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A New Design of Low Cost Energy Efficient Single Phase Brushless DC Motor

***Abstract**. In the past few years Genetic Algorithms (GAs) have proved to be a very powerful and reliable optimisation tool. They have also been successfully applied in the design optimisation of many electromagnetic devices. Therefore, in this paper the optimal design performed on the single phase permanent magnet brushless DC motor (SPBLDCM) is done by using a Genetic Algorithm. The objective function of the optimisation search is selected to be the efficiency of the motor and the design process is defined as a maximisation 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 modelling and analysis of both models is also performed.*

***Streszczenie.** W ostatnich kilku latach algorytmy genetyczne staly się jednym z poważniejszych narzędzi w rozwiązywaniu problemów optymalizacji. Dotyczy to również optymalizacji licznych urządzeń elektromagnetycznych. W tym artykule pokazano zastosowanie algorytmu genetycznego w optymalizacji silnika jednofazowego z magnesem trwały w wykonaniu bezszczotkowym. Funkcją celu w procesie optymalnego projektowania jest efektywność silnika jako wartość maksymalna. Biorąc pod uwagę kilka specyficznych parametrów silnika przeprowadzono analizę porównawczą modeli optymalnego i początkowego, a także dla obu modeli przeprowadzono analizę pracy silnika metodą elementów skończonych. (**Nowy projekt jednofazowego silnika bezszczotkowego prądu stałego o maksymalnej wydajności**)*

Keywords: finite element method, genetic algorithm, permanent magnet motor.
Słowa kluczowe: metoda elementów skończonych, algorytm genetyczny, silnik z magnesem trwałym

Introduction

The problem of design optimisation of motors sometimes arises because of the stiff competition among manufacturers to produce a motor giving the same performance but at a reduced cost. Sometimes the application requires a motor of certain weight or shape that has to satisfy certain requirements. Design optimisation of electrical machines, in particular permanent magnet disc motors, is very important but quite a complicated problem. In general the optimal design of electrical machines is a complex multi-variable, non-linear and constrained optimisation procedure. The non-linear nature of the active materials, together with the discreteness of some design parameters, renders the task of optimisation a mixed real number programming problem. A reasonably simplified form of the design procedure may be attacked by various approaches accumulated into two main topics: classical optimisation techniques (deterministic methods) versus genetic algorithm (stochastic methods). Researchers have used classical (usually gradient based) optimisation techniques for this task for a long time. However, recently, evolutionary computation techniques such as Genetic Algorithms (GAs) have been used for optimisation procedures. These methods are claimed to be more successful in converging to a global maximum/minimum, avoiding the local ones. Also, they avoid the problem of starting the search from a suitable feasible solution, often encountered in classical optimisation techniques. Therefore, in this study, the authors of the paper decided to use the genetic algorithm as a search tool in the optimal design of a SPBLDCM.

Genetic Algorithm Optimisation Method Description

Since John Holland presented the GA as a computer algorithm, a wide range of applications of GA has appeared in various scientific areas, and GA has been proved powerful enough to solve complicated problems, especially optimal design problems. GAs are evolutionary search algorithms based on the mechanics of natural selection and natural genetics. GAs implement, in the most simplistic way, the concept of survival of the fittest. The reproductive success of a solution is directly tied to the fitness value it is assigned during evaluation. In this stochastic process, the least-fit solution has a low chance at being reproduced, while the most-fit solution has a greater chance of reproduction. The search starts from a randomly created population representing the chromosomes, and reaches the optimum solution after a certain number of generations of genetic operations. The optimisation is based on the survival of the string structures from one generation to the next, where a new improved generation is created by using the bits of information-genes of the survivors of the previous generation.

The optimal design programme GA-ODEM (Genetic Algorithm for Optimal Design of Electrical Machines) uses the Genetic Algorithm as an optimisation tool [1]. The design variables are presented as vectors of floating-point numbers. The search starts from a randomly created population of strings representing the chromosomes and reaches the optimum solution after a certain number of generations by applying genetic operations. The search can continue indefinitely. Therefore, a stopping rule is necessary to tell the algorithm when it is time to stop. This is achieved in many different ways and is also user and problem dependent. Some of the possible methods are; to fix the number of generations and to use the best individual of all generations as the optimum result; or, to fix the time elapsed and to select the optimum result similarly; or to let the entire population converge on to an average fitness with some error margin. The stopping rule applied in the GA-ODEM programme is the number of generations.

The parameters of the GA shape the way the algorithm runs. They could be grouped in two groups such as: primary and secondary parameters. The population size N, which is the number of chromosomes in the population, is one primary parameter and the crossover probability p_c and the mutation probability p_m are the two secondary parameters.

The values that are assigned to all of them are user and problem dependent. The values for this optimal design problem are presented in Table 1.

Table 1. Values of GA Parameters

GA Parameters	Value
Population size	N=20
Number of generations	G=15000
Crossover probability	p_c =0.85
Mutation probability	p_m=0.07

The main genetic operators of the genetic algorithm in general are reproduction, crossover and mutation.

Reproduction

Working on the entire population, the reproduction operator creates a new generation from the old generation. Based on the fitness measure of an individual and the average fitness of the population, the reproduction operator determines the number of copies that particular individual will have in the next generation. The underlying idea in designing the reproduction operator is to give the individual with higher fitness a better chance to be represented in the next generation but leaving the decision to a random variable. The reproduction procedure that is implemented in the GA-ODEM programme is performed by a linear search through a 'roulette wheel' with slots weighted in proportion to string fitness values. In the previously mentioned computer programme an additional function has been implemented called elitism. With this function the GA-ODEM programme detects the best solution and automatically moves it to the next generation without performing any genetic operation on it. By the implementation of this function the loss of the best solution during the generations is excluded.

Crossover

A central feature of genetic algorithms that creates a new chromosome from two "parents" is crossover. Corresponding to biological crossover, the software version combines a pair of parents by randomly selecting a point at which pieces of the parents' vectors of numbers are swapped. Instead of using the simple crossover the swapping is done with the so called arithmetical crossover which is defined as a linear combination of two vectors x_1 and x_2, after which the resulting offspring is

(1) $$\mathbf{x}_1^{'} = c \cdot \mathbf{x}_1 + (1-c) \cdot \mathbf{x}_2$$

(2) $$\mathbf{x}_2^{'} = (1-c) \cdot \mathbf{x}_1 + c \cdot \mathbf{x}_2$$

In the previous equations *c* could be any number between 0 and 1 or it can be taken as a fixed number; in this case it was adopted to be equal to 0.5. This type of crossover is called uniform arithmetical crossover and with its usage it is guaranteed that the values of the new parents will always be in the domain.

Mutation

Another step in reproduction is mutation, which involves the random real number generation of a selected variable in its upper and lower bound domain, of the new population. The primary purpose of mutation is to introduce variation into a population. This process is carried out randomly and it is done at a randomly selected place.

Another procedure that is implemented in the optimal design programme is the fitness scaling which improves the overall performance and leads towards better reliability of the GA search.

Linear Fitness Scaling

Linear fitness scaling adjusts the fitness values of all chromosomes such that the best chromosome gets a fixed number of expected offspring and thus prevent it from reproducing too many. The linear fitness scaling method implemented in this optimisation procedure can be presented with the following equation

(3) $$f_k^{'} = a \cdot f_k + b$$

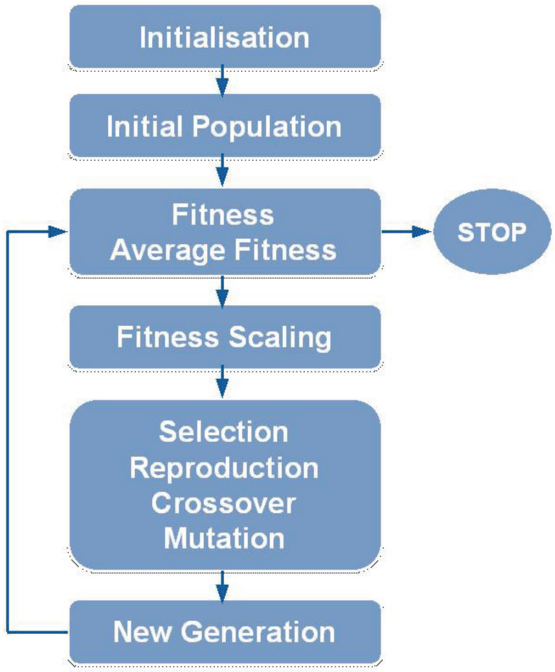

Fig. 1. Main steps of the GA-ODEM programme

After the operators perform their functions, the new generation is produced of members, which have gained new information through the exchange between pairs. The better traits of the "parent" chromosomes are carried along to the future generations. The optimal solution of the single phase brushless DC motor is selected as the best solution of the GA search. A block diagram representation of the GA-ODEM programme, used for the optimal design of the single phase brushless DC motor, is presented in Figure 1.

Genetic Algorithm Optimal Design Motor Model

The efficiency of the motor is selected as an objective function of the optimisation, because efficiency and energy saving are topics of current interest. The motor efficiency is calculated analytically in the optimisation process. The general aim of the single phase brushless DC motor optimal design is to obtain a motor with maximised efficiency while satisfying certain performance, magnetic and geometric constraints. The design optimisation is performed on a previously defined topology of single phase brushless DC motor [2] 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 the asymmetrical stator poles and has 4 permanent magnets with B_r=1.13 T mounted on the rotor. A 2D partial cross-section presentation of the prototype motor and some of the optimisation parameters is shown in Figure 2. It should be mentioned that the motor has an asymmetrical air gap, which is made by modifying the small stator poles, and the rotor permanent magnets [2].

According to the design characteristics of the SPBLDCM, some of the parameters are chosen to be constant and some to be variable, such as: outside radius of the rotor iron core $\boldsymbol{R_{ro}}$, permanent magnet radial length $\boldsymbol{l_m}$, air-gap between the rotor PM and stator poles **g**, opening between the stator poles $\boldsymbol{b_{so}}$, axial length of the motor ***L***, and radius of the stator winding single wire $\boldsymbol{r_{cu}}$. Some of these parameters are presented in Figure 2. All the other geometrical parameters are determined as function of the optimisation parameters.

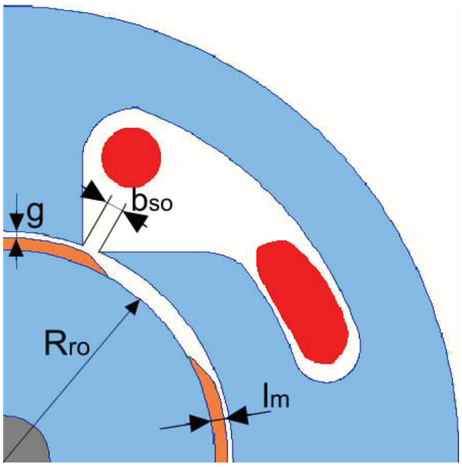

Fig. 2. SPBLDCM optimisation parameter presentation

The efficiency of the motor, as an objective function of the optimisation can be presented with the following equation:

$$efficiency = \frac{T \cdot \omega_m}{T \cdot \omega_m + P_{Cu} + P_{Fe} + P_s} \tag{4}$$

where: T-rated torque, ω_m-rated speed, P_{Cu}-ohmic power losses, P_{Fe}-core losses and P_s-other constant losses calculated from no load test of the machine. The optimal design process of the single phase brushless DC motor is a maximisation problem of the objective function, where the torque is one of the constraints.

Some of the design constraints used in the optimal design of the single phase brushless DC motor are geometrical, and the other constraints concern the motor performance and material characteristics. The choice of these constraints has been carefully selected to reduce the number of independent design variables. 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 2. GA parameter optimisation boundaries

Parameters	Lower boundary	Upper boundary	Basic 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	0.005	0.0023
L (m)	0.0972	0.1188	0.108
r_{cu} (m)	0.0002	0.0006	0.0004

Table 3. Comparative Data of the Two Models

Optimisation parameters	Basic Model	GA SPBLDCM Solution
R_{ro} (m)	0.0380	0.0357
l_m (m)	0.0020	0.0022
g (m)	0.0010	0.0009
b_{so} (m)	0.0023	0.0040
L (m)	0.1080	0.1089
r_{cu} (m)	0.0004	0.0005
Efficiency (/)	0.8828	0.9048

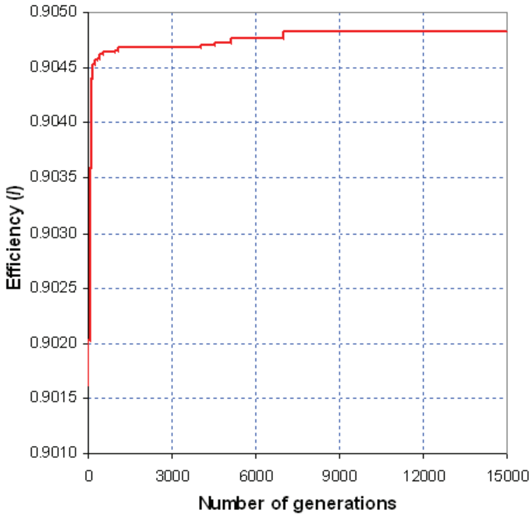

Fig. 3. GA search efficiency change during generations

The stopping rule was selected to be the number of generations, which in this case was 15000 generations. The computation time to reach the optimal design of SPBLDCM using GA takes only a few minutes. The values of the lower and upper boundaries are presented in Table 2. The values of the optimisation parameters including the efficiency of the basic and optimised model are presented in Table 3. The convergence of the efficiency of the motor as an objective function during the GA optimisation search for 15000 generations is shown in Fig. 3. It should be mentioned that after the optimisation the motor is redesigned in order to modify the air gap and make it asymmetrical as it is in the initial model.

GA Optimal Design Results of SPBLDCM

In order to be able to compare the two solutions some specific parameters of the prototype and of the GA optimal solution are shown in Table 4.

Table 4. Initial motor and GA solution data comparison

Parameters	Description	Initial Motor	GA Solution
N (turns)	total number of turns of stator winding	648	644
X_n (m)	gap between the pole shoe and the stator inner radius	0.00757	0.0117
X_c (m)	stator pole shoe thickness stator back iron thickness	0.014	0.0133
X_p (m)	stator pole width	0.028	0.0266
R_{so} (m)	stator outside radius	0.0766	0.0771
I_{ph} (A)	phase current	3.30	3.37
R_{ph} (ohm)	phase resistance	6.987	4.328
P_{Cu} (W)	ohmic losses	91.38	59.73
P_{Fe} (W)	iron losses	32.06	31.81
η (/)	efficiency	0.8828	0.9048

The new optimised values of the parameters and characteristics show improvement of the single phase brushless DC motor model in relation to the prototype. It is evident that the GA optimised solution has a better efficiency, which is due to the increased cross-section of the stator winding wire and hence a decrease of the resistance of the stator winding. The decrease of the stator winding resistance results in a decrease of the ohmic losses, and hence an improvement in the efficiency of the GA solution. From the data presented in Table 4 it can be noticed that the outer radius of the motor changed very little and therefore, the net volume of the motor, as a result of the small increase in the axial length and the outer motor radius, also increased a little, although some of the dimensions of the magnetic circuit inside the motor changed.

In order to be able to perform a more detailed comparative analysis of the two motor models a finite element method approach was adopted. FEM analysis is regarded as a very sophisticated and frequently used tool for motor analysis.

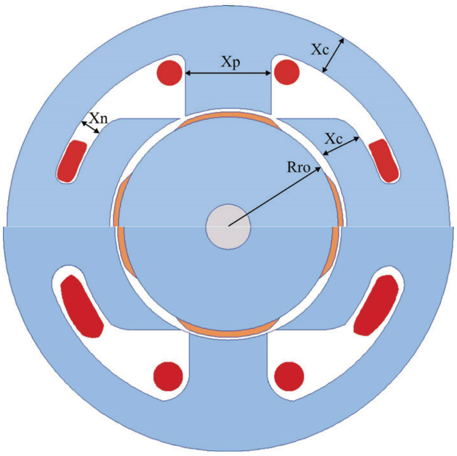

Fig. 4. Presentation of the two SPBLDCM models

SPBLDCM FEM Modelling and Magnetic Field Analysis

In order to be able to get the necessary data for the SPBLDCM, a calculation of the magnetic field has to be performed [3,4]. 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 time computation, which for one segment is done in several minutes. The mesh for the two motor models consisted of 91125 nodes and 181478 elements.

After modelling the single phase brushless DC motor and with adequate mesh size refinement, especially in the air gap, a magnetic field calculation was performed for different load currents and for different rotor displacements. As an example, the magnetic field distribution within the motor at rated load, for both the initial motor model and the GA solution is presented in Fig 5 and Fig. 6, respectively.

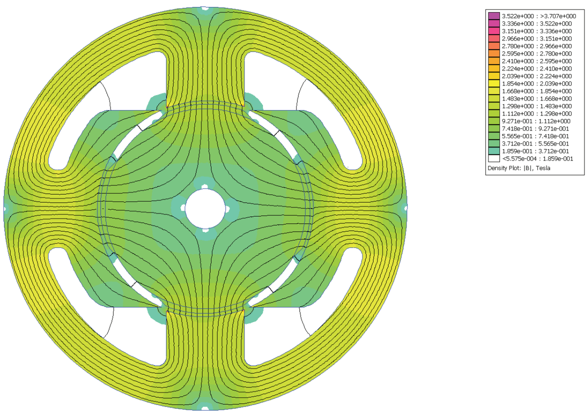

Fig. 5. Magnetic field distribution of initial model at rated load

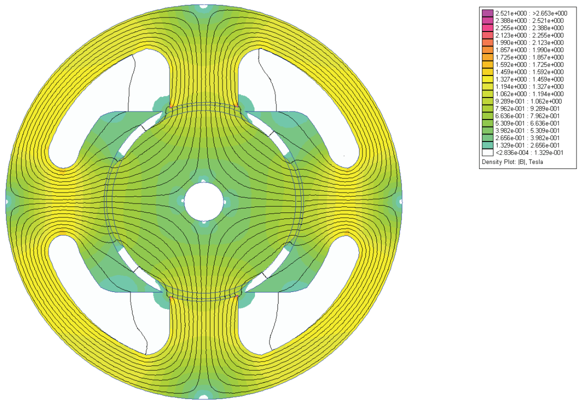

Fig. 6. Magnetic field distribution of GA solution at rated load

Conclusion

An optimisation technique based on GAs has been developed and applied to the design of a single phase brushless DC motor. According to the results and subsequent investigation presented in this paper, it can be concluded that the GA is a very suitable tool for design optimisation of a single phase brushless DC motor and electromagnetic devices in general. By using GAs for the optimisation, the risk of trapping in a local maximum or minimum is reduced, especially by using some search improvements, which is very difficult to eliminate in deterministic methods. The quality of the GA optimised model has been proved through the data analysis of the initial model and optimised solution. This improvement resulted in an efficiency improvement of the motor. At the end, the quality of the GA solution has been proved by comparative analysis of the two motor models using a Finite Element Method as a performance analysis tool. The proper modelling of the single phase brushless DC motor is presented and partial comparative results of the magnetic field at rated load are presented.

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