ARCHIVES OF ELECTRICAL ENGINEERING VOL. 65(2), pp. 285-294 (2016)

DOI 10.1515/aee-2016-0020

Genetic algorithm as a tool for multi-objective optimization of permanent magnet disc motor

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(Received: 10.06.2015, revised: 05.02.16)

Abstract: The analysed permanent magnet disc motor (PMDM) is used for direct wheel drive in an electric vehicle. Therefore there are several objectives that could be tackled in the design procedure, such as an increased efficiency, reduced iron weight, reduced copper weight or reduced weight of the permanent magnets (reduced rotor weight). In this paper the optimal design of PMDM using a multi-objective genetic algorithm optimisation procedure is performed. A comparative analysis of the optimal motor solution and its parameters in relation to the prototype is presented.

Key words: design optimisation, electric vehicle, genetic algorithm, multi-objective optimisation, permanent magnet disc motor

1. Introduction

When optimizing an electric motor, there are varieties of choices for defining the objective function. In fact the objective function is a specific feature of the machine to be optimised, for example efficiency, torque, volume or cost. Sometimes it is important to tackle several objectives at once [1-2]. In this paper the authors present the optimal design of PMDM using a genetic algorithm as an optimisation tool and a multi-objective function, which combines the efficiency, the weight of the iron, the permanent magnet weight, and the weight of the copper, as separate objective functions.

The optimized motor is a brushless three phase synchronous permanent magnet disc motor, with rated torque 54 Nm at 750 rpm@50 Hz, fed by a pulse width modulated (PWM) inverter. PMDM is a double sided disc motor with two laminated stators having 36 slots and a centered rotor with 8 skewed neodymium-iron-boron permanent magnets (B_r=1.17 T and H_c= −883 kA/m). The prototype of the motor is designed by hand based on the knowledge of the designer without any optimization tool.

Consequently, the investigation is focused on the design improvement of PMDM by using a genetic algorithm as an optimization tool to increase the efficiency of the motor and to reduce the total weight of the motor, as well as the weight of the rotor including the PM. In order to tackle all these objectives a multi-objective genetic algorithm optimization is performed.

The optimal design program GA-ODEM (Genetic Algorithm for Optimal Design of Electrical Machines) uses the Genetic Algorithm as an optimisation tool. This optimization tool has been selected based on the investigation realised in reference [3] where several optimisation techniques were investigated and compared and GA was selected as the most suitable for the purpose of this optimization. The design variables are presented as vectors of floating-point numbers. The main genetic operators of the GA-ODEM implemented in the GA optimisation procedure are reproduction, crossover and mutation. The reproduction procedure is performed by a linear search through a roulette wheel with slots weighted in proportion to string fitness values. The crossover that is used is called the uniform arithmetical crossover and with its usage it is guaranteed that the values of the new parents will always be in the domain. 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 the mutation is to introduce variation into a new 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 so called linear fitness scaling which improves the overall performance and leads towards better reliability of the GA search. The linear scaling adjusts the fitness values of all chromosomes such that the best chromosome gets a fixed number of expected offspring and thus prevents it from reproducing too many times. After the operators perform their functions, the new generation of members, which have gained new information through the exchange between pairs is produced. The better traits of the "parent" chromosomes are carried along to the next generations. The search can continue indefinitely. Therefore, the stopping rule applied in this GA optimal design programme is the number of generations. The values of the parameters of the GA that shape the way the algorithm runs are user and problem dependent. In order to make a proper selection of the crossover probability p_c and the mutation probability p_m values, a very robust and detailed analysis of these parameters and their influence on the quality of the GA search, has been performed.

In this investigation each parameter has been changed separately, while the other are kept constant and afterwards there influence has been analysed. The GA parameters to be considered for this optimal design problem are: population size $N = 20$, $p_c = 0.85$, $p_m = 0.07$ and number of generations, as stopping rule, $G = 15000$. The definition of the GA parameters values is performed in reference [3], and it is realised after an investigation of the individual influence of each parameter value on the quality of the search. Each parameter was changed in certain range while all the others were kept constant. The optimal solution of PMDM at the end is selected as the best solution of the GA search. A flow chart representation of the GA-ODEM programme, used for the optimal design of PMDM, is presented in Fig. 1.

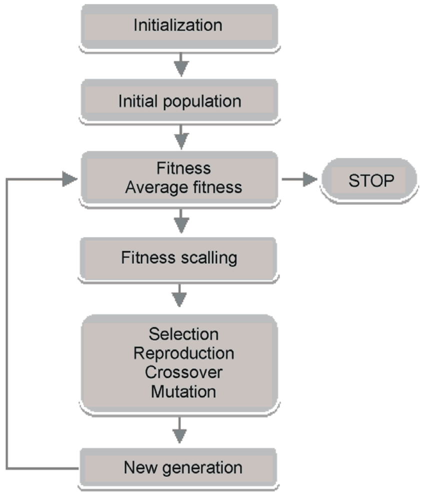


Fig. 1. Flow chart of the GA-ODEM programme

2. Multi-objective optimisation of PMDM

In this design optimisation the following 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_{cu}, and stator sloth width b_{so}, Some of those optimisation parameters are presented in Fig 2. In this research the optimal design of the PMDM will be analysed as a multi-objective function which is a sum of the individual values of the efficiency, the iron weight, the PM total weight and the copper weight. Each term of the objective function is multiplied by its own weight factor to represent how much is attached to this individual term. Since the GA optimisation in general is a maximisation problem some of the multi-objective terms have to be defined properly. Therefore the efficiency has to be defined as a maximisation term and the weight of the iron, the weight of the PM and the cooper weight as minimisation term. The proper values of the weight factors were selected after a detailed investigation where different combination of values has been taken under consideration. The multi-objective function ($F_{m-\mathrm{o}}$) for the PMDM optimisation can be ($F_{m-\mathrm{o}}$) presented with the following equation:

$$F_{m-\mathrm{o}} = Efficiency + \left(\frac{1}{c_1 \cdot W_{\mathrm{tot}Fe}}\right) + \left(\frac{1}{c_2 \cdot W_{\mathrm{tot}PM}}\right) + \left(\frac{1}{c_3 \cdot W_{Cu}}\right), \tag{1}$$

where: *Efficiency* is the motor efficiency, $W_{\mathrm{tot}Fe}$ is a total weight of the stator and rotor iron, $W_{\mathrm{tot}PM}$ is a total weight of the PMs and W_{Cu} is a total weight of cooper. The efficiency of the motor is described with the following equation:

$$Efficiency = \frac{T \cdot \omega_m}{T \cdot \omega_m + P_{Cu} + P_{Fe} + P_s}, \tag{2}$$

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

Most of the constraints applied in the optimal design are of a geometrical nature, where others are materials characteristics and motor performance parameters. Most of them are presented in Table 1. 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 values of the lower and upper bound for each optimization parameter are presented in Table 2. The selection of the upper and lower bound of the motor parameters is based on the knowledge and the previous experience of the authors, as well as on the principle that each parameter should be changed in the range of ±12% of the initial value. The range for each parameter is defined separately depending on the structural constraints of the parameter and the influence that has on the optimisation process and the design. The comparative parameters data of the initial and the optimized model are presented in Table 3.

Table 1. Optimization constraints and material properties

Description	**Parameters**	**Value**
Torque	T (Nm)	54
Phase voltage	U_{ph} (V)	181
Number of phases	N_{ph}	3
PM residual flux density	B_r (T)	1.17
Number of permanent magnets	N_m	8
Number of stator slots	Z	36
Stator back iron flux density	B_{mbi} (T)	≤ 1.7
Stator teeth flux density	B_{mst} (T)	≤ 1.7
Stator core mass density	ρ_{st} (kg/m^3)	7300
PMs mass density	ρ_{PM} (kg/m^3)	7400
Rotor core mass density	ρ_{rot} (kg/m^3)	7850
Copper mass density	ρ_{Cu} (kg/m^3)	8930

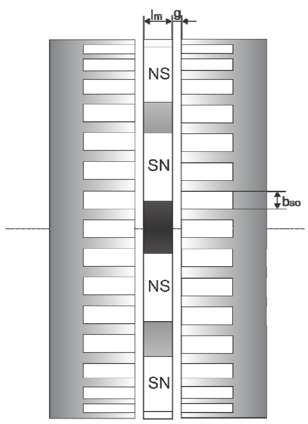


Fig. 2. Optimized motor parameters

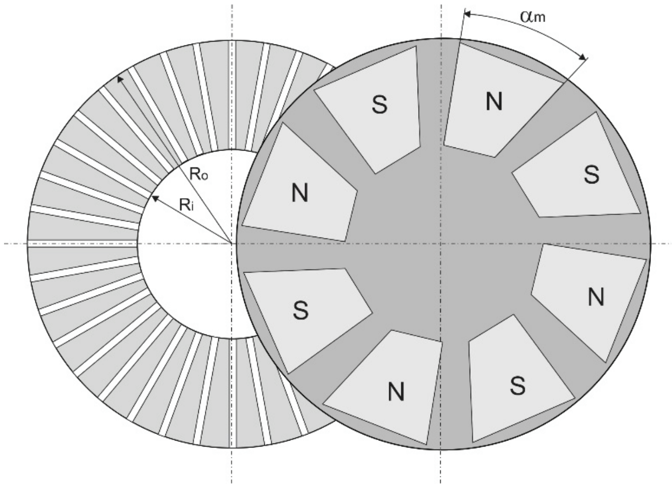


Fig. 3. Optimized motor parameters

Table 2. Upper and lower bounds of GA optimization parameters

Parameters	Lower bound	Upper bound	Initial model
R_i (m)	0.070	0.074	0.072
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
R_o (m)	0.128	0.138	0.133
d_{cu} (m)	0.0006	0.0014	0.001
b_{so} (m)	0.0070	0.0090	0.008

Table 3. Genetic algorithm optimisation results

Parameters	Initial model	GA solution
R_i (m)	0.072	0.07028
α_m (/)	0.6646	0.70448
l_m (m)	0.01	0.009
g (m)	0.002	0.0018
R_o (m)	0.133	0.134665
d_{cu} (m)	0.001	0.0011
b_{so} (m)	0.008	0.009
Objective function	1.1444	1.5365
Efficiency	0.8325	0.8411

The convergence of the multi-objective function of the motor during the GA optimization search for 15000 generations is shown in Fig. 4. The change of the values of the GA optimisation parameters during the GA search are presented in Fig. 5 and Fig. 6.

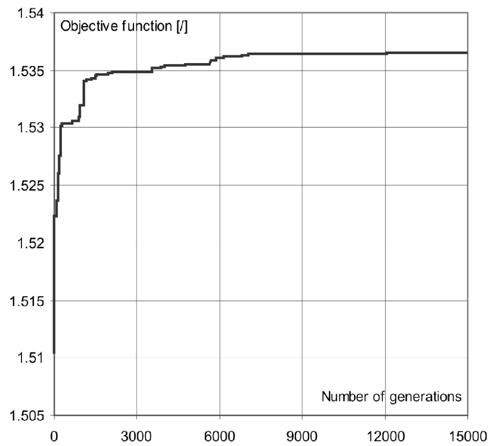


Fig. 4. Multi-objective value change during GA optimisation search

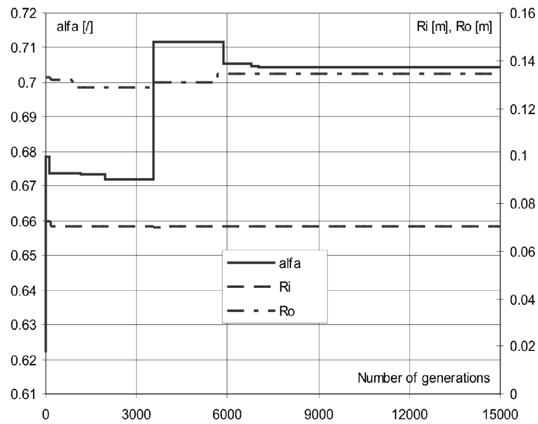


Fig. 5. GA parameters value change during GA optimisation search

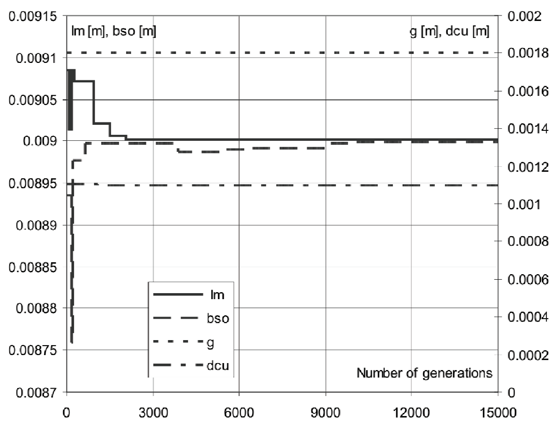


Fig. 6. GA parameters value change during GA optimisation search

3. Multi-objective optimisation data analysis

Several specific parameters values for the initial model and the GA optimal solution are shown in Table 4. It is evident that the GA solution in comparison to the prototype has less total weight, as well as reduced total rotor weight. This is due to the decrease of the PMs overall weight and the weight of the rotor iron. The reduction of rotor weight, as well as total rotor weight of the motor could also lead to an electric vehicle performance improvement, due to the fact that the rotor is directly mounted on the shaft of the vehicle. Also, the efficiency of the GA solution is a bit higher than the efficiency of the initial model. The improvement of the efficiency of the GA solution in relation to the initial model is due to the decrease of the total ohmic power losses in the stator windings of about 15%. This reduction of the ohmic losses will reduce the energy consumption from the batteries and therefore improve the electric vehicle autonomy. 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 analyse in more detail the GA solution and the initial model.

TABLE 4. Data comparison of PMDM prototype and GA solution

Parameters	Description	Initial model	GA Solution
Efficiency (/)	Efficiency	0.8319	0.8411
W_{Cu} (kg)	Total weight of winding	4.702	4.904
$W_{Festator}$ (kg)	Weight of stators iron	12.687	7.872
W_{totPM} (kg)	Total weight of PM	3.714	3.647
W_{Fer} (kg)	Weight of rotor iron	2.993	2.582
$W_{tot\ rot}$ (kg)	Total weight of rotor	6.707	6.229
W_{total} (kg)	Weight of the motor	24.096	23.331
N (/)	Number of turns/coil	13	11
B_g (T)	Air gap flux density	0.695	0.713
I_{ph} (A)	Phase current	8.716	9.508
R_{ph} (ohm)	Phase resistance	1.513	1.078
P_{Cu} (W)	Ohmic losses	344.95	292.38
P_{Fe} (W)	Iron losses	11.69	11.73
T (Nm)	Torque	54	54

4. PMDM FEM modelling and magnetic field analysis

In order to get the necessary data for the PM disc 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 [4] 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. 7.

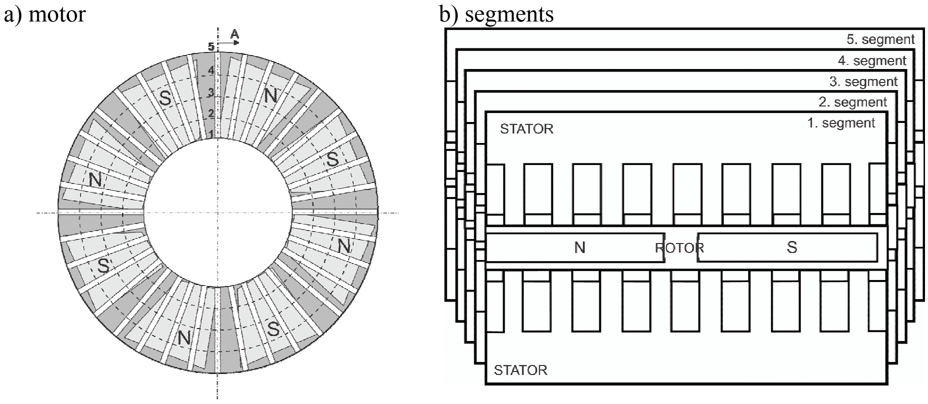
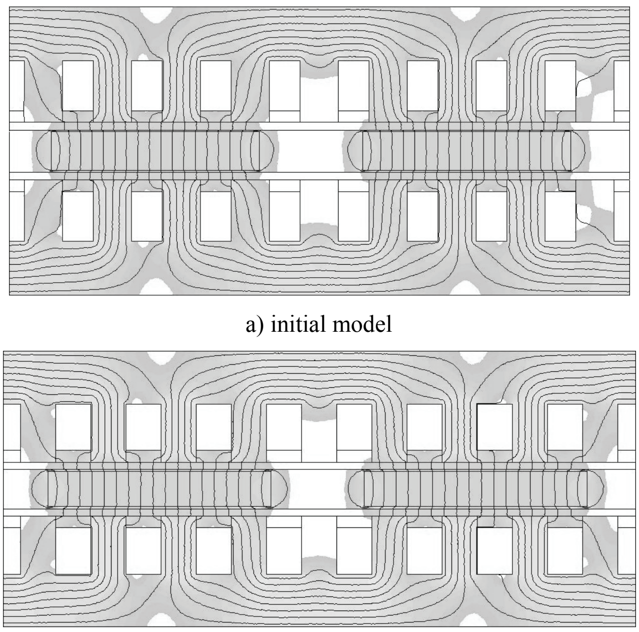


Fig. 7. Radial division of the motor into 5 segments

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.



a) initial model

b) GA optimised model

Fig. 8. Magnetic field distribution at no load in the middle segment

After the modelling of PMDM, an adequate mesh size refinement, especially in the air gap, is performed. The magnetic field calculations are performed for no load 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 GA solution is presented in Fig 8(a) and Fig. 8(b), respectively.

From the presented magnetic field distribution of the two motor models it can be concluded that in the GA model the magnetic field distribution is improved in relation to the one in the initial model. Also, the values of the flux density in certain parts of the GA model are very close to the one calculated or prescribed as an optimisation constraint.

In Fig. 9 and Fig. 10 a flux density distribution at no load in the air gap of the middle segment for both PMDM models is presented. As a result of the change of the dimensions of the motor, the air gap flux density shape and magnitude have changed. How these changes affect the overall performance of the motor, e.g. electromagnetic and cogging torque, will be analysed in the near future works.

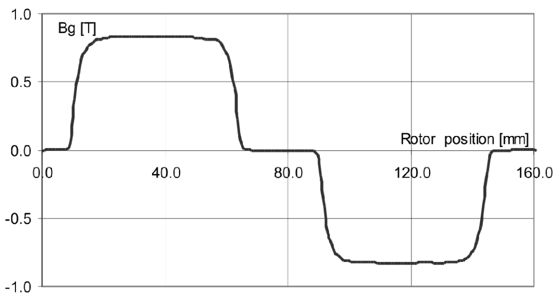


Fig. 9. Air gap flux density distribution at no load in the middle segment for the initial model

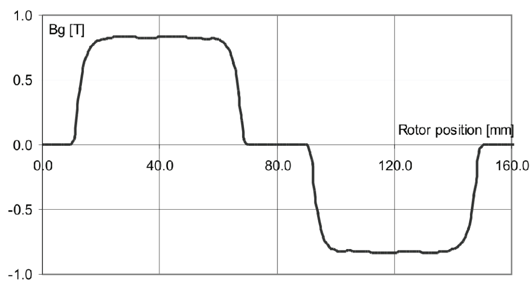


Fig. 10. Air gap flux density distribution at no load in the middle segment for the GA optimised model

5. Conclusion

The authors propose a procedure for the optimal design of PMDM with maximum efficiency, minimum PM weight, minimum iron weight and minimum copper weight at rated load and speed. The multi-objective aspect of the optimisation problem has been approached by maximising the sum of the conflicting objectives that are normalised using predefined constants. The design problem has been solved by using a genetic algorithm as an optimisation tool. The improvement of the GA optimised model has been proved through the data analysis of the prototype model and the GA solution. This improvement resulted in an efficiency improvement, reduced weight of the PMs of the motor, reduced iron weight, and reduced copper weight. At the end, the improvement of the GA solution has been proved by the comparative analysis of the two motor models using a FEM as a performance analysis tool. The proper modelling of the PMDM 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 GA solution will be constructed and tested in order to compare the calculated parameter values with the measured ones.

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