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VOLTAGE STABILIZATION OF A CONTROLLED AUTONOMOUS MAGNETOELECTRIC GENERATOR WITH A MAGNETIC SHUNT AND PERMANENT MAGNET EXCITATION

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The paper presents the results of testing and research of the characteristics of a controlled autonomous magnetoelectric synchronous generator with a magnetic shunt. Structurally, the studied generator is a modified asynchronous machine in which the rotor is made with permanent magnets and an additional system in the form of a magnetic shunt. By adjusting the winding current of the magnetic shunt, the output voltage of the generator is regulated. The following characteristics were investigated: the no-load characteristic during operation with permanent magnets and when the winding current of the magnetic shunt changes with forward and reverse polarity. Also, the external characteristic for active and active-inductive loads; the control characteristic when the load current changes at a constant generator voltage.

Analysis of the obtained characteristics makes it possible to determine the limits of regulation of the external characteristic, which is ≈40 % relative to the main magnetic flux. The obtained regulation depth allows maintaining the stability of the external characteristic for power factors not exceeding 0.9, which is the usual passport value for autonomous power plants based on synchronous generators. Comparison of the data of research conducted on the experimental setup shows sufficient convergence for engineering and practical tasks. The maximum quantitative difference is 9.3 %, which suggests the adequacy of the previously developed mathematical model. The control characteristic, constructed experimentally at constant generator voltage, is the control law of the magnetic shunt winding for the studied generator.

The investigated version of a synchronous generator with a magnetic shunt should be used for autonomous power plants, renewable energy systems, and autonomous power supply systems

Keywords: magnetic shunt, generator voltage regulation, magnetizing winding, magnetoelectric excitation, permanent magnets, experimental research

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1. Introduction

The achievements of the last 10 years in the field of creating new highly coercive rare-earth permanent magnets (NdFeBr and SmCo) made it possible to develop new contactless electric machines with powerful magnetoelectric excitation systems. A feature of these structures is the absence of excitation losses and large specific mass-energy indicators.

An example of a promising development is stand-alone magnetoelectric synchronous generators for unconventional and renewable energy sources. These designs do not need excitation from an external source through a contact system, as in traditional generators with an electromagnetic excitation system. At the same time, the proposed magnetoelectric systems also have disadvantages associated with difficulties in controlling the excitation flow and, accordingly, maintaining the external characteristics of the generator. One of the promising areas of this topic is the development of magnetoelectric generators with magnetic shunting, which allows controlling the magnetic flux in the core.

A relevant scientific and practical direction is the study of the efficiency of the developed and manufactured magnetoelectric generator with a magnetic shunt and radial magnetic flux. This generator is based on the design of a classic AC machine with a traditional stator. The difference lies in the design of the rotor (inductor), which has permanent magnet poles and an additional magnetic system in the form of ferrous conductive shunts for regulating the magnetic flux in the core.

The relevance of the work lies in the use of commercially available asynchronous motors, which can be modified to produce controlled permanent-magnet synchronous generators.

2. Literature review and problem statement

Synchronous generators with a magnetic shunt (SGMS) are electric generators that use two sources for the main magnetic field of excitation – permanent magnets (PM) and the flux created by the magnetic shunt winding. The magnetic circuit of the shunt, with an excess of the main magnetic flux (low loads), conducts a flux through the shunt. With a lack of the main magnetic flux (rated loads), it increases due to the weakening of the shunt winding current. This gives advantages – under rated loads, electrical losses, and hence heating, are reduced, the speed of such a system increases, under medium loads, core losses are reduced (due to saturation).

Combining both excitation sources aims to combine the advantages of permanent-magnet machines and synchronous machines with electromagnetic excitation. When operating in the motor mode, the use of a magnetic shunt improves performance, and the use of permanent magnets helps to improve energy efficiency. The use of synchronous generators with a magnetic shunt allows reducing the volume of PM and the total cost of products.

In [1], the authors proposed a method for calculating the characteristics of a synchronous generator with hybrid excitation. The design of the generator stator is as unified as possible and built on the same principle. The essence of the technique is to compare the results of generator modeling using three-dimensional and two-dimensional mathematical models. The convergence of the results is 5–10 %, which is satisfactory. The authors of the paper also argue that the results obtained using the 3D model are more accurate. Although, there are no grounds for such conclusions since there is no comprehensive comparison of the characteristics obtained. The main disadvantage of this approach is the lack of results of experimental studies of such a generator, which may differ significantly from the simulation results.

The authors in [2] consider a synchronous electric generator with hybrid excitation. As a source of additional magnetic flux, the field winding, which is powered by direct current, and the magnetic circuit of the rotor are used. The authors of the paper consider it as the result of modeling and experimental research. However, as an experimental study, the results of calculating the magnetic circuit of such a generator are proposed, although photographs of the real structure are shown.

The paper [3] presents an innovative approach to controlling a hybrid synchronous machine, which can be used for electric vehicles. Hybrid excitation is realized by an additional control coil located on the machine rotor, implemented by a wireless power transmission system connected to the rotor shaft. The experimental results obtained on the prototype were compared with the results of three-dimensional mathematical modeling by the finite element method. This design, despite some additional complexities in the power supply of the machine, simplifies the mechanical design and reduces losses in the control coil compared to the design in which the coil is placed on the stator. Given the high cost and complexity of such a system, it does not seem advisable to use it in energy-efficient systems.

In [4], the authors describe a new methodology for developing a reliable permanent-magnet synchronous generator with axial flux. This methodology uses a modified version of the non-dominated sorting genetic algorithm III (NSGA-III) multipurpose evolutionary algorithm. Since the design procedure correlates with dimensional and electromagnetic parameters, uncertainties may arise that reduce generator efficiency due to inaccuracies in design and field calculations. In addition, the results of experimental studies are shown indistinctly, without a description of the required equipment and test program, which casts doubt on the adequacy of the results.

The paper [5] presents a study of a new synchronous double excitation machine using three-dimensional finite element analysis and experimental research. It is shown that the machine is indeed capable of adjusting the field. The work shows the operating principle and design features of this generator of the original design. It also compares the results of three-dimensional modeling with an experimental study conducted on a prototype with a different rotor design. Accordingly, it is difficult to use the results of such studies and build such a concept on their basis.

The existing versions of the SG with a magnetic shunt do not have an original design and operating principle. Their main direction is the use of an additional magnetizing winding with its own magnetic system or the magnetic system of the machine. These solutions do not give sufficient limits of output voltage and power control in real operating modes [6]. In [7], there is no comparison of experimental data of the previously described SG with a magnetic shunt under different operating conditions and loads. The stator design of such a generator practically does not differ structurally from the classical design, with the exception of the magnetic shunt installed on the rotor and an additional magnetizing winding.

The work [8] presents a comparison of experimental and calculated data of traction small-sized permanent-magnet machines. The disadvantage of the proposed system is the increased cost and complexity of the system; the reliability of such systems is also questioned. The problem of regulating external parameters is solved by the authors in [9] using a complex mathematical model, a computer with subsequent control of the armature field of the test sample. Comparison of the developed models (which are the software of the system) with the experimental results shows a fairly high convergence.

In [10], a synchronous machine with parallel hybrid excitation is considered. The authors investigate the structural topology and operating principles of the hybrid excitation machine. The ability to control the flow in open circuit conditions and the results of the developed models are confirmed by comparison with experimental measurements. The paper compares various approaches to calculating the magnetic system of hybrid machines with experimental data. However, there are no conclusions about the efficiency of the investigated generator and errors of the presented methods for calculating the magnetic system.

As a result, it can be seen that magnetoelectric systems used as synchronous generators have obvious advantages. These include the absence of excitation losses, the absence of a contact system, compared to electromagnetic excitation generators. This simplifies the design and increases its reliability. At the same time, the considered magnetoelectric generators have disadvantages associated with the impossibility of regulating the magnetic flux without additional devices. This makes it difficult to maintain the external characteristic under loads, especially with a low power factor. Based on this, it is necessary to evaluate the use of a magnetic shunt for regulating a magnetoelectric permanent-magnet synchronous generator. At the same time, the criterion for the adequacy of the results obtained is the comparison of experimental data with the results of mathematical modeling carried out earlier.

3. The aim and objectives of the study

The work aims to determine the possibility of voltage stabilization when the load changes by regulating the flux of the magnetic shunt with an autonomous magnetoelectric generator with a magnetic shunt and excitation from permanent magnets. As a result, it becomes possible to determine and provide the required depth of regulation of the external characteristic in the range of 0.5–1.2. In with standard requirements for the generator in terms of the nature of the load.

To achieve the aim, the following objectives were set:

– to obtain the no-load characteristics with the direct and reverse polarity of the power supply of the magnetic shunt winding with a further comparison with the calculated data;

– to obtain the external characteristic at different power factors and compare the results with the calculated data;

– to determine the control law of the magnetic shunt winding current, while maintaining a constant value of the output voltage, which is analogous to the traditional control characteristic.

4. Research materials and methods

Fig. 1 shows the design of the investigated magnetoelectric synchronous generator based on a serial electric motor of type AIR100L4. This series of electric motors was chosen as the base since it corresponds to the declared generator power and makes it possible to unify, simplify and reduce the cost of mass production of such electric generators as much as possible.

In general, the rotor magnetic system is made with permanent magnets installed through a double pole pitch and having the same polarity with respect to the stator bore and the lumped winding of the magnetic shunt mounted on the stator end shield.

Fig. 1. Rotor of the investigated generator and magnetic shunt with concentrated winding: 1 – permanent magnets (NdFeBr-H-38); 2 – rotor core; 3 – rotor shaft; 4 – concentrated winding of the magnetic shunt; 5 – magnetic shunt core

The parameters and characteristics of the investigated magnetoelectric synchronous generator are shown in Table 1.

Table 1

Generator parameters

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 slots on the stator	36
6	Number of conductors in the slot	29
7	Diameter of the winding wire of the armature winding and magnetizing winding, mm	1.32
8	Number of turns of the magnetizing winding	470
9	Active resistance of the stator winding, Ohm	1.43
10	Active resistance of the magnetic shunt, Ohm	49.0
11	Number of turns in the shunt winding	420
12	Longitudinal inductance, mH	8.9
13	Transverse inductance, mH	4.8
14	Maximum value of flux linkage, Wb	0.372

As part of the work, an experimental stand was developed to study the parameters and characteristics of the magnetoelectric synchronous generator based on the AIR100L4 serial motor. The general view of the stand is shown in Fig. 2.

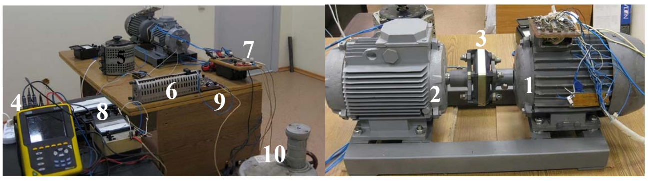

Fig. 2. General view of the experimental stand for studying the magnetoelectric synchronous generator: 1 – generator; 2 – drive motor; 3 – elastic coupling; 4 – 3-phase power quality analyzer S.A. 8334B; 5 – laboratory control transformer, type RNO-250-2, with a single-phase rectifier bridge, for powering the magnetic shunt winding; 6 – adjusting rheostat RSP, 33 Ohm, 3 A; 7 – three-phase load switch (active-inductive); 8 – instrumentation of the magnetic shunt winding; 9 – three-phase rectifier bridge; 10 – potential regulator FR-52, 3ph, 220/380 V, 21/12 A, 8 kVA (source of inductive load)

The electrical schematic diagram of the experimental setup for studying the magnetoelectric generator is shown in Fig. 3.

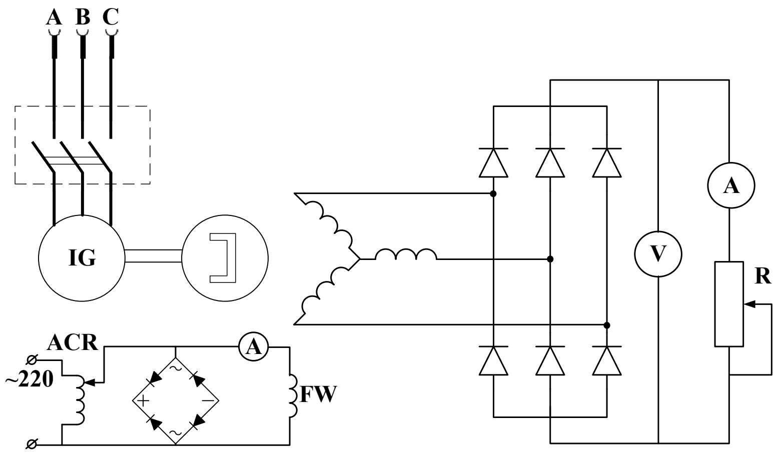

Fig. 3. Electric test diagram of a three-phase magnetoelectric generator

Experimental tests of the generator were carried out according to the program below, which makes it possible to study methods of regulating the generator voltage when the load changes under different operating modes and loads of the generator:

1. Measurement of the active resistance of the generator windings and excitation, inductive resistance of the generator windings.
2. Characterization of the no-load characteristic during operation with permanent magnets and when the magnetization current is changed.
3. Characterization of the external characteristic during operation with permanent magnets and for active and active-inductive loads.
4. Characterization of the external characteristic during operation with permanent magnets and various magnetization currents for active and active-inductive loads.
5. Characterization of the control characteristic when the load current is changed at a constant generator voltage.

5. Results of modeling a magnetoelectric synchronous permanent-magnet generator

5. 1. No-load characteristic with the direct and reverse polarity of the power supply of the magnetic shunt winding

According to the test program, Table 2 and Fig. 4, respectively, show the no-load characteristic of the generator for two options for turning on the magnetic shunt winding:

– with the direct polarity of the power supply of the magnetic shunt winding;

– with the reverse polarity of the power supply of the magnetic shunt winding.

Table 2

No-load characteristic of the investigated generator $U_g=\int(I_{em})$, $I_g=0$

I_{em}, A	0	0.25	0.5	0.75	1.0	1.25	1.5	2.0	Note
U_g, V	82.84	86.2	92.5	96.5	99.3	101.2	102.3	103.8	Direct polarity
U_g, V	82.84	79.9	79.4	76.92	76.18	75.44	–	–	Reverse polarity

Also, a comparison of the obtained experimental data with the results of modeling presented in [6, 7] is shown.

In Table 2, with the reverse sequence of turning on the magnetic shunt winding, the generator voltage decreases below the sensitivity limit of the instruments.

To determine the reactive resistance of the generator armature winding, a series of experiments were carried out, which are used for classical salient-pole synchronous generators. The research results are given in Table 3.

Table 3

Generator winding reactance

Spatial position between the phase axis and the rotor pole axis	U_g, V	I_g, A	Resistance, Ohm			
			z_d	x_d	z_q	x_q
d-axis	15.0	4.8	3.125	2.779	–	–
q-axis	15.0	7.2	–	–	2.083	1.516

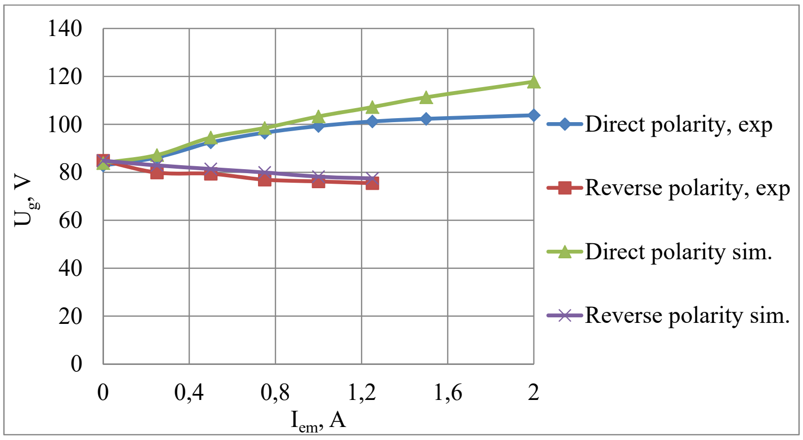

Fig. 4. No-load characteristic of the investigated generator

The reactance values for each axis are determined using the expressions shown below:

$$z_d, z_q = U_\Phi / I_\Phi;\quad x_d = \sqrt{z_d^2 - R_{CT}^2};\quad x_q = \sqrt{z_q^2 - R_{CT}^2}.$$

5. 2. Experimental external characteristic at different power factors

The natural external characteristic of the generator $U_G=\int(I_G)$ at $I_{em}=0$ A was obtained for the active load, in the absence of current in the magnetic shunt winding. The numerical result is shown in Table 4.

Table 4

External characteristic at $I_{em}=0$ A

I_g, A	0	1.575	2.025	2.7	3.375	4.05	4.5
U_g, V	82.84	75.44	73.22	70.26	68.0	65.09	63.61
P_g, W	0	356.45	444.8	569.11	688.5	790.84	858.74

By reducing the active load resistance R_n, the investigated generator is loaded from idle mode $I_a=0$ A to $I_a=1.125 \cdot I_n$. In this case, the corresponding values of the armature current I_a, the voltage on the armature winding U_a, and the active power of the generator P

are recorded. The result of comparing the calculated and experimental data is shown in Fig. 5.

The active load in Table 4 is the total power of all three phases of the generator:

$$P_g=3 \cdot I_g \cdot U_g.$$

Fig. 5 shows that with the value of the armature current $I_g \approx I_n$, the voltage on the armature winding decreases by ≈27 %, which significantly exceeds the permissible limits. This is due to the response of the generator armature and the voltage drop across the internal active and inductive resistances.

The external characteristic in the absence of current in the shunt winding I_{em}=0 A and under active-inductive load is characterized by the data shown in Table 5.

Table 5

External characteristic under active-inductive load

I_g, A	0	1.91	3.5	4.2	6.05
U_g, V	82.84	71.9	63.2	59.5	49.3
P_g, W	–	67.8	124.0	151.0	211.0
Q_g, VAr	–	403.0	651.0	726.0	849.1
S_g, VA	–	408.66	562.7	741.54	874.92
cosφ	–	0.166	0.187	0.204	0.241

The data shown in Table 5 were taken as the armature current increased ≈1.5 times in order to obtain a similar active power at the generator output.

Comparison of the external characteristics under active and active-inductive loads with the calculation results is shown in Fig. 6.

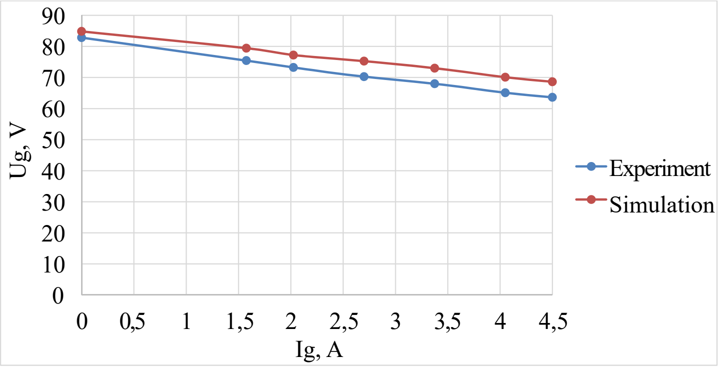

Fig. 5. External characteristic at I_{em}=0 A

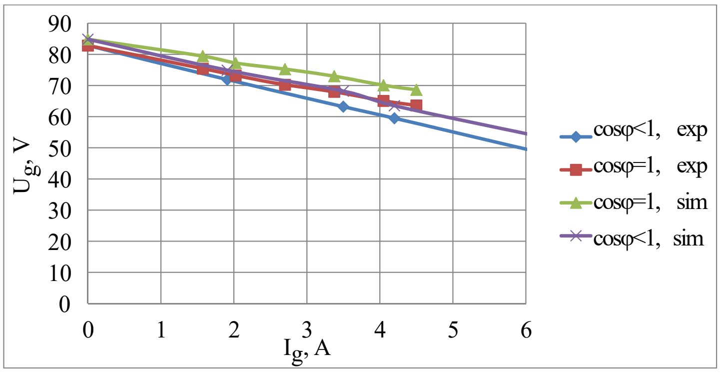

Fig. 6. Comparison of external characteristics at cosϕ=1 and cosϕ<1

The voltage drop under active-inductive load and at rated load current is ≈39 %, which is explained by the demagnetizing reaction of the armature.

To increase the rigidity of the external characteristic, special methods must be used. One of these was proposed by the authors of the paper, which is implemented with a special rotor design using an additional magnetic shunt winding.

Fig. 7 shows the external characteristic of the investigated generator under active-inductive load and at fixed values of the magnetic shunt current: I_{em}=0.5 A; I_{em}=0.75 A, compared to the natural external characteristic. For clarity, Fig. 7 shows a comparison of the external characteristic with the results of mathematical modeling only at a current I_{em}=0.5 A.

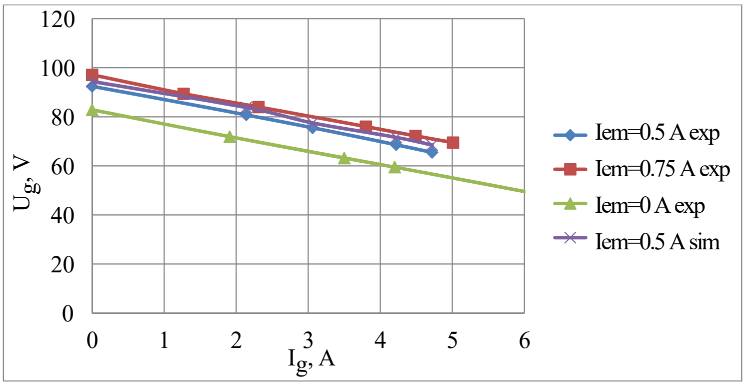

Fig. 7. External characteristics at different control current values I_{em}

To stabilize the external characteristic, direct control of the magnetic shunt current when the generator load changes is required.

5. 3. Determination of the control law of the magnetic shunt winding current while maintaining a constant output voltage value

To obtain such a dependence, it is necessary to take the control characteristic, which is the following dependence: $I_{em}=\int(I_g)$ at U_g=const. The experimental results for active and active-inductive loads are given in Tables 6, 7.

Table 6

Control characteristic under resistive load

U_g, V	76.92				
I_g, A	1.2	1.67	2.27	3.38	4.3
I_{em}, A	0	0.2	0.31	0.5	0.75

Table 7

Control characteristic under active-inductive load

U_g, V	76.92		
I_g, A	1.5	3	3.8
I_{em}, A	0	0.5	0.75

The goal of the experiment is to stabilize the output voltage at the level of ≈130 V line voltage. The control characteristic at a purely resistive load and active-inductive load of the generator is shown in Fig. 8.

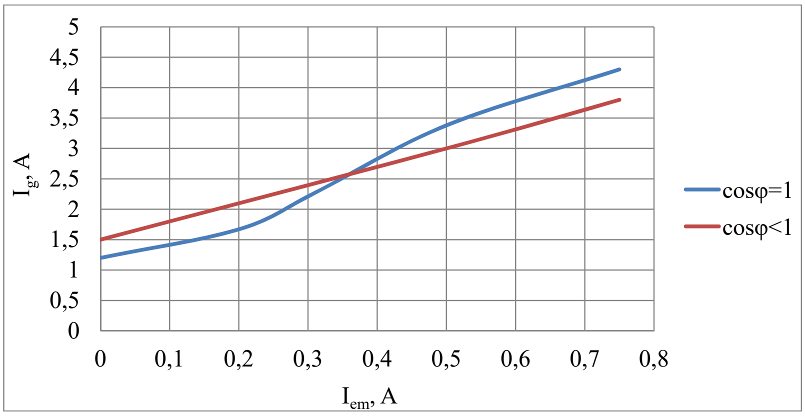

Fig. 8. Control characteristic at U_g=const

Fig. 8 shows that with an active-inductive load, it is necessary to increase the shunt winding current value by ≈45 %, since it is necessary to compensate for the demagnetizing reaction of the armature.

6. Discussion of the experimental study of a controlled autonomous magnetoelectric synchronous generator with a magnetic shunt

The no-load characteristic (Fig. 4) shows that the generator output voltage is significantly reduced when the polarity of the supply to the magnetic shunt winding is reversed. This is due to the fact that part of the main magnetic flux in this mode is closed through the magnetic circuit of the shunt and is not coupled with the armature winding of the generator under study. With the direct polarity of the power supply of the magnetic shunt winding, the generator output voltage increases. This is due to the increase in the main magnetic flux of the generator due to the magnetic flux of the shunt. At the same time, the difference between the calculated and experimental data is about 5–7 %, which indicates the adequacy of the previously developed mathematical model.

The value of the generator output voltage U_a at a magnetic shunt current I_{em}=0.5 A; I_{em}=0.75 A is higher by 11.5 % and 17 %, respectively, which is explained by an increase in the main magnetic flux due to the magnetic flux of the shunt. The nature of the external characteristic with an active-inductive load and in the presence of current in the magnetic shunt is mild, for example, at I_{em}=0.5 and at $I_g \approx I_n$, the voltage at the generator terminals decreases by 34 %. The decrease in voltage with increasing load is explained by the influence of the armature reaction and voltage drop across the internal active and inductive resistances (Table 3). At different values of the magnetic shunt winding current (Fig. 6, 7), the rigidity of the external characteristic changes. With an increase in the magnetic shunt current, the external characteristic has a more rigid form, which is explained by an increase in the main magnetic flux.

The obtained control characteristic (Fig. 8) shows that with a purely active load, in the area close to the rated power, a higher value of the rated current is obtained, compared to an active-inductive load. This is consistent with the physics of processes in magnetoelectric generators with magnetic shunts.

The existing methods of stabilizing the external characteristics of magnetoelectric generators are based on the use of external step capacitive regulators. On the one hand, they load the generator with additional reactive capacitive current, on the other hand, they require a switching system, which complicates the design as a whole and reduces its reliability. The proposed system is devoid of these disadvantages, allows you to smoothly regulate the output voltage in a given load range and does not cause additional losses in the armature winding.

The limitations of this solution are related to regulation limits, compared to electromagnetic excitation systems. Also, the permanent magnets used in this sample have limitations on the constancy of magnetic characteristics at increased thermal conditions.

The disadvantages of this study are associated with the lack of continuous measurement of the induction in the air gap, when the load and currents of the magnetic shunt system change.

The development of this study lies in the field of manufacturing experimental samples of magnetoelectric generators with double-sided magnetic shunting, which will increase the depth of regulation of the working magnetic flux. The proposed design has prospects for serial use, since its basic design is serial asynchronous motors.

7. Conclusions

1. The no-load characteristic in the mode of direct and reverse polarity of the magnetic shunt winding shows the possibility of using a magnetoelectric generator in the mode of generation or consumption of reactive power. When working with a load of $\leq 0.4R_n$, it is advisable to use the reverse polarity mode in order to reduce the voltage to nominal values. With increasing load, it is necessary to increase the magnetic shunt current to compensate for the increasing demagnetizing response of the generator armature.

2. The obtained experimental external characteristics have satisfactory convergence with the results of mathematical modeling described by the authors earlier. The difference between the data is 7–10 %, which confirms the adequacy of the previously developed mathematical models and the reliability of the experimental data obtained.

3. As a result of the study of the control characteristic, the control law of the field winding current for different loads was obtained. Despite the presence of additional losses in the magnetic shunt winding, which are about 5 % of the generator power, the use of a generator of this design makes it possible to solve the problem of controlling the external characteristic of permanent-magnet generators.

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