New Method of Optimal Design of Electrical Rotating Machines

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Abstract

The article presents a new method of the optimal design of the electrical rotating machine based on the genetic algorithm which can used for all electrical rotating machine types and to predict their properties. The new method for optimal design allows obtaining the new electrical rotating machine which mass is lower than mass of the conventional electrical rotating machine by two times. As the result of optimal electrical rotating machine design by using the proposed method, the value of the rotor active length is lower by 2.37 times, and the current density is higher by 1.7 times in comparison with the initial electrical rotating machine. The losses are increased by only 25% (power, rotation and materials frequency of both electrical rotating machine are the same). It was also found that the optimality of a particular design scheme, including the rotor magnetic system or the groove type depends on the complex of sizes. Moreover, the change of this complex leads to a change in the optimum design scheme.

Keywords: electrical rotating machines, optimal design, genetic algorithms

1. Introduction

The design of the new perspective Electrical Rotating Machines (ERM) with the unique characteristics and the functionality requires solving the following tasks:
a. the development of the new design schemes, the methods of calculation and design;
b. the development and the application of new materials with the previously unattainable properties;
c. the use of methods and algorithms of the rational choice of the ERM geometric dimensions (based on the price, the completeness use of the material properties and the energy characteristics);
d. the forecasting the future prospective development of the ERM and the receipt of the certain parameters under the certain material properties, possibly attainable in the future (for example, in many publications [1-3] states that the high-coercitivity permanent magnets (PM) with the higher energy characteristics are required for the increasing energy performance of the ERM, but it is not considered how to change the ERM design and materials due to the increasing the energy characteristics of the PM).

Usually, all these tasks are performed by different unrelated approaches. Initial ERM design is considered as the most efficient (the mostly used criteria is reliability, the technological effectiveness, rates, the minimum weight and dimensions at the maximum power and the maximum efficiency). Then the calculation parameters of the ERM design is carried out according to the known methods, the modern software and the methods of the Finite Element Method Magnetics (FEMM), taking into account the properties of the used materials. If necessary, the ERM geometric dimensions are optimized and adjusted. This approach necessitates the use of significant resources. This leads to the inefficient use of all materials properties; to the impossibility of identifying the most optimal ERM design; to the inability to predict the ERM development and to formulate requirements based on this forecast for materials and constructive parts of the ERM. Moreover, the traditional approach does not fully take into account the multidisciplinary of the ERM design process.

To solve the problems of traditional approaches to the ERM design, the various methods of the optimization and the ERM optimal design are offered. Most of them are devoted to the numerical optimization of the specific ERM on any parameter using the FEMM or the known methods, taking into account the multidisciplinary of the tasks, and it does not solve the problem of the ERM optimal design in the general terms. One of the main methods for solving the identified problems is the Interval Branch and Bound based Algorithms (IBBA) proposed by Frederic Messine and his research team. The IBBA allows solving the inverse problem of the ERM optimal design, i.e. the selection of the ERM optimal design under the certain size. The IBBA are based on the interval analysis and the combinatorial methods [4-8]. However, it is not always possible to find the global optimal design solution [6] and to predict the ERM design with the desired parameters and characteristics. The IBBA does not allow the prediction of the ERM development for the particular properties and conditions. Moreover, most of the solutions presented by the IBBA relate only to the ERM with high-coercivity PM.

Therefore, the aim of presented work is the creation of the new method of ERM optimal design, which can be used to optimal design of all ERM types and to the prediction of their properties.

2.   Research Method

To achieve the similar goals in other science fields (crystallography, engineering, chemistry), the design methods based on the evolutionary algorithms [9-14] are widespread. However, in electromechanics and electric power engineering, the genetic algorithms (GA) are used only for the numerical ERM optimization and for creating the ERM control systems.

In [15], the task of choosing the optimal size of the induction motor from the small parameters set has been solved using the GA; the optimality criteria is the induction motor cost. In [16], the numerical optimization of the dimensions of the synchronous motor with incorporated PM is considered using the GA. In [17], the optimization problem of the ERM pole form is solved using the GA. In [18], the optimization of the induction motor parameters is considered using the GA. In [19], the synchronous motor parameters are determined using the GA, the optimality criterion is the maximum torque. In [20], the method of the ERM size optimizing is implemented with the GA in the Ansoft Maxwell software package. Thus, the GA are used in the engineering to select any numerical parameters (for optimization purposes), but has not been used to optimal design and in the choice of the ERM constructive scheme, including the ERM type (for example, the permanent magnets ERM or the ERM with electromagnetic excitation), and has not been used for the forecasting of the ERM properties. Thereby, for solving these problems, the GA are used for the first time in Electromechanics.

3.   Algorithm Description

In the proposed algorithm, the following sequence of the actions is envisaged. Figure 1 shows a graphical representation of the proposed algorithm.

1) The initial desired ERM characteristics are defined. In particular, the capacity, type, voltage (or output voltage), frequency, rotor speed and desired mass and dimensions parameters should be defined. All of these initial parameters form the three initial sets:

a.   the set of the total parameters (the pole pairs number, the power, the speed, the construction diagram, the supply voltage, the environment temperature) – $(x_1 .. x_i) \in X_0$;

b.   the set of the materials properties, including their temperature dependence and mechanical properties – $(m_1 .. m_i) \in M_0$;

c.   the set of the initial geometrical sizes – $(r_1 .. r_i) \in R_0$.

The R_0 set is complemented by the ERM sizes at the later stage.

2) Based on the initial parameters, the structural diagram is calculated by the standard methods and the FEMM. The calculated parameters form the sets of the dimensions, the ERM characteristics and the material properties $(x_1 .. x_i) \in X_0$, $(m_{1r} .. m_{ir}) \in M_r$, $(r_{1r} .. r_{ir}) \in R_r$. The groove dimensions are represented as its area parameter. The sets of the dimensions and the material properties are fixed for the next algorithm step; the $(x_1 .. x_i) \in X_0$ set is ranged.

3) Based on the fixed geometric dimensions and the material properties, the ERM design optimization is performed using the GA. The GA is chosen because the solution of this problem is practically impossible by using the exhaustive method due to the variety of competitive options. The use of the traditional optimization methods based on the mathematical operations with the derivative of the fitness function is also impossible for this task, as the mathematical formulation of the fitness function requires the sufficient set of assumptions, which significantly limits the accuracy of the solution.
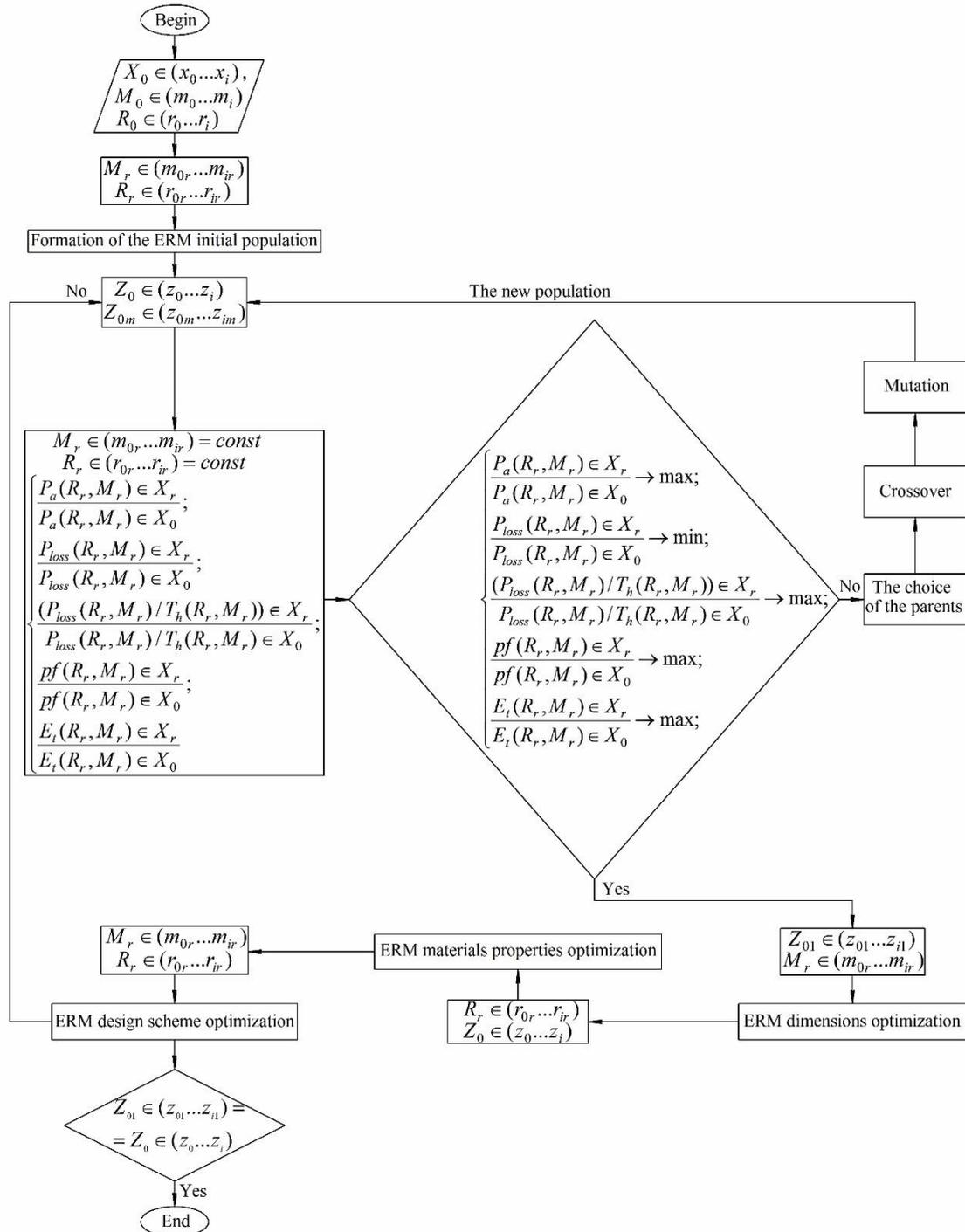
Figure 1. Graphical representation of the proposed algorithm

To implement the GA, every constructive element of the ERM (the rotor pole form, the stator groove type or the winding type, the slotted or slotless stator, the cooling system and the bearings) is encrypted in the genetic code. The use of the GA in fixed dimensions and material properties, in this case, allows quickly determining the most optimal design of the many variants and modifications. The choice of the optimal ERM design is based on the fitness function. It is obviously for this stage of the proposed algorithm that the fitness function should not be focused on the geometric dimensions, because they are fixed. Moreover, the rotation speed of the ERM rotor is considered as fixed.

For special ERM applications, the different fitness function can be used. In this work, the overall fitness function is applied: the active power or torque losses, manufacturability, power factor, as well as heat load (ratio of the ERM total losses to the temperature of its surface). The overall fitness function at this stage is formulated as follows:

$$
\begin{cases}
\dfrac{P_a(R_r, M_r) \in X_r}{P_a(R_r, M_r) \in X_0} \to \max; \\[2mm]
\dfrac{P_{loss}(R_r, M_r) \in X_r}{P_{loss}(R_r, M_r) \in X_0} \to \min; \\[2mm]
\dfrac{(P_{loss}(R_r, M_r)/T_h(R_r, M_r)) \in X_r}{P_{loss}(R_r, M_r)/T_h(R_r, M_r) \in X_0} \to \max; \\[2mm]
\dfrac{pf(R_r, M_r) \in X_r}{pf(R_r, M_r) \in X_0} \to \max; \\[2mm]
\dfrac{E_t(R_r, M_r) \in X_r}{E_t(R_r, M_r) \in X_0} \to \max; \\[2mm]
R_r = const, \\[1mm]
M_r = const,
\end{cases}
\tag{1}
$$

where P_a is the ERM active power; P_{loss} is the ERM complete loss; $\dfrac{P_{loss}}{T_h}$ is the ERM heat load;

T_h is the temperature of the ERM frame; pf is ERM power factor; E_t is the ERM manufacturability, X_r is the set of energy parameters of the considered design; X_0 is the set of energy parameters of the initially specified (in step 1) design.

Since this problem is multi-criteria, the Pareto-optimality solution is searched. In the result of this step, the $(z_1...z_i) \in Z_0$ set of the ERM optimal design is determined using the GA. It is important to note that each step of the algorithm has its own fitness function.

4) After selecting the ERM optimal design, it is necessary to optimize the geometric parameters. In this step, the $(z_1...z_i) \in Z_0$ set is fixed; the $(r_{1r}...r_{ir}) \in R_r$ set is variable. The active length of the rotor and stator, the air gap, the rotor diameter, the groove dimensions etc. are optimized by using the GA for numerical optimization, which is implemented in various software packages, e.g. in Ansys Maxwell. For this step, the fitness function is used, which is considered the materials price with their mass: the specific power, the specific power of losses and the specific thermal efficiency, the unit price and power factor (if the power is set and fixed).

$$\begin{cases} \dfrac{P_a / M_r \in M_r}{P_a(R_r, M_r) \in X_0} \to \max; \\[2ex] \dfrac{P_{loss}(R_r, M_r) \in X_r}{P_{loss}(R_r, M_r) \in X_0} \to \min; \\[2ex] \dfrac{(P_{loss}(R_r, M_r)/T_h(R_r, M_r)) \in X_r}{P_{loss}(R_r, M_r)/T_h(R_r, M_r) \in X_0} \to \max; \\[2ex] \dfrac{pf(R_r, M_r) \in X_r}{pf(R_r, M_r) \in X_0} \to \max; \\[2ex] \dfrac{E_t(R_r, M_r) \in X_r}{E_t(R_r, M_r) \in X_0} \to \max. \end{cases} \qquad (2)$$

5) In this step, the materials optimization is produced. It is performed similar to step 4 with the same fitness functions. The sets $(z_1...z_i) \in Z_0$ and $(r_{1r}...r_{ir}) \in R_r$ are constant; the set $(m_{1r}..m_{ir}) \in M_r$ is variable.

6) In the result of step 4 and step 5 of the proposed algorithm, the new sets of optimal geometrical dimensions, material properties and energy characteristics of the ERM are formed: $(x_{10}..x_{i0}) \in X_{r0}$, $(m_{10}..m_{i0}) \in M_0$, $(r_{1r0}..r_{ir0}) \in R_{r0}$. These sets allow the iteration of step 2 and step 3. The result of step 3 with a new set of fixed size is a new set, which describes the optimal ERM design for a new geometrical dimensions and material properties.

7) In this step, comparison of the Z_r and Z_0 sets is produced. If these sets are equal, the developed ERM will be considered optimal. If not, the steps 4, 5, 6, 7 will repeated with the replacement of the set Z_0 on Z_r until compliance with the equality of sets Z_0 and Z_r.

8) As a result of the proposed algorithm, 4 sets are obtained. They describe the design concept, geometric dimensions, energy performance and material properties of the optimal ERM. Thus, there is the possibility of defining such sets for different ERM types and their competitive comparison. In this case, it will be the comparison of the optimal ERM for their type and parameters. It is important to note that a similar method should be optimized the external and internal rotor.

4. The Use of the GA for ERM Design Optimization

Main part the proposed method is the use of GA. It is necessary to provide the ERM design features in the binary code form that describe the chromosome properties with allowance for the multidisciplinary of the task. Unlike the standard GA, it is proposed to use the several chromosome, each of which describes the ERM elements (Figure 2): cooling system, bearings, rotor, stator and structural elements. The latter chromosome describes the ERM type (generator or motor). Each ERM chromosome is different in size from the other chromosomes of the same ERM, but equal to its length. Each gene of the chromosome has a size ranging from 2 to 100 units and depending on the ERM properties. The ERM crossover is inside chromosomes, but the crossing point for each chromosome is individual.

This view is closer to living organisms than to the traditional GA. Therefore, in addition to the optimization problems, it will allow solving problems of the new ERM creating with optimal characteristics based on the synthesis of the plurality of structural schemes and the calculation of the fitness function. The description of the stator properties is presented in Table 1. After the formation of the ERM digital code, based on the GA rules, the initial population is formed as the combination of various ERM design. The formation of the parent population occurs by panmixia. The calculation of fitness function for this population is produced according to the step 3 of the described algorithm. For the selected pair, the crossover and mutation is produced by a roulette method, and a new ERM generation with new fitness function is formed (Figure 3).

The cooling system and the refrigerant properties	00	0110101	001	0001	101		
Housing components	00	0110101	001	00	1001	001	
Rotor	00	011	001	0001	111	001	101
⠿⠿⠿							
Bearings	00	00	01	00			
ERM type	00						

Figure 2. The description of the ERM structural characteristics

Table 1. Option of the digital code of the stator chromosome

Design parameters	Digital code
Radial / axial	00; 01; 10
External / internal	00; 01
Slotted / slotless	00; 01
The type of groove	00–1010
The number of phases	00000–10010
Type of winding	00–1010
Laminated / non-laminated	00; 01
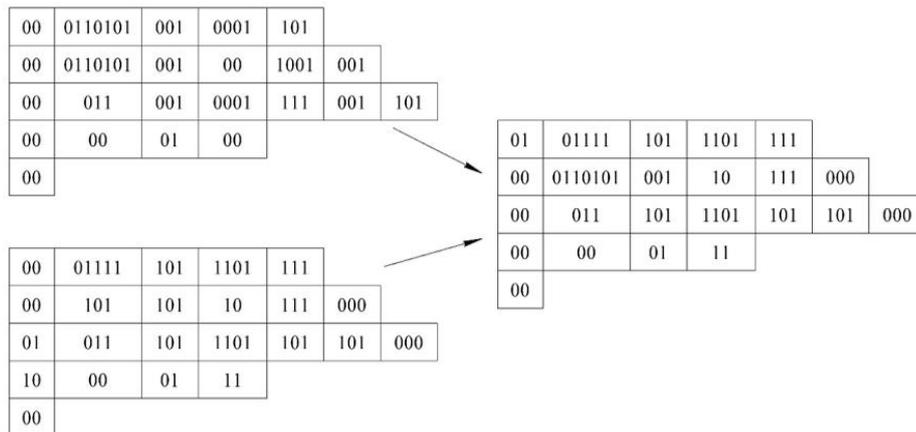
Figure 3. The crossover of two structural schemes of the ERM

5. Design and Optimization of the ERM using the Proposed Algorithm

For testing the proposed algorithm, the optimization of high-speed three-phase ERM with PM and with a capacity of 100 kW and a rotor speed of 60,000 rpm is considered. The design and main dimensions are presented in Figure 4a (they are the same to the generator of the Turbec T-100 microturbine). Cooling system of this ERM is liquid and channel.

The calculations of the original design was produced (Table 2). Based on this data, the initial sets $(x_1..x_i) \in X_0$ of material properties was formed including their temperature dependence and mechanical properties $(m_1..m_i) \in M_0$; initial geometrical sizes $(r_1..r_i) \in R_0$ and the original population of 30 individuals. As a result, the optimal design of the ERM at constant geometrical dimensions and materials properties were identified at 5 iteration (Figure 4b). Unlike the original design, the optimal design has the maximum power factor (0.9) with a minimum value of losses (1300 W), i.e. the maximum value of the fitness function.

To find the optimal geometric dimensions (the size of the air gap, the active length of stator and rotor, etc), the Ansoft Maxwell software (module Optimetrics) was used. The size optimization is carried out by four parameters (but it is possible to optimize with a larger number of parameter): the rotor active length, the inner diameter of the stator, the size of the air gap and the size of the slot gap. For each parameters, the geometric constraints were imposed. The

minimum value of the air gap is ranged from 1 to 6 mm and the minimum value of the inner stator diameter is ranged from 66 to 75 mm. The slot gap width is ranged from 0.5 mm to 5 mm (open slots). To reduce the calculation time, only one fitness function (the ratio of power factor to the total mass of the ERM) was considered. In the result, the maximum of the fitness function is observed for an air gap of 2.6 mm, the active length of 76.39 mm, the width of the slot gap of 2.16 mm and an inner diameter of the stator of 71.37 mm. This result was obtained for 123 iterations. The number of iterations was 600. The running time was 20 minutes. Calculations of the initial and optimized ERM was carried out using the same calculation methods of the Ansoft Maxwell software (module RMxprt). Due to the ERM optimization, the mass and, therefore, the materials cost are decreased by almost 2 times, while losses are increased by only 30% and the current density has not exceeded the allowable limits for the given cooling system. In addition, the ERM power factor was also increased to 0.98. Thus, the obtained results of numerical optimization are Pareto-optimality.
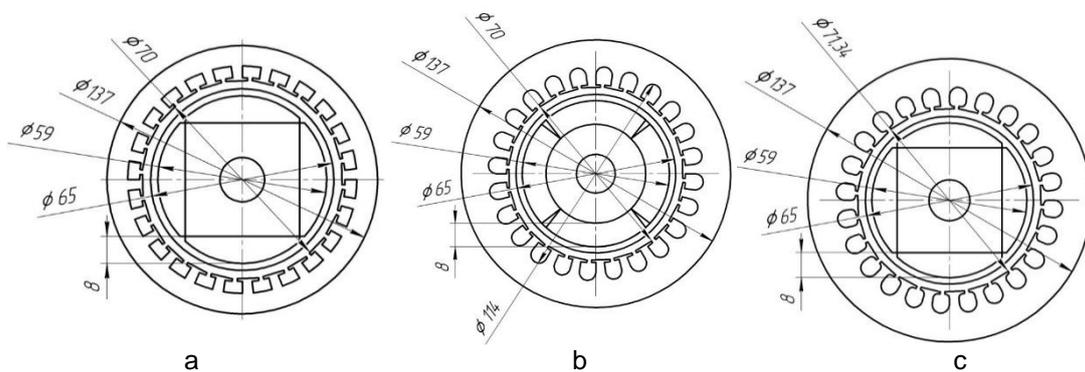
Figure 4. a. The original design for optimization of the ERM; b. Optimal design of step 5 of the proposed algorithm; c. Optimal design of step 6 of the proposed algorithm

The next step (step 6) is the check the optimality of the obtained set of dimensions and material properties for the considered design (verification of the globality of the found extrema). In the result, the optimum design with the initial size has a lower fitness function in comparison with other design. This shows the optimality of a particular design, including the magnetic rotor system or the groove type depends on the complex of sizes. The change of this leads to the change in the optimum design. In addition, for the new optimal design (Figure 4c), the power factor is 0.99, the loss equal to 1775 W (for design of Fig. 4b, the power factor is 0.98, the loss is 1790 W). Table 2 shows a comparison of the initial and optimized ERM. The maximum of the fitness function for this ERM is observed for the air gap of 0.8 mm (the non-magnetic gap is 3.8 mm), the active length of 70.39 mm, the width of the slot gap of 4.1 mm and the inner diameter of the stator of 67.74 mm. This result was obtained for 154 iterations. The number of iterations was 600. The running time was 20 minutes.

For these dimensions, the re-optimization of the constructive scheme was carried out using the GA that shows the selected design of ERM is optimal.

Table 2. Comparison of the initial and optimized ERM

Parameters	Initial ERM	Optimized ERM
Rotor speed, rpm / current frequency, Hz	60000 / 2000	60000 / 2000
Mass of the ERM, kg	24.158	11
Active length, mm^2	165	70
Current density, A/mm^2	3.16	5.43
Induction in the air gap, T	0.589	0.687885
The area of the groove, mm^2	199	200
The type of magnet / type of steel	Sm_2Co_{17} / 2421	Sm_2Co_{17} / 2421
Loss, W	1390	1640
The width of the slot gap, mm	1	4,12
Power factor	0.88	0.99

6. Results and conclusion

The article presents a new method of optimal ERM design based on the GA. The mathematical description of the proposed algorithm is developed, and optimal design of the high-speed ERM by proposed method is performed. The new method for optimal design allows obtaining the new ERM which mass is lower than mass of the conventional ERM by two times.

As the result of optimal ERM design by using the proposed method, the value of the rotor active length is lower by 2.37 times, and the current density is higher by 1.7 times in comparison with the initial ERM. The losses are increased by only 25% (power, rotation and materials frequency of both ERM are the same). It was also found that the optimality of a particular design scheme, including the rotor magnetic system or the groove type depends on the complex of sizes. Moreover, the change of this complex leads to a change in the optimum design scheme.

The presented method can used to optimal design of all ERM types and to predict their properties.

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