Topological optimization of the design of a permanent magnet synchronous motor using a genetic algorithm

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Abstract. The operating efficiency of a synchronous motor strongly depends on the design of its component parts, including the arrangement of materials (topology) of the rotor. An important element of the rotor, and at the same time the most expensive, are permanent magnets made of NdFeB material. Topological optimization allows you to reduce the volume of permanent magnets, which will reduce the price of the motor, or switch to cheaper materials, for example, ferrite, while maintaining performance characteristics. A genetic algorithm is used as a search method. And an important feature is that topological optimization is complex; not only electromagnetic parameters are checked, but also the thermal and strength characteristics of a synchronous motor. This test allows us to obtain designs that can be manufactured in practice. The article discusses the developed method of complex topological optimization using a genetic algorithm, optimization results and methods for testing the resulting structures. Optimization allows you to reduce the volume of NdFeB magnets by 22-32%, which reduces the cost of the motor by 14-21%, or switch to ferrite magnets, which reduces the cost by 24-33%, while the torque value changes within 2%, which indicates about conservation of torque.

1 Introduction

Improving design efficiency without additional investments is a promising area of research, not only for power engineering and mechanical engineering, and one of such methods is topological optimization. This idea is not new, and it has been used in construction and strength calculations for a long time, and effectively. But for optimization of electric machine design, topology change is a relatively fresh area of research, and only in the last 5-10 years it has been actively developed [1-4].

The object of study - permanent magnet synchronous motors (PMSM) is chosen for several reasons.

1. This type of motor has the greatest potential for topological optimization because of the specifics of the rotor design. The large topology area and the standard magnet arrangements used only make it possible to obtain promising results [5].

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2. The work is done with NdFeB permanent magnets, the cost of which can reach up to 50% of the cost of the whole motor, and there is a risk with the supply of material, as up to 90% of the raw material suppliers are in China. And through optimization, we can reduce the volume of these magnets or switch to other types (e.g. ferrite magnets) [6].
3. Synchronous motors with permanent magnets are in the trend, they are, today, the main type of motors for electric transportation, which indicates the relevance of research [7].

The paper will present the result of the development of complex topological optimization, the implementation of the algorithm, the work of genetic algorithm [8-11]. On the basis of the method results are obtained, some of which have been experimentally verified, and the effectiveness of the method is confirmed, at least for a particular design variant.

2 Method of complex topological optimization using genetic algorithm

First, we need to define why we use an integrated approach in the implementation of topological optimization.

Simple optimization by electromagnetic calculation (defining the torque value as the target function) will provide the most efficient design, but it will be difficult to implement this design due to two factors:

1. NdFeB magnets have an irreversible demagnetization temperature (approximately equal to 180°C), after which the motor performance will decrease to the minimum values. Therefore, the method item to check the rotor heating temperature during operation is mandatory.
2. When the rotor topology is changed, there is a possibility of deteriorating the strength characteristics of the motor, which will lead to a change in the air gap value, and this in turn will lead to a decrease in the efficiency of the electric machine.

Thus, the method will consist of 4 steps:

1. 1 Topological optimization based on the calculation of electromagnetic parameters (the target function is torque).
2. Topological optimization based on the calculation of thermal parameters (target function - rotor temperature).
3. Topological optimization on the basis of strength parameters calculation (target function - air gap value).
4. Verification of the final topology for the initial target parameters.

Stages 2,3,4 are iterative, and in case of failure to achieve the specified parameters, the return to the previous stage takes place.

Let's consider more features of the implementation of the method of complex topological optimization.

Optimization will not be performed for the entire engine design, but only for a sector of 45°C, this is due to the symmetry of the engine, and proved in the works of both the author of the article and other researchers, while the calculation time is reduced by 3-4 times.

As a method of enumeration of variants (rotor topologies) genetic algorithm is used, the advantages of which are suitable for solving the problem posed by the authors. But an important feature is the mandatory use of the mutation stage to solve problems with getting into local optima.

For example, let us consider the 1st stage of calculation of optimization by torque (Figure 1). Let's consider a simple example when the rotor topology consists of only 11 cells for clarity. First, we randomly get 4 sequences of numbers, where each sequence is responsible for a certain material. Then there is a calculation for each variant of the torque value based on the definition of the electromagnetic field of the motor, 19 times the calculation is done to simulate the rotation of the rotor and interaction with a different combination of stator slots. And then there are the standard steps of the genetic algorithm: selection for crossbreeding, crossbreeding, mutation, creation of the next generation.

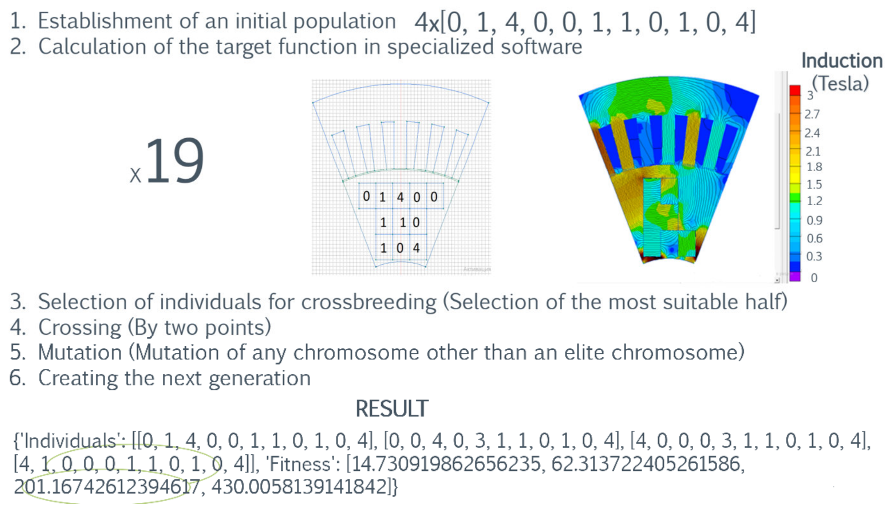


Fig. 1. Example of topological optimization stage by electromagnetic parameter calculations using genetic algorithm.

The end of optimization occurs after reaching two options: reaching a predetermined, or at a certain number of repetitions, value of the target function.

A similar method is used to verify the temperature performance, the only feature is the initial verification of the design obtained after optimization by electromagnetic design. If the rotor temperature does not reach 180°C, the algorithm proceeds to the next step. In the negative case, topological optimization is carried out.

In order to verify the strength characteristics, the following paragraph of the method "Calculation of permanent magnet synchronous motor air gap change to verify the results of comprehensive topological optimization" is used.

In the role of the target function will be the change of the air gap of the synchronous motor with permanent magnets, a reduction in the size of which may lead to a decrease in the energy characteristics of the machine, and to the impossibility of implementing the design of the optimized motor in practice.

The item is designed to determine whether the measured parameter (change in the value of the air gap) is within the permissible limits, and in case of a negative variant, topological optimization of the rotor of a permanent magnet synchronous motor is carried out in order to increase the strength characteristics of the electric machine.

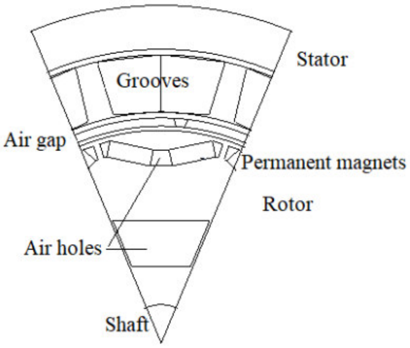
3 Topology optimization results

The developed method of complex topological optimization was implemented for two cases:

1. changing the arrangement of NdFeB magnets.
2. Replacement of NdFeB magnets with ferrite magnets.

PMSMs with surface magnet arrangement on the rotor, standard design, were used. Topological optimization was performed for these motor models and motor sectors with the new magnet arrangement were obtained.

Figure 2 demonstrates the model with the new arrangement of NdFeB magnets, which theoretically allowed to reduce the volume of permanent magnets by 30%, and a real rotor prototype was assembled in practice, also shown in Figure 2.



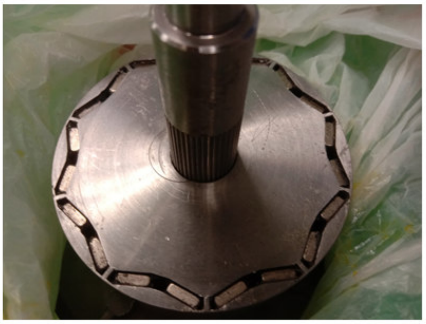
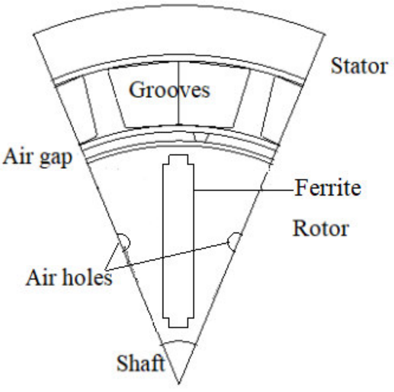


Fig. 2. PMSM with new magnet arrangement.

Figure 3 shows the performance result when topologically optimized replacement with ferrite magnets. Although the volume of magnets increased by more than 110%, the reduction in the cost of the motor was 15%, due to the low cost of the ferrite magnets themselves.



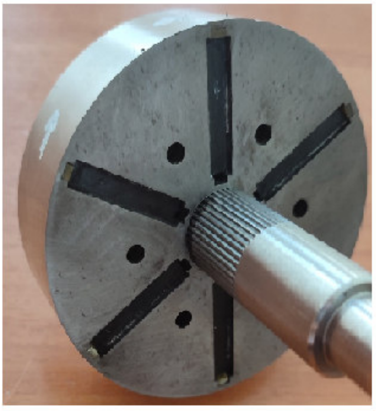


Fig. 3. PMSM rotor with ferrite magnets.

Thus, theoretical calculations confirmed the effectiveness of complex topological optimization, and there is a need to verify the obtained models and experimental data.

4 Checking the results of topological optimization

The resulting structures, after carrying out complex topological optimization, must be checked for maintaining operational characteristics, namely torque and rotational speed [12].

For this purpose, a diagram of a modernized experimental stand has been developed to test the results of complex topological optimization of PMSM, presented in Figure 1222.

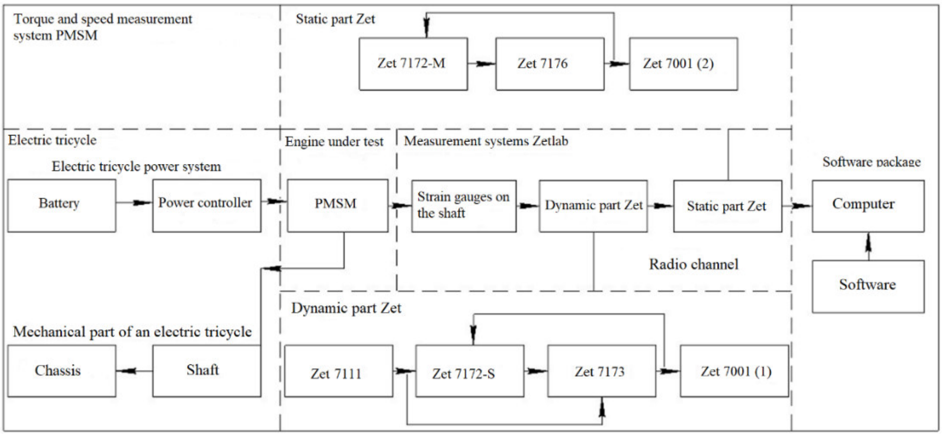


Fig. 4. Diagram of the torque and speed measurement system.

An electric tricycle was selected as a load in the stand system (and not an asynchronous motor in antiphase, as previously planned). The electric tricycle will be responsible for the load as an electric vehicle, simulating the full operation of an electric motor. Integration into the stand will be carried out by transferring the modernized engines to the shaft of the electric tricycle, but it will be necessary to change its design or add a special platform in order to transfer the vehicle to a constant static position (no movement along the plane). This requirement arises from the limited capabilities of the measuring equipment and the general complexity of testing in the dynamic mode of electric vehicles. Next, it will be necessary to remove the standard engine from the electric tricycle, and implement the ability to quickly connect any engines to the mechanical part of the vehicle. And integrate all the necessary systems for measuring torque, rotation speed and temperature onto the shaft. A ready-made solution from Zetlab is used as a measuring system, which consists of a dynamic part and a static part. The strain gauges on the shaft transmit information to the 7111, which converts to digital values, and transmits to the 7172-S, which transmits via Bluetooth to the 7172-M, and to the 7173, which stores the results for signal duplication. 7176 is necessary for communication with a PC, and 7001 acts as power supplies.

Using this stand, the results of topological optimization with a decrease in the volume of NdFeB permanent magnets were checked, and experiments showed that when the volume of permanent magnets was reduced by 31%, the change in torque was ±2%, which confirms the theoretical calculations and the results of the considered method.

5 Conclusion

A comprehensive topological optimization method is suitable for obtaining efficient permanent magnet synchronous motor designs, reducing the cost, maintaining the torque value.

1. The developed method of complex topological optimization is presented, where optimization is carried out sequentially for torque value, rotor temperature and air gap value, all steps are iterative. These features of the method make it possible to obtain not just an efficient rotor design, but a practically feasible one.
2. Genetic algorithm with obligatory operation - mutation is used as a search method to solve the problem of hitting local optima.
3. Optimization results are presented for two cases: a new arrangement of NdFeB magnets, and replacement with ferrite magnets.

4. A schematic of the developed test bench is presented to verify the optimization results, and the experimental results obtained confirm the effectiveness of the new arrangement of NdFeB magnets.

Further research is needed to verify the design with ferrite magnets, and to optimize a new type of rotor combining NdFeB and ferrite magnets, which will not only reduce the cost of the motor, but also increase the torque value.

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