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MULTIOBJECTIVE GEOMETRY OPTIMIZATION OF BLDC MOTOR USING AN EVOLUTIONARY ALGORITHM

WIELOKRYTERIALNA OPTYMALIZACJA GEOMETRII BEZSZCZOTKOWEGO SILNIKA PRĄDU STAŁEGO Z WYKORZYSTANIEM ALGORYTMU GENETYCZNEGO

Abstract: This paper presents a methodology for the optimization of a Brush Less Direct Current motor (BLDC) with 4 poles and 24 slots. In particular, it is focused on a multiobjective optimization using a genetic algorithm developed in Matlab optimization Toolbox, that is coupled with Maxwell 14. The first one has been used for the optimization and the post-processing of the data, the second one for the Finite Element (FE) analysis and for the geometry creation. Aim of the optimization was to maximize the maximum torque value and minimize the mass of a motor. The simulation results of a 2D model showed that the coupling was possible and give satisfactory results. Using simple genetic algorithm it was possible to increase the average torque value of 25% and lower the mass of the main part of the motor of 14%. Obtained results were verified using a 3D model.

Streszczenie: W pracy przedstawiono metodę optymalizacji bezszczotkowego silnika prądu stałego z 4 czteroma biegunami i 24 żłobkami. W szczególności praca koncentruje się na optymalizacji wielokryterialnej z wykorzystaniem algorytmów genetycznych (Optimizaton Toolbox) realizowanych w środowisku Matlab, sprzęgniętym ze środowiskiem Maxwell 14. Matlab został użyty do przeprowadzenia procesu optymalizacji oraz przetwarzania danych liczbowych. Środowisko Maxwell zostało użyte do tworzenia geometrii oraz do przeprowadzenia obliczeń Metodą Elementów Skończonych. Celem pracy była maksymalizacja wartości momentu maksymalnego silnika przy minimalnej masie silnika. Wyniki badań symulacyjnych wykonanych dla modelu 2D pokazały, że sprzęgnięcie obu pakietów obliczeniowych jest możliwe i daje satysfakcjonujące rezultaty. Wykorzystując prosty algorytm genetyczny uzyskano 25% wzrost wartości średniej momentu silnika przy spadku masy silnika o 14%. Otrzymane wyniki zostały poddane weryfikacji z wykorzystaniem modelu 3D.

Keywords: *synchronous motor, optimization, genetic algorithm, Pareto Front*
Słowa kluczowe: *silnik synchroniczny, optymalizacja, algorytm genetyczny, front Pareto*

1. Introduction

Nowadays it became clear that the shape design of electromagnetic devices has to fulfill multiple objectives concurrently [1,2,3]. The objectives of the optimization are not always the same because they vary with the application in which the device is used [4, 5, 6]. In a multi-criteria optimization (MCO) the general solution is represented by the Pareto front of non-dominated solutions. This represents the list of all the designs that allow to reach the objectives of the optimization. Only one of these solutions will be selected, thanks to the experience and the personal evaluations of the designer that may consider further mechanical and thermal constraints. In the last decade, in many fields of engineering, evolutionary algorithms have been developed in order to find properly the Pareto front [2].

BLDC motors are being manufactured and used increasingly from low to medium power range applications due to their inherent advantages – high efficiency, high torque/mass parameter value, low rotor moment of inertia and very simple control systems [7]. Such features can be achieved thanks to the development in the field of materials engineering and power electronics. It is of great interest to improve motor geometry by design optimization, thus reduce production costs and improve performance of the motors [8].

In recent years, compact and high efficiency brushless direct current motors are being increasingly used in many industry sectors in new applications such as robots, electric vehicles, elevators, or as alternatives to induction motors in current applications [7, 9].

Increasing capabilities of nowadays tools and packages connected with greater performance of computers allowed to successfully achieve good results in optimization of electrical machines with a computational cost compatible with the industrial processes.

The aim of the article is to present simple optimization capabilities of combined software packages in the field of BLDC motor geometry optimization process.

2. Design problem

The case of study is represented by a Brushless DC Motor, with a rated speed of 1500 rpm, rated power of 550 W and rated voltage of 220 V. Design variables are presented in Table 1 and showed in Figure 1.

The motor consist of PM type XG196/96 (B_R=0.96T, 690'000A/m) with 2 phase whole–coiled winding (30 conductor per slot). The rated torque of a model is 3.5Nm.

Design Variables	x1 [mm] Rotor Outer Diameter	x2 [mm] Rotor Inner Diameter	x3 [mm] Stator Outer Diameter	x4 [mm] Magnet Thickness
Prototype	74	26	120	3.5

Tab. 1. Values of design variables

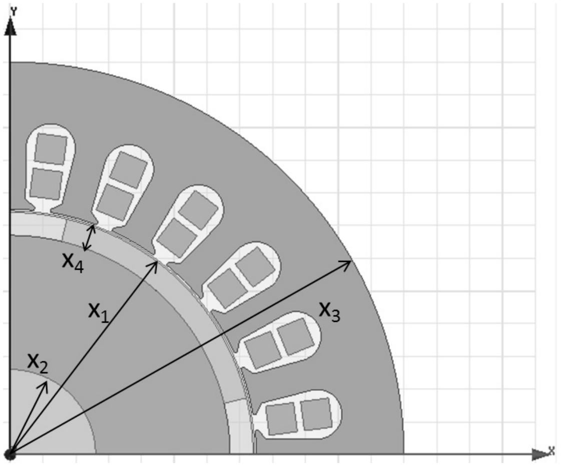

Fig. 1. Design variables

3. Multiobjective optimization

Generally multiobjective optimization involves minimizing or maximizing multiple objective functions to a set of constraints. The inverse problem consists of identifying the feasible geometries of the machine in order to maximize the torque and minimize the mass. This set of objectives is of great interest in all the problems of optimization of modern motors applied in electrical vehicles [2, 3, 10], where maximum torque provides the maximum acceleration, while minimum weight is necessary in order to lighten cars and lower the price of a hybrid or electric vehicle. The following objective functions are defined:

$$f_1(x) = \int_\Omega \rho(x) d\Omega \qquad (1)$$

$$f_2(x) = T(x) \qquad (2)$$

where ρ is the density of materials and T is the torque.

The first equation represents the mass of the motor that has to be minimized, while the second one represents the nominal torque that has to be maximized. With regard to the time consumption for the evaluation of the functions, the first one is a geometry dependent function and the cost for its calculation is almost inexpensive, while the torque is field-dependent and needs many iterations of nonlinear FE analysis. As mentioned in the introduction, there may exist multiple solutions to this problem. After solving the MCO problem a set of optimal non-dominated solutions is generated and the Pareto Front is determined. With the information provided by the Pareto Front, the motor designer may select the proper geometry, according to his designing experience. The direct problem has been solved using a 2D FE model of the motor, calculating the torque with the virtual work principle. Even if the shape of the motor changes and the mesh changes for every model, the number of elements of the mesh is almost the same in every model. The first and the final geometry were verified with the 3D model.

4. Matlab and Maxwell

Linking Matlab with Maxwell is a good way to solve optimization problems regarding the electrical machines. In fact, Matlab is a powerful software for numerical analysis that allows, thanks to the ActiveX controls, to command other software and to exchange data with them. All of the calculations, optimization and post-processing are carried out by Matlab, while all the geometry variations, model meshing and FE calculations are carried out by Maxwell. Starting from one of the BLDC sample models that are present in Maxwell, Matlab begins the optimization and changes all the design variables values following the Genetic Algorithm rules. When the algorithm reaches the stopping criteria (e.g. maximum generations number, maximum computation time, etc.) Matlab closes Maxwell and plots the Pareto front.

In Fig. 2 the flow-chart of the whole process is presented.

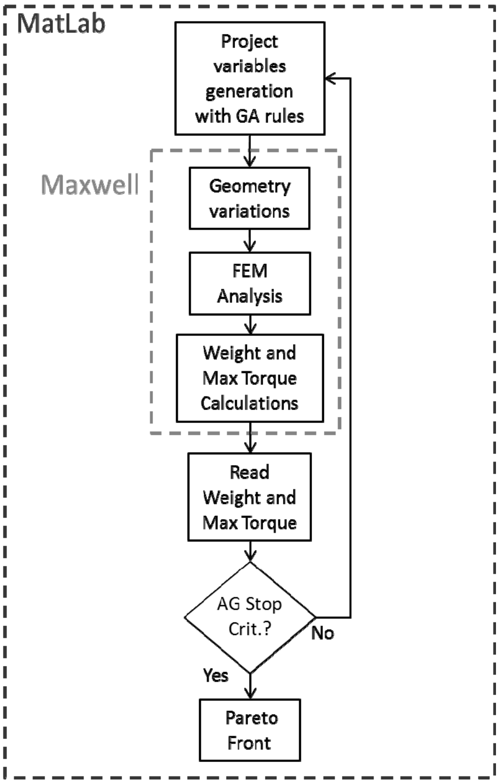

Fig. 2. Process flow chart

5. Genetic Algorithm Setup

Matlab's multiobjective genetic algorithm has different parameters that the users can set up; it is possible to define the number of design variables and their upper and lower bounds, constraints of the variables values, the stopping criteria (e.g. maximum generation limit, time limit, etc.), the number of individuals for each population, the number of individuals of the Pareto Front and so on.

In the case of study all the parameters were left at their default values, with exception of the number of variables and of the stopping criteria (maximum generations number):

Number of variables: 4;
Maximum generations number: 20;
Number of individuals for each population: 60;
Number of individuals in the Pareto Front: 21.

In Table 2 upper and lower boundaries for the variables are reported; the air-gap is kept constant at a width of 1 mm.

Design Variables	x_1 [mm] Rotor Outer Diameter	x_2 [mm] Rotor Inner Diameter	x_3 [mm] Stator Outer Diameter	x_4 [mm] Magnet Thickness
Lower	70	20	110	2.5
Upper	74	26	180	3.5

Tab. 2. Upper and Lower Boundaries

6. Maxwell Setup

In Maxwell all the settings were left at the default values that are generated automatically when a 2D model is created. The analyzed model is just a quarter of motor, because the software sets the proper boundary conditions. The solver is set to 'transient', because the software automatically moves the rotor in order to describe the behavior of the machine during one round of the motor shaft. The automatically generated mesh is made up of almost 1800 elements. Some simulations were run in order to check if a higher number of elements of the mesh could have affected the values of maximum torque; the result was that this value was almost the same even with more elements. Considering that, the whole algorithm creates 1200 models, it is useful to keep the low number of elements if possible, in order to achieve the low computational time.

Every FEM analysis lasted for 240 seconds (for the i5 2.5GHz, 8GB RAM computer), so that the whole optimization process lasted approximately 240s*1200=288'000s=80h.

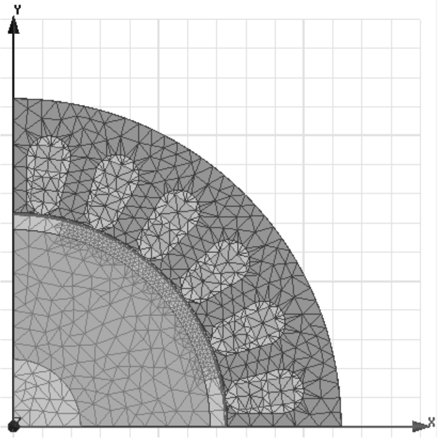

Fig. 3. Solution mesh

For the cogging torque calculation, in order to have a smoother waveform, the mesh was substituted with another one made of almost 6000 elements. Of course, it is possible to change the density of the mesh, changing proper mesh parameters.

7. Results

The first result generated by Matlab is the Pareto Front, a graph that shows a family of non-dominated solutions. The designer should choose the optimal solution from this graph. There is not a model that is absolutely better than the others, all of them are feasible and the choice can be made taking in to account other features that the motor should have. Figure 4 shows the Pareto front obtained during the optimization process.

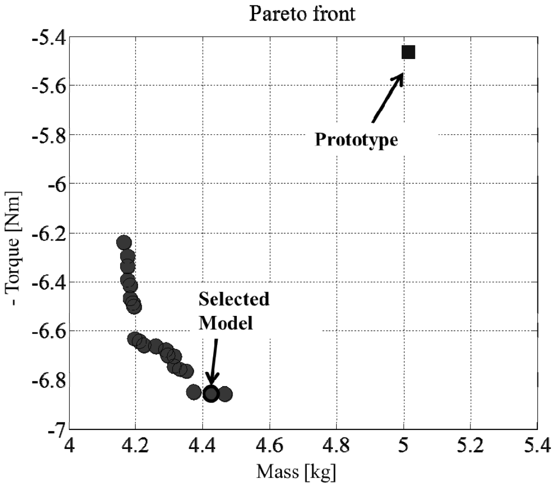

Fig. 4. Pareto Front

Let's assume to choose the model with the highest maximum torque between all the others; this model is indicated in the Pareto front in Fig. 4. The geometric differences between the selected model and the prototype are presented in Table 3.

Design Variables	x_1 [mm] Rotor Outer Diameter	x_2 [mm] Rotor Inner Diameter	x_3 [mm] Stator Outer Diameter	x_4 [mm] Magnet Thickness
Prototype	74	26	120	3.5
Optimized model	72.7	23.1	112.8	2.53

Tab. 3. Initial and final values of design variables

As it can be seen, a general reduction of the dimensions of the motor is obtained; interesting result is the reduction of the thickness of PMs, because it implies a reduction of the material needed for the magnets and, consequently, a reduction of the cost of the motor.

Figure 5 shows torque ripple defined as the ratio between RMS/Mean values of the torque and fig. 6 shows the waveforms of the cogging torque between two teeth for the prototype model and for the optimized one. It is important that the torque ripples did not change significantly in the function of the model dimensions and thus the increase in the maximum torque also meant the increase in the average torque value.

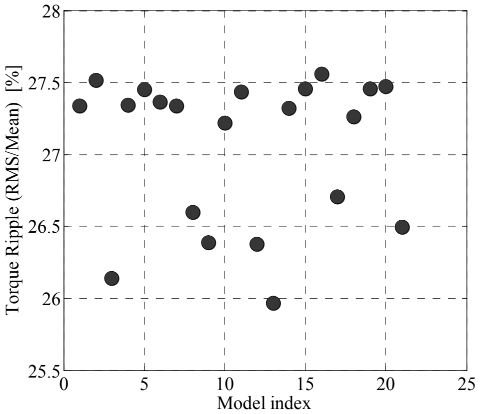

Fig. 5. Torque ripple for each model

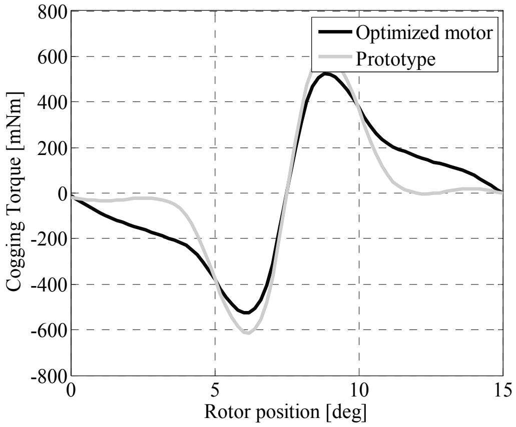

Fig. 6. Cogging torque

Figure 7 illustrates the torque developed during the start-up of the motor. The maximum and average value of torque is increased in comparison with default model.

Figure 8 illustrates the cross section of pre- and post-optimized geometries.

Results were verified using the 3D model (Fig. 10) – the differences for cogging torque and torque value were non-significant.

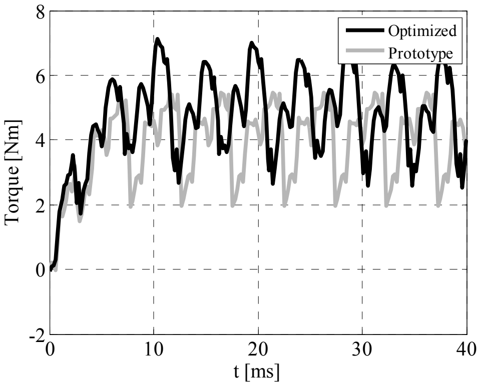

Fig. 7. Torque for 3D models

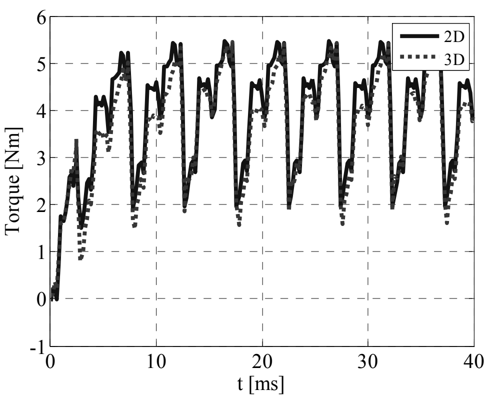

Fig. 8. 2D and 3D default model comparison

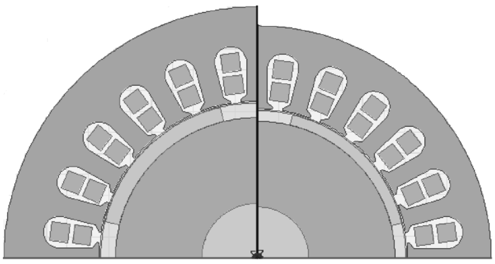

Fig. 9. Geometries comparison: Prototype motor (left), optimized motor (right)

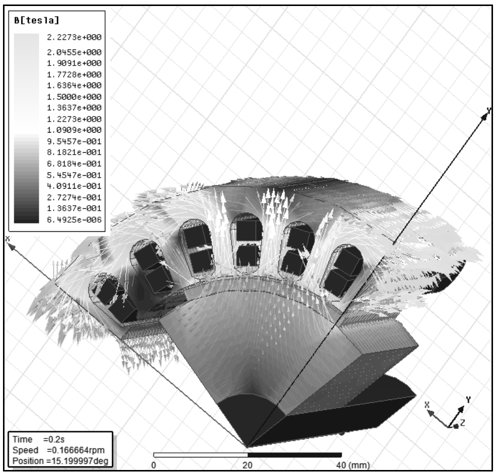

Fig. 10. 3D model with B vector plot

8. Conclusions

The improvement of motor performance is significant. The simulation points out the benefits of the optimization using a genetic algorithm. In fact, if such improvement has been possible with just four design variables, certainly, even better performances improvement will be achieved using more design variables, selected properly according to the design needs (e.g. the polar shoes shape, the skewing of the magnets, etc).

In particular, Matlab is very helpful for its capability in different kind of optimization and in post processing the data; Maxwell, instead, is a well-known software for the design and the analysis of electrical machines via FEM. It is needless to say that Maxwell can be also connected with Simplorer, thus whole performance of a drive system may be evaluated [4].

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