Інтерес представляють генератори класичної конструкції – із циліндричним статором та ротором. Це обумовлено тим, що дана конструкція є найбільш розповсюдженою, простою та технологічною. Результатом розробки таких електричних машин є можливість створення об'єднаної серії асинхронних двигунів та магнітоелектричних синхронних машин. В цих машинах заміна КЗ ротора на ротор з постійними магнітами та керованим робочим магнітним потоком перетворює асинхронну машину в магнітоелектричну синхронну. Всі існуючі генератори із постійними магнітами мають головний недолік: практично відсутня можливість регулювання вихідної напруги та в окремих випадках потужності. Це особливо актуально для автономних енергосистем. Відомі методи регулювання вихідної напруги призводять до підвищення вартості, зниження надійності, погіршення вагогабаритних показників.

Розроблено тривимірну польову математичну модель магнітоелектричного синхронного генератора із постійними магнітами. Модель реалізована методом скінченних елементів в програмному пакеті COMSOL Multiphysics. Показано розподіл електромагнітного поля в активній зоні генератора при управлінні і без нього. Розраховано вплив струму управління в підмагнічуючій обмотці на зовнішні характеристики генератора при різному коефіцієнті потужності навантаження. За допомогою розробленої моделі синтезовано закон управління струмом в підмагнічуючій обмотці при зміні навантаження в широких межах.

Отримані результати показують, що існує можливість регулювання вихідної напруги генератора з постійними магнітами з допомогою використання додаткової підмагнічуючої обмотки. Обмотка виконує роль електромагнітного шунта для основного магнітного потоку, який створюють постійні магніти. Аналіз результатів показав, що існує можливість в широких межах регулювати вихідну напругу генератора із постійними магнітами в межах – 35 %, +15 %

Ключові слова:регулювання напруги генератора, підмагнічуюча обмотка, магнітоелектричне збудження, постійні магніти

UDC 621.313.332
DOI: 10.15587/1729-4061.2020.193495

MATHEMATHICAL MODELING OF A SYNCHRONOUS GENERATOR WITH COMBINED EXCITATION

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Received date 03.12.2019
Accepted date 23.01.2020
Published date 24.02.2020

1. Introduction

New technologies for the production and design of electric machines, the invention of powerful high-coercive permanent magnets gave rise to a rapid impetus in the development of electrical mechanics in general and generators with permanent magnets in particular. This, in turn, actively stimulated the development of non-traditional and renewable energy sources and autonomous electricity generation. Renewable energy accounts for an increasing percentage of the total amount of electricity generated. This helps resolve important technical issues in electricity supply. Electric generators with permanent magnets are at present the main type of electric machines that are used as generators for autonomous power systems. Wind power engineering is developing particularly rapidly. Hundreds of thousands of small wind plants and thousands of large wind turbines are currently in operation worldwide. The electric generator with permanent magnets has a series of significant drawbacks. Existing generators need to be improved to overcome these deficiencies, resulting in additional investment. That could improve efficiency of such generators, but would also increase their cost and compromise their reliability. New high-performance magnetoelectric generators on permanent magnets could contribute to solve a given task.

A relevant scientific and practical field is the development of new types of generators with permanent magnets. Underlying such designs is a conventional cylindrical electric machine excited by permanent magnets. To control the output voltage of such a generator, there is an additional magnetizing winding. In order to assess the designed structure and to estimate efficiency of magnetized winding operation, it is necessary to build a model of such a generator and to perform a series of calculations.

2. Literature review and problem statement

Electric generators for autonomous power supply systems should have increased reliability, the minimum possible mass-size indicators, and high dynamic properties. Given the rapid growth of science and technology, the invention of new types of permanent magnets with high magnetic energy, the design of generators with permanent magnets has changed significantly over recent time [1]. Serial power generators for autonomous power systems are typically excited by permanent magnets, in addition, they are widely used in aviation, vehicles, robotics, etc.

Contactless electric generators with electromagnetic excitation will be advanced and implemented further as they have a series of advantages over standard generators excited by permanent magnets. Electric generators with permanent magnets are fabricated in a wide variety of types and variants of structural execution, depending on the scope of application, different purposes, and working conditions [2].

On the other hand, synchronous generators with permanent magnets (SGPM) have fundamental flaws, significantly limiting their scope of application and speed of implementation:

1) SGPMS almost defy control, while the rated voltage is maintained within a rather narrow range;

2) existing ways to stabilize voltage lead to complexity and an increase in the cost of a structure;

3) permanent magnets demonstrate low mechanical strength and a narrow working temperature range.

Paper [3] reports results from mathematical modeling of the end-side generator with permanent magnets and an additional winding. It was shown that it was possible to control output voltage in such a generator design up to 40 %. The following drawbacks are inherent in this design:

1) low specific capacity, significant dimensions and weight;

2) the output tension is not sinusoidal.

The reason for this is the technological difficulties in the manufacture of such a structure and the presence of fully open grooves.

Authors of work [4] reviewed and proposed a variant of the design of an electric machine with permanent magnets and two armature windings: on the stator and rotor (in conjunction with permanent magnets). This solution significantly improves the efficiency of generator operation, but increases its cost and dimensions by 2–3 times. The reliability of such a system is reduced by about 10 %. These types of electric machines should be used as traction electric motors.

One of the solutions to the existing issues related to magnetoelectric generators was proposed in works [5, 6]. The authors of these papers propose using a magnetized winding to control a magnetic flux in the air gap of the generator. This implies control over the component of a magnetic flux along the "*d*" axis. This solution makes it possible to deeply regulate the generator output voltage (up to 30–50 % depending on the design features), but significantly complicates the set-up and makes it more expensive in general. Because the authors looked at the end-side generator, they were unable to fully solve the issue of output voltage non-sinusoidality.

A design of the cylindrical generator with magnetoelectric excitation was proposed in work [7]. If one uses the structure without permanent magnets, the excitation winding and the armature's winding are located on the stator. The rotor is either fabricated with permanent magnets or made from a magnetic soft material without permanent magnets. The design proposed in [7] is a modification of previously known induction generators. Induction generators make it possible to obtain a high frequency voltage (≈100–2,000 Hz). To improve the shape of the output voltage curve, the authors propose a modified rotor design. However, a given structural solution is not advisable to use for industrial production of electric generators, as they are 1.5–2 times the size of classic generators.

There are structural executions of cylindrical generators with a double rotor [8] and an external rotor with an additional winding on the rotor [9] (a dual power machine). The designs of these prototypes are effective, but they do not resolve the issue of reliability, durability, and simple maintenance. In addition, such generators are extremely un-technological and make the production process more expensive.

All the previously proposed design options and technical solutions lead to a significant increase in cost, complexity of synchronous generator structure, hence to an increase in cost, weight, and volume of the generator, and to a decrease in its reliability. In addition, the output voltage of such generators, in some cases, differs from sinusoidal.

Given this, it is necessary to study the magnetoelectric synchronous generator with a combined excitation, which would meet the requirements for reliability, manufacturability, high specific power, unification, and operational efficiency. Our analysis of the above literary sources reveals the lack of information on the designs of magnetoelectric generators capable of maintaining external characteristic at different types of load in the range of ±15 % U_r under a load of up to 1.2 I_r. Such a structure has been proposed in this article by authors and is detailed in paper [10]. Such a generator is practically no different in terms of design from a classical structure except for the installed additional magnetizing winding.

3. The aim and objectives of the study

The aim of this study is to construct a three-dimensional field mathematical model of the synchronous generator with permanent magnets and a magnetizing winding. Followed by analysis of the parameters and characteristics of the generator, evaluation of the effectiveness of output voltage control, and synthesis of the law that governs control over a magnetizing winding.

To accomplish the aim, the following tasks have been set:

– to choose the tools to construct a mathematical model in order to calculate the characteristics of a magnetoelectric synchronous generator with permanent magnets in an automated design environment;

– to simulate operational modes of the magnetoelectric synchronous generator with permanent magnets under different modes of magnetizing winding operation.

4. Materials and methods to study a magnetoelectric synchronous generator with permanent magnets

Fig. 1 shows the structure of the examined generator, made on the basis of a serial electric motor, type AIR100L4.

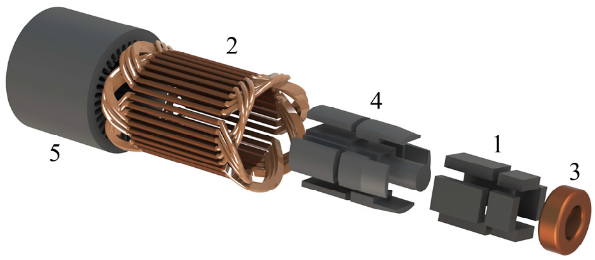


Fig. 1. General view of the examined synchronous generator with combined excitation: 1 – permanent magnets (NdFeBr-H-38); 2 – three-phase armature winding; 3 – magnetizing winding; 4 – rotor magnetic wire; 5 – stator magnetic wire

To accomplish the set goal, one needs to use the methods and tools of 3D modeling. This is predetermined by that the existing mathematical models of synchronous generator do not take into consideration the three-dimensional nature of the electromagnetic field of a generator with a magnetizing winding. The presence of a magnetizing winding contributes to the emergence of an axial component of the magnetic flux.

The main advantages of a three-dimensional field mathematical model:

– accounting for the effects from magnetic scattering fields;

– accounting for the inter-sheet insulation of a magnetic wire;

– accounting for longitudinal and transverse end effects;

– taking into consideration the design features of synchronous generator.

Some technical parameters and characteristics of the examined synchronous generator with a combined excitation are given in Table 1.

Table 1

Parameters of the examined generator

No.	Parameter	Value
1	Rated power, kW	4.0
2	Rated current Δ/Y, A	14.7/8.5
3	Axial length, mm	127.0
4	Stator inner diameter, mm	103.8
5	Number of grooves on stator	36
6	Number of conductors per groove	29
7	Diameter of armature winding and magnetizing winding wires, mm	1.32
8	Number of magnetizing winding turns	470

Table 1 gives basic design parameters of the examined generator, which are used to build a 3D model in the COMSOL Multiphysics environment.

Table 2 gives basic geometric parameters for the examined generator.

Table 2

Generator geometrical parameters

Parameter	Value
Stator outer diameter – D_e	150 mm
Stator inner diameter – D_{in}	96 mm
Stator groove number – Z_1	36 mm
groove height – h	14 mm
groove narrow part width – b_1	4.4 mm
groove wide part width – b_2	6.1 mm
groove neck width – m	2.6 mm
groove slot height – e	0.5 mm
rotor length – L	137 mm
Magnet length – L_m	60 mm
rotor diameter – D_m	94 mm
magnet height – h_m	13 mm
magnet width – b_m	37 mm

The parameters given in Table 2 correspond to the design prototype of the serial electric motor AIR100L4, AIS112M4, which is taken as a base for building a given magnetoelectric generator. This makes it possible to unify industrial production in the future.

When calculating a magnetic field, we used a non-stationary non-linear differential equation for a vector magnetic potential (A) in a mobile electricity conductive environment:

$$\vec{\nabla}\times\frac{1}{\mu}\left(\vec{\nabla}\times\vec{A}\right)-\gamma\frac{\partial\vec{A}}{\partial t}+\gamma\vec{V}\times\left(\vec{\nabla}\times\vec{A}\right)=-\vec{J}_{ex},$$

where μ, γ are the magnetic permeability and electrical conductivity; $\vec{V}$, $\vec{J}_{ex}$ are the vectors of an environment motion speed and a side current density; $\vec{\nabla}$ is the differential Nabla operator.

The estimated region of the machine has different physical properties. For each region, a stationary field equation is solved with respect to the vector magnetic potential. For the region that includes an air gap, a magnetic wire, a shaft, pole tips, and an armature winding, the equation take the following form:

$$\sigma\frac{\partial A}{\partial t}+\nabla\times\frac{\nabla\times A}{\mu_0\cdot\mu_r}=J_e,$$

where J_e is the density of currents in the stator winding, which characterizes the mode of generator operation; σ is the electrical conductivity of the region's materials; μ_r is the relative magnetic permeability of materials.

The magnetic field of permanent magnets is calculated from the following equation:

$$\sigma\frac{\partial A}{\partial t}+\nabla\times\frac{\nabla\times A-B_r}{\mu_0\cdot\mu_r}=J_e,$$

where B_r is the residual induction of permanent magnets.

Current density in the armature winding is set as a function of time and takes the following form:

$$J_A=J_m\cdot\cos\left(\omega_1\cdot t\right),$$

$$J_B=J_m\cdot\cos\left(\omega_1\cdot t+2\pi/3\right),$$

$$J_C = J_m \cdot \cos(\omega_1 \cdot t + 4\pi / 3),$$

where J_m is the amplitude value of current density in the armature winding phase, which is determined by a current load on the generator's slot (the magnitude of the armature's current, the number of turns and the area of the slot cross-section).

To calculate the induced EMF in the generator armature winding phase, the COMSOL Multiphysics environment employs the following integral expression:

$$E_A = \frac{L \cdot U_w}{S_w \cdot a}\left(\oint_{S_q} E_{zA} \cdot ds - \oint_{S_q} E_{zX} \cdot ds\right),$$

where L is the generator axial length; U_w is the number of turns in the groove; S_w is the area in a groove for conductors; E_{zA}, E_{zX} is the intensity of an electric field at the location of phase zone coils "A" and "x"; S_q is the area occupied by conductors within the same phase zone; a is the number of parallel branches of the armature winding. EMF in the winding phases "B" and "C" is determined in the same way.

In order to obtain an unambiguous solution at the boundaries of the estimated region, boundary conditions of the first kind are set:

$$A\ (x, y, z, t)|G_1=0,\ \{x, y, z\}.$$

A solution to the field equations by a finite element method is determined based on the condition for a minimum of energy functional or the orthogonal non-binding of field equations and the interpolation functions of finite elements. When modeling the characteristics of SGPM for an autonomous power plant, a grid of finite elements (GFE) was built, which covers the estimated region (Fig. 2).

GFE of the examined generator consists of:
– 3,098,682 tetrahedra;
– 66,670 triangular elements;
– 5,411 edge elements;
– 163 vertex elements.

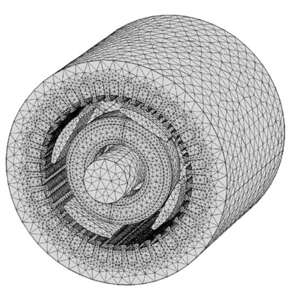
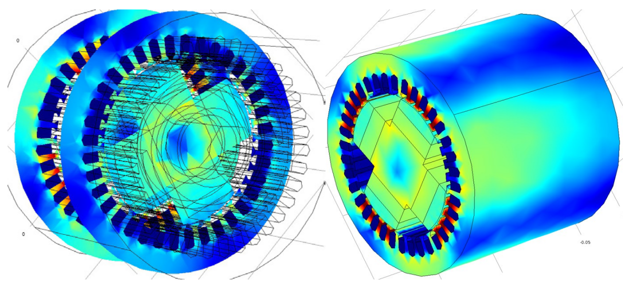


Fig. 2. Grid of finite elements of the examined generator

The quality of the built GFE and the number of elements shown in Fig. 2 would suffice to produce adequate results. GFE evenly covers the entire estimated region and has a denser distribution for small details (for example, teeth, air gap).

5. Results of modeling a magnetoelectric synchronous generator with permanent magnets

Fig. 3 show the distribution of a magnetic field within the estimated volume of the examined synchronous generator. The average value of magnetic induction in the stator teeth is 1.64 Tl, in the stator yoke ≈1.12 Tl, in the air gap – 0.64 Tl. Values of the magnetic induction are within the acceptable range, which indicates proper calculation of the basic dimensions.



a *b*

Fig. 3. Distribution of electromagnetic field in the estimated region: *a* – in a principal cross-section of the magnetoelectric generator and in the region of a magnetizing winding; *b* – over the full estimated region of the generator

We examined a given generator under two modes of operation:

1) without current in the magnetizing winding;

2) with current in the magnetizing winding, with an active character of the load and an active-induction at cosφ=0.95.

In the absence of current in a magnetizing winding (I_c=0A), a given generator operates like a regular synchronous generator with a radial magnetic flux. In this case, the axial component of a magnetic flux, which is closed through the shaft, is negligible (Fig. 4) and there is only a radial component of the magnetic flux.

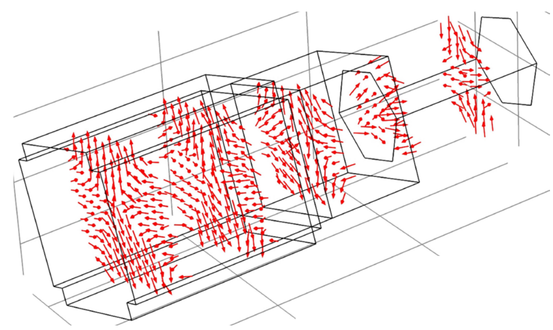


Fig. 4. Magnetic flux of rotor at I_c=0

If there is a current in the magnetizing winding of magnitude, for example, I_c=1 A, the pattern of the magnetic field in the rotor changes, as there emerges an axial component of the magnetic flux (Fig. 5), which is closed through the shaft of the generator.

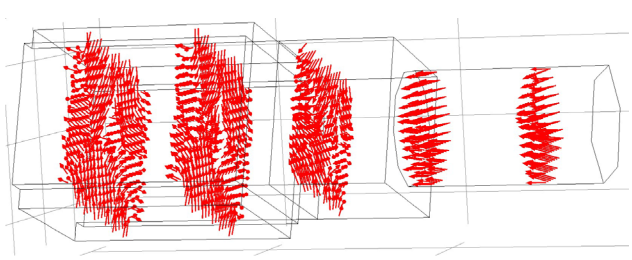


Fig. 5. Direction of magnetic flux motion in synchronous generator shaft, created by a magnetizing winding at I_c=1 A and by permanent magnets

A series of field calculations was performed to assess the functional parameters and characteristics of the examined generator. In each individual calculation, we changed the magnitude of the generator's load from idling to the rated mode of synchronous generator operation for two cases: a purely active load and an active induction load with a power factor of 0.95.

Fig. 6 shows the direction of magnetic flux movement in the air gap and in the core of the examined generator.

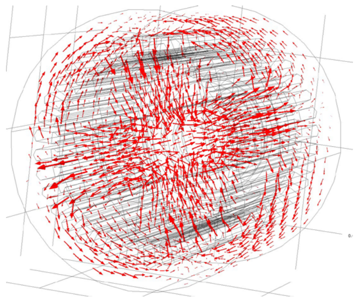


Fig. 6. Closing the principal magnetic flux in the estimated region

The result is the derived natural external characteristic (Fig. 7). The external characteristic is the voltage dependence at the output of the generator on a load current at I_c=0 A.

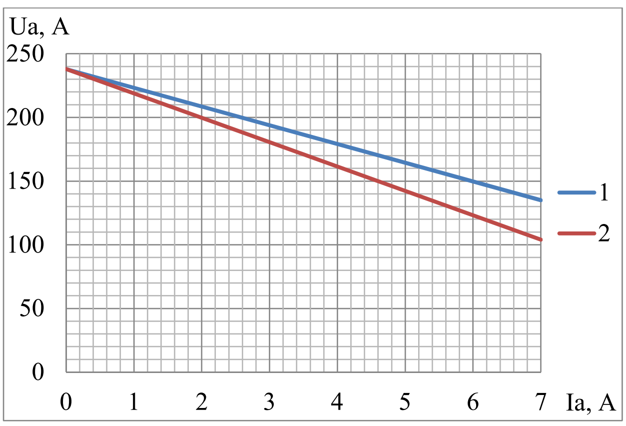


Fig. 7. Natural external characteristic:
1 – external characteristic at cosϕ=1;
2 – external characteristic at cosϕ=0.95

It is evident that at a rated voltage current of ≈6.8 A the voltage drop ranges from 93 V to 115 V under an active-induction load. At idling, voltage is 234 V, which is necessary for the natural stabilization of the external characteristic.

In the presence of a control current in the additional winding, the external characteristic takes the form shown in Fig. 8.

At I_c=const in the control winding and at the rated load current of 6.8 A the voltage deviation from the rated one is from 30 C to 52 V under an active-induction load.

Fig. 9 shows the result of calculating the generator regulatory characteristic under an active load and an active-induction load with a power factor of cosϕ=0.95. To calculate the dependence shown in Fig. 9, we changed the magnitude of the generator's load and iteratively selected such a current value in the control winding at which U_1=const.

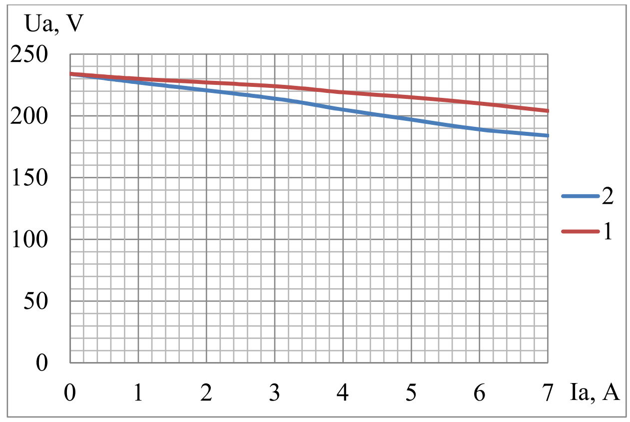


Fig. 8. External characteristic of generator at I_c>0:
1 – external characteristic at cosϕ=1;
2 – external characteristic at cosϕ=0.95

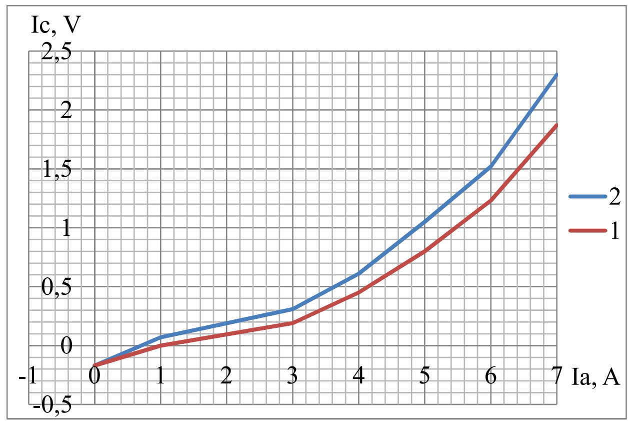


Fig. 9. Regulatory characteristics of the examined generator:
1 – external characteristic at cosϕ=1;
2 – external characteristic at cosϕ=0.95

Fig. 9 shows that starting at idling mode to a load current of 1 A the voltage controller should perform the reverse of current in the magnetizing winding. At the same time, the magnetic flux created by permanent magnets is closed not through the stator and rotor, but by the magnetic system of the rotor, the total flux is reduced and the constant voltage on the clamps of the generator is maintained. There is a family of similar regulatory characteristics built for each type of load: active, active-induction, active capacitive.

Fig. 10 shows the distribution of the normal component of magnetic induction in the air gap for two cases: 1 – in the absence of current in the magnetizing winding; 2 – at I_c=1 A.

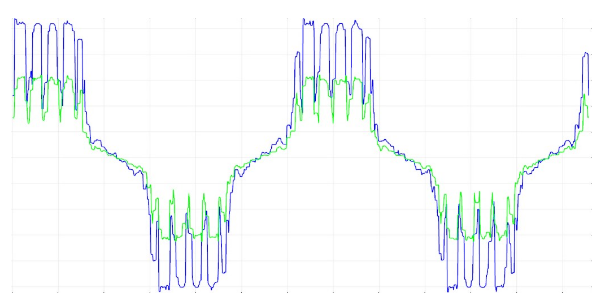


Fig. 10. Distribution of the normal component of magnetic induction in the air gap: blue curve – I_c=1 A; green curve – I_c=0 A

The blue curve corresponds to the mode at I_c=1 A, the green one was built at I_c=0 A. The amplitudes of the resulting curves differ by about 40 %. Fig. 10 clearly shows that if there is a current in the control winding, the normal component of the magnetic flux increases, which is responsible for the magnitude of EMF induced in the armature winding.

The tangential component affects the magnitude of the electromagnetic momentum. Our calculations helped derive the distribution of the tangential component of magnetic induction in the air gap, as shown in Fig. 11.

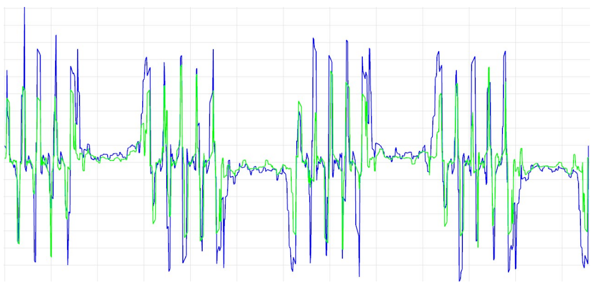


Fig. 11. Distribution of the tangential component of magnetic induction in the air gap: Blue curve – I_c=1 A; green curve – I_c=0 A

The blue curve corresponds to the I_c=1 A mode, the green one – I_c=0 A. One can conclude from Fig. 11 that the flux in the additional winding also affects the magnitude of the total electromagnetic momentum, as the average induction value in the air gap increases.

6. Discussion of results of studying the magnetoelectric synchronous generator with permanent magnets

The natural external characteristic of the examined generator (Fig. 7) demonstrates a steeply descending shape. The steepness of characteristic descent is larger in proportion to a decrease in the power factor. This is due to the effect of the demagnetizing reaction of the armature and a voltage drop on the internal active and induction resistance of the armature winding.

Our calculation of the magnetic field in a 3D statement of the problem for the model of synchronous generator with combined excitation in the COMSOL Multiphysics environment has made it possible to fully account for the magnetic flux created by the magnetizing winding. When the load current is I_a≈0–1.5 A (Fig. 8) the current in the magnetizing winding has a negative direction (Fig. 9). This means that part of the principal magnetic flux is shunted through the magnetic chain of the bridge and leads to a reduction in voltage at low loads, that is it maintains U_1≈const. At loads that exceed I_a≈3.5–4 A the magnetizing winding creates a flux that amplifies the principal magnetic flux of permanent magnets. This results in that the voltage is maintained within U_1≈220–230 V.

When constructing a mathematical model, the following assumptions were made: the discreteness of the magnetic chain of the stator is not taken into consideration; magnetic losses in the stator on hysteresis and vortex currents are not taken into consideration; the heat modes of the generator are not taken into consideration; the scattering fields from the frontal parts and differential scattering are not taken into consideration.

In order to adequately interpret the results obtained and assess the effectiveness of the proposed design, it is necessary to compare our results with known prototypes. It is also necessary to experimentally study an actual synchronous generator with combined excitation to assess the adequacy of the obtained results and confirm its effectiveness. These drawbacks could be easily eliminated in subsequent studies.

Since the design of the proposed generator is as simple as possible, it has not led to any difficulties in manufacture and significant material costs. A separate issue is the calculation of reliability and durability of such a structure. At present, this problem is common to all electric machines with permanent magnets.

7. Conclusions

1. The proposed design of the generator with adjustable working flux has made it possible to stabilize the external characteristic over the entire range under an active and active-induction load at an accuracy of ±5–7 %.

2. We have built a three-dimensional model that fully takes into consideration the features of the design of the examined synchronous generator, including the presence of a radial-axial magnetic flux. The model has been applied to calculate a regulatory characteristic of the automated voltage control system for the examined generator.

3. Special features of the devised structure of the examined generator allow its use as a reliable source of electricity for autonomous power plants. As the derived calculations show, the accuracy of output voltage stabilization is within the range of ±3 V.

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