COMPUTER-AIDED DESIGN SYSTEMS

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DESIGN OF SYNCHRONOUS GENERATOR WITH PERMANENT MAGNETS BASED ON GENETIC ALGORITHM

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Abstract**—***The synchronous generator with permanent magnets is proposed as an effective mean for transformation mechanical energy in electrical one under its use in wind energy plant with vertical rotors. It is considered the design problem of synchronous generator with permanent magnets. It is shown that this problem is the problem of conditional multicriteria optimization. The objective functions of this task are: machine cost, energy loss, weight loss, torque of rotation. The approach of its transformation into unconditional multicriteria optimization is proposed. Based on analysis of magnetic field it is determined the basic parameters of generator which strong influence on its efficiency. For the problem solution of given problem it is used the genetic algorithm. The structure of chromosome is determined. The results of design are represented.*

Index Terms—Synchronous generator with permanent magnets; multicriteria optimization; genetic algorithm.

I. INTRODUCTION

Synchronous generator (SG) with permanent magnets (PM) has a number of advantages: high efficiency, low losses, high mass and dimensions, high overload capacity, reliability, and a wide range of regulation [1].

Designing such an object is a challenging problem. The generator has a complex structure and a large number of parameters. In addition, most of the design requirements are in conflict with each other, for example, minimizing the volume or mass while ensuring optimal power.

At sufficiently large diameter of D_p rotor even for SG of small power the main mass of magnets is concentrated on the periphery of the rotor, the internal volume of which is underutilized in the magnetic relation, however, the considerations of increasing the moment of inertia of rotating masses dictate the necessity to make the rotor core a massive one. For a star-type rotor, the pole width of the producing magnet is naturally determined by the pole fission τ (with a certain pole overlap coefficient of a_δ), and its thickness h_m should provide the calculated volume of magnet V_m. It is clear, therefore, that one of the main design tasks is to determine the optimal ratio between the magnet size, volume and main geometric dimensions of the stator bore, i.e. active length L, and diameter D. These ratios naturally include many other parameters of the magnetic circuit, as well as the stator winding, mass and energy parameters [1].

Relationships for calculating the size of the magnet and the magnetic circuit of the rotor depend on the type of magnetic system, and the required volume of magnets is mainly determined by the power and nature of the load, the parameters of the magnets themselves and the ratios of certain coefficients characterizing the magnetic circuit. At the same time, electromagnetic loads ($A1$ and B_δ) and air gap are quite interrelated with the magnet sizes. Thus, it turns out to be extremely necessary at the stage of formation of the initial data for the design of SG to conduct a comparative assessment of the ratios of geometric dimensions of the stator and rotor, as well as the magnetic system, and on this basis to choose the variant at which the highest value of electromagnetic power (or torque) is achieved.

Therefore, the definition of a variant of such generator structure, which would satisfy all the criteria and technical limitations, will requires a lot of work. Therefore, the task of designing is a task of multi-criteria optimization (MCO). To solve this problem, a system approach based on an iterative scheme is required, which gradually leads to an optimal solution.

Basically, there are two approaches to solving the problem: the classical approach and the approach of evolutionary algorithms.

The classical approach has a large number of algorithms, developed by researchers in mathematics. These algorithms usually give one solution. Many of them transform the MCO problem into a single-criterion problem. As examples, we can cite the scalar convolution method, the ε method-limitations, lexicographical ordering and target programming [2], [3].

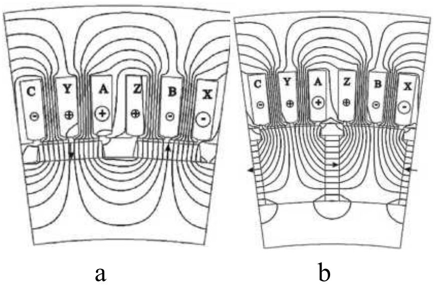
On the other hand, the approach of evolutionary algorithms represents a new field of research. The evolutionary algorithm preserves the population of solutions during the entire optimization process, so at the end of the optimization process there are many solutions.

It is better to get a lot of solutions instead of one for the task of multi-criteria optimization [5], and consequently evolutionary algorithms represent a more attractive approach.

This paper considers the genetic algorithm, which is the most famous of the evolutionary algorithms. The implementation of the genetic algorithm on a computer and its application to optimize the parameters of the synchronous generator are presented also.

II. EFFECT OF MAGNETIC SYSTEM CONFIGURATION

The configuration of the magnetic system of an electric machine has a significant influence on its characteristics [3], [5]. Figure 1a shows the picture of the magnetic field in the cross-section of the investigated generator with radial magnetization of PM on the rotor, and Fig. 1b – with tangential one. The vector of PM magnetization in this figure is shown by arrows. At calculation boundary conditions are accepted: $A = 0$ for the upper and lower bounds of the calculation area, for the right and left bounds of the calculation area – even periodicity ($A1 = A2$).

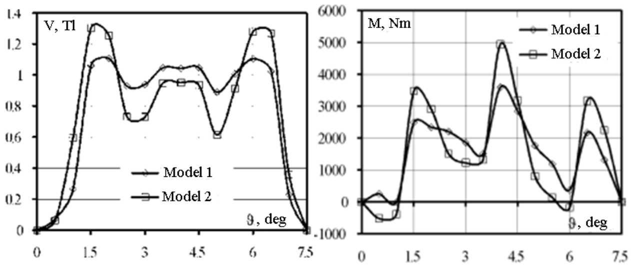


a b

Fig. 1. SGPM magnetic field patterns for a given time point

In Figure 1, the magnetic permeability of magnets is $\mu_m = 1.05$. Figure 2a the distribution curve of the normal (radial) magnetic induction component $B = D$) in the middle of the air gap within one pole fission τ for two generator models, respectively, with radial (model 1) and tangential (model 2) magnetization of PM.

As shown on the Fig. 3, the distribution of magnetic induction in the air gap depends significantly on the configuration of the rotor magnetic system: for model 2, there is a very large difference between the maximum and minimum values of induction in the air gap, for model 1, the distribution graph of the normal magnetic induction component has a form closer to trapezoidal, and the difference between the average minimum values of induction between the two models is an average of 0.2 Tl. Figure 2b shows the picture of the braking electromagnetic moment *M*, acting at the breastplate. As can be seen from Fig. 2b, the electromagnetic moment also depends significantly on the configuration of the rotor magnetic system.



a b

Fig. 2. Field and torque dependencies on the rotation angle within the pole division

For model 1 (with radial magnetization of PM), the torque ripple is significantly less than for model 2 (with tangential magnetization of PM). Taking into account these results, as well as the technological features of the assembly at the second stage of numerical research, a variant of the rotor design with radial magnetization of magnets at the same stator design was considered.

The purpose of the second stage of the numerical study was to determine the influence of the PM size on the value of the generator electromagnetic moment according to model 1. The initial PM size – width at the base $b_{m1} = 32$ mm, thickness $h_m = 7$ mm.

Since the pole fission width and the pole overlap coefficient for the structure in question are not subject to change, a series of calculations was made for the values of the PM width not exceeding the initial value – $b_{m1} = 28.6$ mm, $b_{m1} = 25.3$ mm and $b_{m1} = 21.9$ mm.

From the point of view of maximizing the use of the SGPM, choosing its geometry as a whole, including both the size of the rotor with permanent magnets and the configuration of the stator core, it is interesting to consider different variants of the ratio of the groove height and stator yoke, as well as changes in the diameter of the inner bore of the stator and, accordingly, the outer diameter of the rotor. It will give the possibility of the most correct choice of the basic ratios of the machine at a stage of formation of the order for stamping of sheets of electrotechnical steel and assemblage of a package.

For these reasons, for the SGPM variant under consideration, the values of the outer diameter D, the width of the slot h_g and the active length L_i varied the values of the height of the slot h_g and the values of D and D_r in the following proportions: initial values: $h_g = 26$ mm, $D = 630$ mm, $D_r = 628$ mm; increase in the height of the slot up to $h_g = 45$ mm at $D = 630$ mm and $D_r = 628$ mm; decrease in the diameter up to $D = 592$ mm, $D_r = 590$ mm at the same height $h_g = {=}45$ mm; the same with increase in the height up to $h_g = 64$ mm. In this case it is a question of estimation of possibilities, at invariable overall dimensions (D and L), increase in active power of SGPM at the expense of increase in linear loading of a stator at simultaneous decrease in the sizes and weight (at smaller diameter of a rotor) of constant magnets which in an initial variant for reasons of preservation of mechanical durability have been chosen overestimated.

On the Figure 3 the calculated dependencies of the electromagnetic moment on the rotor angle of all the above models are shown. The basis is a magnetic system configuration with a PM width of b_{m1} = 28.6 mm, at which the value of the electromagnetic moment and its ripple are determined as acceptable (Fig. 3).

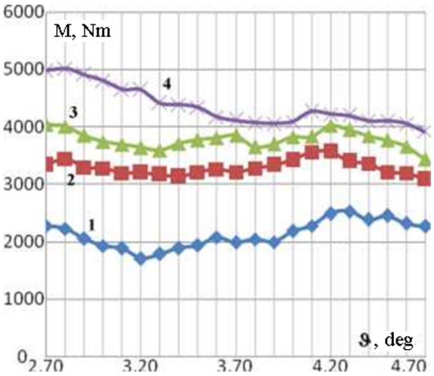


Fig. 3. Influence of stator and rotor geometry on the value of SGPM electromagnetic moment at different values of rotor rotation angle: *1* are $h_g = 26$ mm; $D_r = 628$ mm; *2* are $h_g = 45$ mm, $D_p = 590$ mm; *3* are $h_g = 45$ mm, $D_r = 628$ mm; *4* are $h_g = 64$ mm, $D_p = 590$ mm

The results of the computer simulation show that the configuration of the magnetic system, including the PM, the ferromagnetic inserts between the magnets and the winding elements of the stator, have a significant influence on the characteristics of the synchronous generator. At the stage of preliminary design of the generator with PM, the distribution of the radial component of the magnetic induction in the machine gap at the pole width is important and must be taken into account as the main factor determining the dependence of the electromagnetic moment on the rotor angle of rotation.

It is clear that the final decisions on all geometric and electromagnetic parameters, winding data and sizes of permanent magnets can be made only after the complete calculation of SG, the construction of the working diagram of the magnet of its characteristics, as well as the thermal calculation at nominal load [10].

III. PROBLEM STATEMENT

The machine design can be described by the parameter vector ($\vec{x}$) (dimensions, dimensionless parameters, types of materials used, etc.). The design takes into account many m-restrictions, which may include technical standards, electromagnetic, thermal, mechanical or manufacturing limitations. The purpose of optimization is to maximize the selected target functions $\vec{f}(\vec{x})$, and to provide technical indicators within the allowable areas.

The general task of multi-criteria optimization is formulated as follows: to find the vector of parameters $\vec{x} = [x_1, x_2, ..., x_n]T \in S$, taking into account m-restriction functions

$$g_j(\vec{x}) \le 0, \quad j = 1, ..., m, \tag{1}$$

to maximize the vector of criteria (target functions) $\vec{f}(\vec{x}) = [f_1(\vec{x}), f_2(\vec{x}), ..., f_p(\vec{x}),] \to \max.$

IV. PROBLEM SOLUTION

Functions of limitation imposed by technological requirements and restrictions on the development of the generator. One of the methods of accounting for the limitations of the type of inequalities (1) is that an extended criterion:

$$F_k(\vec{x})x = f_k(\vec{x}) - \sum \lambda_{jkg} j(\vec{x}), \tag{4}$$

where λ_{jk} is the penalty factor for the target function f_k $(\vec{x})$, if the limit $g(x_j) \le 0$ is breached $j = 1, ..., m$; $k = 1, ..., p$.

This method allows to convert a task with restriction functions into a task without restriction function. However, the choice of suitable penalty coefficients is not easy. The engineer chooses the coefficient based on his experience and / or receives it after several optimization iterations.

Technological requirements:

- wide range of speed control;
- minimization of steel losses during idling.

Based on the algorithm of SGPM regulation by the optimal current vector, the condition for obtaining the maximum control range is obtained [11]:

$$q_k = I_n - \psi_M / L_d \le 0,$$

where ψ_M is the stator coil threading from permanent magnets; L_d is the d-axis inductance; I_n is the nominal current value.

In multi-criteria optimization tasks, f_k optimization criteria are usually contradictory, and optimization of each of them separately can lead to different values of optimized parameters. The solution of the multicriteria optimization task in general is not optimal for any of the criteria, it turns out to be a compromise for the vector $\vec{f}(\vec{x})$ as a whole.

Solving the problem of multi-criteria optimization (compromise solution) $(\vec{x})* \in S$ called the best solution for Pareto if there isn't $\vec{x} \in S$ such as $f_k(\vec{x}*) \le f_k(\vec{x})$ for $k = 1, ..., p$ and $f_k(\vec{x}*) \le f_k(\vec{x})$ at least one k [6]. A lot of all Pareto optimal solutions are called a lot of Pareto, as well as a non-dominant set [6], or Pareto-frontier. Pareto-frontier optimality of the vector criterion $\vec{f}(\vec{x})$ means that one of the criteria cannot be further reduced without increasing at least one of the others.

In the absence of additional information, none of these decisions can be made better than others. As a general rule, the decision maker (DM) should provide additional information on the preferred characteristics and determine the most appropriate solution. Thus, multicriteria optimization has two aspects: optimization and DM.

In a problem of optimization of designing of generators some parameters are discrete, for example, number of turns, number of poles, etc.; explicit functions of restriction and target functions not always turn out; value of target functions and restriction functions does not exist on all points of space of search. Therefore, the derivative of target functions does not always exist. Besides, the restriction functions are nonlinear, which makes it difficult to determine the starting point and the next points satisfying the restriction functions.

Due to the peculiarities of the task of optimizing generators, the evolutionary algorithm is a more attractive approach. Genetic algorithm (GA) is the most popular algorithm in the group of evolutionary algorithms. GA does not require a given starting point and allows the use of nonlinear, discrete target functions and restriction conditions. Although it does not strictly mathematically guarantee that the optimal solutions will be found, there is a high probability that a solution close to the optimal one will be found [7]. Many of these solutions are very close to the real Pareto front and are called approximation of the Pareto set [4].

Genetic algorithm (GA) and its implementation on a PC Genetic algorithm (GA) is a search algorithm that simulates natural selection using natural evolutionary methods such as reproduction, inheritance, mutation, and selection.

Genes are optimizable parameters. A population is a possible solution. Target functions express the adaptability of individuals in different aspects. Genetic operators (crossing and mutation) serve to find new solutions while preserving the best solutions.

The scheme of genetic algorithm is presented in Fig. 4. At the beginning, the first population was created randomly (block 1). The cycle uses genetic operators such as crossbreeding (multiplication) and mutation (block 2, 3), the results of which serve to obtain a new generation. Genes are transformed into SGPM parameters (block 4). The generator model is created and analyzed in block 5. Based on the indicators obtained from the analysis of the SGPM, the target functions are calculated in block 6 [8].

Based on the results of the target functions, a non-dominant set (population) is selected for the next generation (block 7).

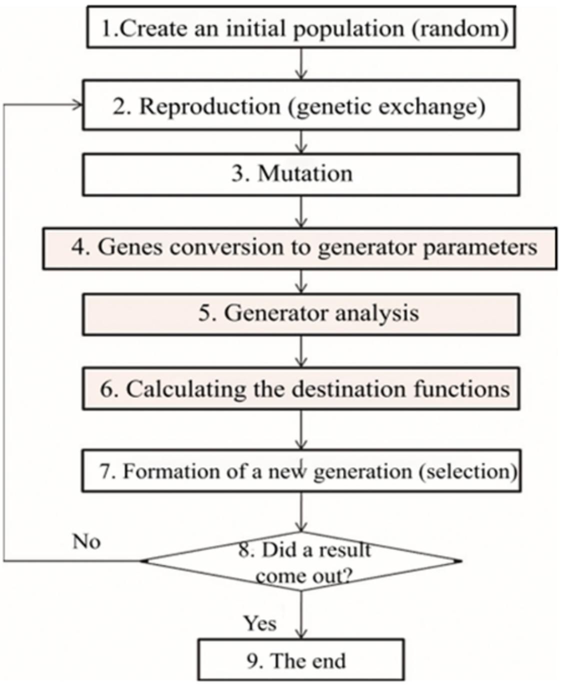


Fig. 4. Genetic algorithm scheme

Unlike deterministic optimization, there is a randomness in the genetic algorithm and there is no rigor in mathematics. That's why the condition of completion (block 8) is not obvious. Usually, for simplicity, the process ends when the number of generations exceeds the maximum.

The main disadvantage of GA is that it requires large computational costs [9]. Besides, with the increase of approximation accuracy achieved by increasing the number of nondominable solutions, the task of choosing a single solution from the presented set becomes more time-consuming for DM. However, good visualization of Pareto-front helps DM to choose the solution.

V. REALIZATION OF THE GENETIC ALGORITHM ON THE PC

To optimize the synchronous generator was used software implementation of the genetic algorithm in Java in the environment of NetBeans. To solve this problem we will use the freely distributed Java-library EvoJ (Evolution Java) [12].

The EvoJ project is conceived as an extensible framework of Java classes to solve various optimization tasks with the help of evolutionary (genetic) algorithms. EvoJ allows you to change variables without specifying the range of variables to change. However, if you need to implement your own mutation strategy, you will have to declare the setters – otherwise you will not be able to change the variables.

To solve a problem with EvoJ you need to:

1) create an interface with variables;
2) implement the fitness function interface;
3) create a population of solutions and implement the required number of GA iterations over them

In the example its considered about two important variables: the inner diameter of the stator package and the stator package length [6].

EvoJ allows variables to be changed without setting the variable change range. However, if you need to implement your own mutation strategy, you will have to declare the setters – otherwise you will not be able to change the variables.

If the solution does not satisfy, iteration of GA (increasing the number of populations and iterations) can be continued the until the desired quality of the solution is achieved. The following parts have been implemented in the optimization module: blocks 1, 2, 3, 5, 7, and 8, which are the main part of the genetic algorithm; block 4 (transformation of genes into generator parameters); block 6 (calculation of target functions) will allows enter these optimization tasks flexibly.

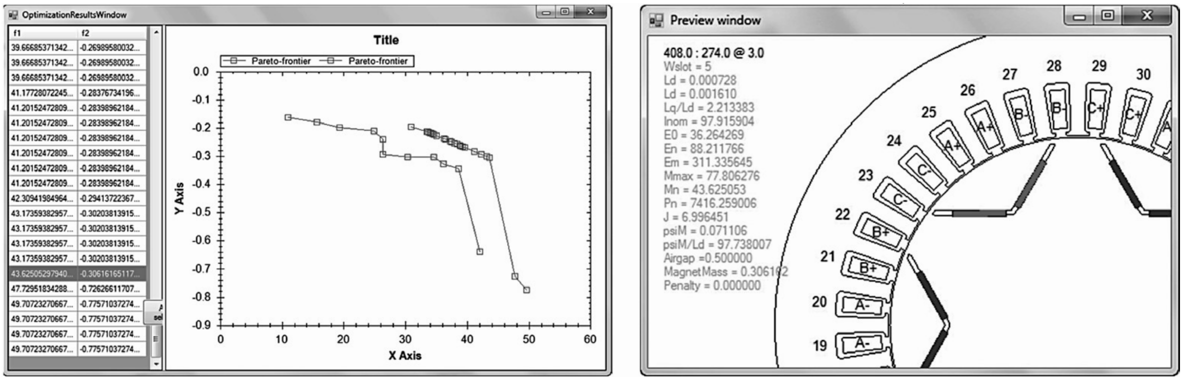
Block 5 (generator analysis) creates a generator model and analyzes it. Parameters of the model are calculated in block 4. Two types of generator models are used: the analytical model and the finite element method (FEM) model. The analytical model, which is based on the electromagnetic equations of an equivalent magnetic circuit, serves to pre-assess the generator and check the feasibility of the FEM model.

In Figure 5 presents the interface of the synchronous generator optimization module. As a result of the optimization process, the Pareto set is approximated, which is represented in the form of a table and a graph (Fig. 5). Based on his experience and preferences, the engineer chooses one of these solutions (Fig. 5b).

VI. THE OPTIMIZABLE PARAMETERS

Optimized parameters that make up the vector $\vec{x}$ are geometric dimensions and other values describing the generator model, such as the number of turns, types of materials, etc. Some parameters are real numbers (geometric dimensions), while others are integers (number of turns, number of poles).

The parameters being optimized are presented in Fig. 6 and in the Table I.



f1	f2
39.66685371342...	-0.26989580032...
39.66685371342...	-0.26989580032...
39.66685371342...	-0.26989580032...
41.17728072245...	-0.28376734196...
41.20152472809...	-0.28398962184...
41.20152472809...	-0.28398962184...
41.20152472809...	-0.28398962184...
41.20152472809...	-0.28398962184...
41.20152472809...	-0.28398962184...
41.20152472809...	-0.28398962184...
42.30941984964...	-0.29413722367...
43.17359382957...	-0.30203813915...
43.17359382957...	-0.30203813915...
43.17359382957...	-0.30203813915...
43.17359382957...	-0.30203813915...
43.62505297940...	-0.30616165117...
47.72951834288...	-0.72626611707...
49.70723270667...	-0.77571037274...
49.70723270667...	-0.77571037274...
49.70723270667...	-0.77571037274...
49.70723270667...	-0.77571037274...

```
408.0 : 274.0 @ 3.0
Wslot = 5
Ld = 0.000728
Ld = 0.001610
Lq/Ld = 2.213383
Inom = 97.915904
E0 = 36.264269
En = 88.211766
Em = 311.335645
Mmax = 77.806276
Mn = 43.625053
Pn = 7416.259006
J = 6.996451
psiM = 0.071106
psiM/Ld = 97.738007
Airgap =0.500000
MagnetMass = 0.306162
Penalty = 0.000000
```

a b

Fig. 5. Interface of the SGPM optimization module: (a) is the window representing Pareto-front in the form of a table and a graph; (b) is the window representing the selected solution

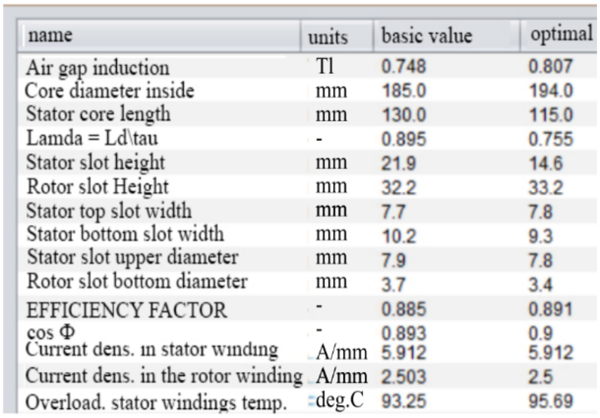
TABLE I. ROTOR OPTIMIZATION PARAMETERS

Symbol	Description	h_{Rib}	Rib length
R_r	Rotor radius	w_{Rib}	Rib width
w_{sb}	Steel bridge width	R_{sh}	Shaft radius

w_M	Width of both magnets	d_1	Distance between shaft and air gap
l_{Ml}	Magnet length of the magnetic direction	d_2	Air barrier width
d_M	Distance between magnets	w_K	Number of turns of one coil
l_n	Air barrier length		

VII. RESULTS

On the Figure 6 presents the optimal Pareto solution as a result of the optimization process and the basic parameters



name	units	basic value	optimal
Air gap induction	Tl	0.748	0.807
Core diameter inside	mm	185.0	194.0
Stator core length	mm	130.0	115.0
Lamda = Ld\tau	-	0.895	0.755
Stator slot height	mm	21.9	14.6
Rotor slot Height	mm	32.2	33.2
Stator top slot width	mm	7.7	7.8
Stator bottom slot width	mm	10.2	9.3
Stator slot upper diameter	mm	7.9	7.8
Rotor slot bottom diameter	mm	3.7	3.4
EFFICIENCY FACTOR	-	0.885	0.891
cos Φ	-	0.893	0.9
Current dens. in stator winding	A/mm	5.912	5.912
Current dens. in the rotor winding	A/mm	2.503	2.5
Overload. stator windings temp.	deg.C	93.25	95.69

Fig. 6. Parameters during optimization with GA

VIII. CONCLUSION

The analysis and comparison of two types of synchronous generators with PM for wind-power plant with radial and tangential magnetization of magnets on the rotor shows that SGPM at identical overall dimensions of the stator with radial magnetization of magnets can have essentially smaller pulsations of electromagnetic moment.

The problem of multi-criteria optimization and the approach of evolutionary algorithms to solve this problem are considered.

Genetic algorithm in the form of software for designing synchronous generators is implemented.

Optimization of SGPM parameters is carried out

A lot of solutions have been obtained and one of the best solutions has been chosen.

The final judgment on the real picture of the field and related interactions, as well as the results of the calculations can be made on the basis of the experimental study of the prototype of the generator in the process of assembly.

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В. М. Синєглазов, В. О. Копанєв. Проектування синхронного генератора на постійних магнітах з використанням генетичного алгоритму

Класичні методи проектування електричних машин спрямовані на досягнення працездатності електричної машини і не забезпечують мінімальних витрат при виготовленні і при експлуатації. Останнім часом оптимізація стає важливою частиною сучасного процесу проектування електричних машин. Мета процесу оптимізації, як правило, зводиться до забезпечення мінімуму вартості машини, втрат енергії, маси, або забезпечення максимуму моменту і коефіцієнта корисної дії. Більшість вимог проектування електричної конструкції машини перебувають в протиріччі один з одним (зменшення обсягу або маси, підвищення коефіцієнта корисної дії, тощо.). Розглянуто компоненти і процедура виконання алгоритму для оптимізації проектування синхронних генераторів. В процесі оптимізації для підвищення швидкості обчислення і точності аналітичний розрахунок використовується разом з розрахунком методом кінцевих елементів. Результатом процесу оптимізація за допомогою генетичного алгоритму є безліч рішень, з яких інженер вибирає найкраще.

Ключові слова: синхронний генератор з постійними магнітами; багатокритеріальна оптимізація; генетичний алгоритм.

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В. М. Синеглазов, В. А. Копанев. Проектирование синхронного генератора на постоянных магнитах с использованием генетического алгоритма

Классические методы проектирования электрических машин направлены на достижение работоспособности электрической машины и не обеспечивают минимальных затрат при изготовлении и при эксплуатации. В последнее время оптимизация становится важной частью современного процесса проектирования электрических машин. Цель процесса оптимизации, как правило, сводится к обеспечению минимума стоимости машины, потерь энергии, массы, или обеспечения максимума момента и коэффициента полезного действия. Большинство требований проектирования электрической конструкции машины находятся в противоречии друг с другом (уменьшение объема или массы, повышение коэффициента полезного действия и т. д.). Рассмотрены компоненты и процедура выполнения алгоритма для оптимизации проектирования синхронных генераторов. В процессе оптимизации для повышения скорости вычисления и точности аналитический расчет используется вместе с расчетом методом конечных элементов. Результатом процесса оптимизация с помощью генетического алгоритма является множество решений, из которых инженер выбирает самое лучшее.

Ключевые слова: синхронный генератор с постоянными магнитами, многокритериальная оптимизация, генетический алгоритм.

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