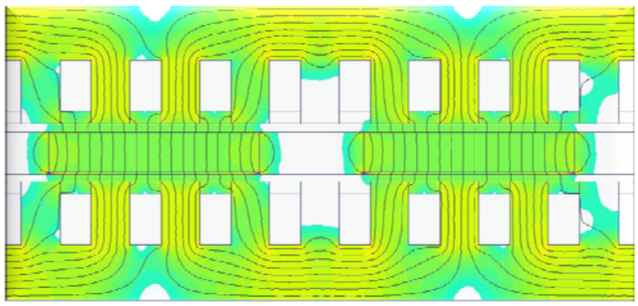


a) Motor

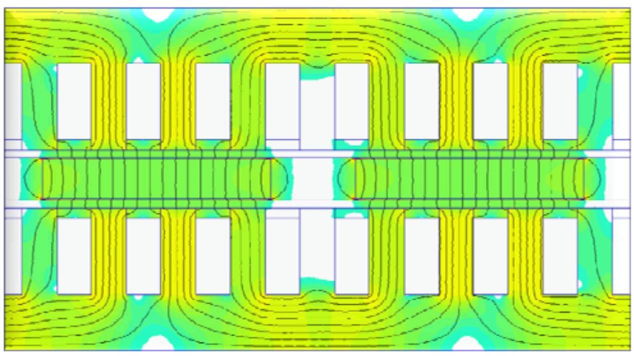


b) Segments

Fig.4. Radial division of the motor into 5 segments



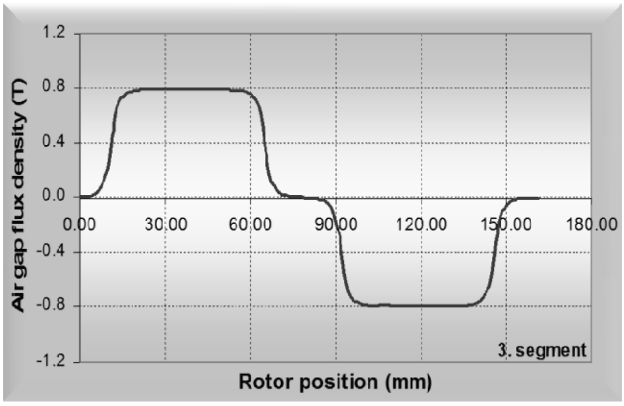
a) Prototype



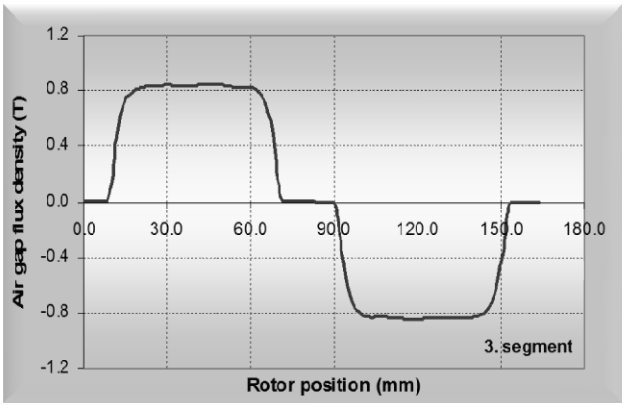
b) CS solution

Fig.5. Magnetic field distribution at no load for the middle segment

From the presented magnetic field distribution of the two motor models it is evident that in the CS model the magnetic field distribution is improved in relation to the one in the prototype. Also, the values of the flux density in certain parts of the CS model are very close to the one calculated or prescribed as an optimisation constraint. In Fig. 6(a) and Fig. 6(b) a flux density distribution at no load in the air gap of the middle segment for both AFPMM models is presented. As a result of the change of the dimensions of the motor, the air gap flux density shape and magnitude has changed. How these changes affect the overall performance of the motor will be analyzed in the near future works.



a) Prototype



b) CS solution

Fig.6. Air gap flux density distribution at no load for the middle segment

In Fig. 6(a) and Fig. 6(b) a flux density distribution at no load in the air gap of the middle segment for both axial flux permanent magnet models is presented.

As a result of the change of the dimensions of the motor, the air gap flux density shape and magnitude has changed. How these changes affect the overall performance of the motor, e.g. electromagnetic and cogging torque, will be analyzed in the near future works.

Conclusion

The authors propose a procedure for optimal design of AFPMM with maximum efficiency using cuckoo search optimization procedure. The design problem has been solved by using Cuckoo Search (CS) as an optimization tool. The improvement of the CS optimized model has been proved through the data analysis of the prototype model and CS solution. This improvement resulted in an efficiency improvement, and reduced weight of the PMs of the motor. At the end, the improvement of the CS solution has been proved by comparative analysis of the two motor models using a FEM as a performance analysis tool. The proper modelling of the AFPMM is presented and a part of the comparative results of the magnetic field and air gap flux density distribution for no load are presented.

For future work first of all a more detailed performance analysis, including electromagnetic torque, for different current loads, and cogging torque analysis, for both models is going to be performed. Secondly a physical model of the CS solution will be constructed and tested in order to compare the calculated parameter values with the measured ones.

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