The object of this study is electromagnetic processes in a magnetoelectric generator with a capacity of 15 kW, operating in a local distribution network.

Using a magnetoelectric generator in parallel with a local distribution network makes it possible to improve the reliability and efficiency of such a system.

The advantages and disadvantages of the options for regulating the load characteristic of magnetoelectric generators for low-power energy complexes, for example, mini-hydroelectric power plants, have been analyzed. A system for regulating the output voltage of magnetoelectric generators with a capacity of up to 15 kW has been proposed and implemented using known and available semiconductor circuit solutions.

Several options for connecting individual coils of the generator armature winding with excitation from permanent magnets were investigated; the external characteristics corresponding to these options are shown. It is shown that when connecting the generator armature winding coils in parallel groups, it is possible to obtain the least distortion of the output voltage. At a load of 0.5–1.1 I_r, the rigidity of the characteristic allows it to meet the regulatory requirements of –10 %...+5 % of the rated voltage.

Analysis of the operation of a magnetoelectric generator when controlled by triacs at a given voltage range and when operating on variable active resistance without the use of semiconductor regulators has been carried out.

The forms of the generator output voltage on real samples with different control schemes are presented. The possibility of connecting an autonomous generator to a local distribution network in the absence of load for the purpose of implementation on the electricity market has been investigated. The form of the output voltage with the least distortion acceptable for the distribution network according to the standards for the quality of electric energy has been selected

Keywords: magnetoelectric generator, voltage stabilization, local distribution network, quality of electric energy

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DETERMINING THE IMPACT OF A MAGNETOELECTRIC GENERATOR ON THE OPERATION OF A LOCAL DISTRIBUTION NETWORK

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1. Introduction

In the Ukrainian power system, the use of renewable energy sources, in particular, the energy of the flow of small rivers, is a significant reserve capacity. Small and medium-power hydro generators with excitation from permanent magnets will make it possible to increase the specific power of power plants, improve reliability due to the absence of a contact node and an electric exciter. A feature of such generators is the absence of an excitation winding on the generator rotor, instead of which permanent magnets are used. In this regard, there is no way to control the generator voltage by changing the current in the excitation winding. There are three known techniques for adjusting the voltage of such a generator:

1. Converting the voltage at the generator output using an inverter [1], in which the voltage is first rectified, and then converted to an alternating voltage of the desired value using power valves. This is the most popular technique due to the fact that these converters are mass-produced and represented on world markets and have a voltage shape that is reasonably close to a sine wave. Although the curve consists of steps, which certainly increase the harmonic coefficient of the output voltage. The disadvantages of this technique include the relatively high cost of the equipment.

2. Support of the generator load characteristic by connecting capacitors [2]. This technique involves the use of capacitor banks, which are turned on as the generator load increases. This technique is used less often than the first one due to the large dimensions of the capacitor banks and stepwise voltage regulation at the generator output. The disadvantage of this technique is the constant switching processes of connecting and disconnecting capacitors, which worsens the shape of the generator output voltage.

3. Technique of using excess excitation of the generator [3]. With this control technique, the excitation of the generator is overestimated over the entire range of operating currents of the generator (about 40 %) so that an increase in the load leads to a decrease in the generator voltage. To compensate for the increased output voltage, the generator is loaded with an active resistance, the value of which decreases with increasing generator load current, equalizing the voltage. The advantages of this technique include its low cost, relatively small dimensions of the control system, and a fairly high quality of the voltage curve. The disadvantages of this system include the fact that the generator always operates at a significant fraction of its power, part of which is spent on the load resistance. The feasibility of using such systems may be due to the need for constant use of power loss energy to maintain the output voltage in autonomous complexes for heating premises or providing hot water supply.

Given the above, the third technique was chosen as the least expensive for analyzing the control system of an autonomous generator with permanent magnets.

A relevant scientific and practical area is studying the efficiency of the designed [4] magnetoelectric generator with a magnetic shunt and radial magnetic flux. The basis of such a generator is the structure of a classical alternating current machine with a traditional stator. The difference is the design of the rotor (inductor), which has poles with permanent magnets and an additional magnetic system in the form of ferroconductive shunts for adjusting the magnetic flux in the active zone.

The relevance of our work relates to investigating the influence of the operation of magnetoelectric generators on the parameters, characteristics, and stability of local distribution networks. Additionally, to the use of serial asynchronous motors, which are modified for the production of controlled synchronous generators with permanent magnets for operation in a local distribution network. This could reduce the cost of the system as a whole and improve the reliability of its operation as well as the reliability of the local network as a whole.

2. Literature review and problem statement

The authors of [5] proposed a methodology for calculating the characteristics of a synchronous generator with hybrid excitation for operation in an autonomous network. The essence of the procedure is to compare the results of generator modeling using three-dimensional and two-dimensional mathematical models. The similarity of the results obtained is 5–10 %, which is satisfactory. The authors also claim that the results obtained using a three-dimensional model are more accurate. However, the work does not include a comprehensive comparison of the resulting characteristics. The main disadvantage of this approach is the lack of results from experimental studies of such a generator, which may differ from modeling results.

Another approach is proposed by the authors in [6], in which a synchronous electric generator with hybrid excitation is considered. An excitation winding powered by direct current and a rotor magnetic circuit are used as a source of additional magnetic flux. The authors position it as the result of modeling and experimental studies when operating in a local network. However, as an experimental study, the results of the calculation of the magnetic circuit of such a generator are proposed, although photographs of the real structure are shown. Experimental studies on the control over a hybrid synchronous machine, which can be used for powerful electric vehicles, are reported in [7]. Hybrid excitation is implemented by an additional control coil located on the rotor of the machine, implemented by a wireless energy transfer system connected to the rotor shaft. The experimental results obtained on the prototype were compared with the results of mathematical three-dimensional modeling by the finite element method. This structure, despite some additional complexities in the machine's power supply system, simplifies the mechanical design and reduces losses in the control coil compared to the structure in which the coil is placed on the stator. Given the high cost and complexity of such a system, it is not advisable to use it in energy-efficient systems.

A solution to this problem is given in [8]. The authors describe a new methodology for developing a reliable axial flux permanent magnet synchronous generator for autonomous complexes. This methodology uses a modified version of the multi-objective evolutionary algorithm without dominant sorting of the genetic algorithm. Since the design procedure correlates with geometric and electromagnetic parameters, errors may occur that reduce the generator efficiency due to inaccuracies in the design and field calculations. In addition, the results of experimental studies are shown vaguely, without a description of the necessary equipment and test program, which casts doubt on the adequacy of the results.

A more precise study on this topic is reported in [9]. The study of a new doubly excited synchronous machine applies three-dimensional finite element analysis and experimental research. It is shown that the machine is indeed capable of regulating the output parameters under different load conditions. The paper shows the principle of operation and structural features of the generator of the original design. The results of three-dimensional modeling are also compared with experimental research conducted on a prototype with a different rotor structure. Accordingly, the results of such research are difficult to use and build a similar concept on their basis.

Existing variants of the design of SG with a magnetic shunt do not have an original structure and operating principle. Their main direction is the use of an additional bias winding, with its own magnetic system or the magnetic system of the machine. These solutions do not provide sufficient limits for regulating the output voltage and power under real operating modes [10].

However, work [11] has no comparison of experimental data described earlier for SG with a magnetic shunt under different operating modes and load characteristics. In addition, the features of the operation of such a generator on a local network are not taken into account. The design of the stator of such a generator practically does not differ from the classical structure, with the exception of the installed magnetic shunt on the rotor and an additional bias winding.

In [12], a comparison of experimental and calculated data of autonomous low-power generators with permanent magnets is given. The disadvantage of the proposed system is the increased cost and complexity of the system while the reliability of such systems is also questionable. In [13], the authors solve the problem of regulating external parameters using a complex mathematical model, a computer with subsequent control of the armature field of the studied sample. Comparison of the developed models (which are the software of the system) with the results of experiments shows a fairly high convergence.

In [14], a synchronous generator with parallel hybrid excitation is considered. The authors investigate the structural topology and principles of operation of a hybrid excitation machine when operating both under an autonomous mode and in the network. The possibility of controlling the flow under open-circuit conditions and the results of the constructed models are confirmed by comparison with experimental measurements. The work compares different approaches to calculating the magnetic system of hybrid machines with experimental data. However, the work does not contain any conclusions regarding the efficiency of the studied generator and the error of the presented methods for calculating the magnetic system.

It is possible to conclude that synchronous generators with permanent magnets and magnetoelectric excitation are used and are of interest to scientists and investors. However, in most studies [6, 7, 12], the influence of parameters of the armature winding on the shape of the output voltage has not been studied. The influence of control schemes for generators with permanent magnets on the shape of the output voltage curve and its quality has not been examined. The effect of the shape of the output voltage curve on the operation of the local distribution network has not been analyzed.

Given the above, it is necessary to conduct a study on the synchronous magnetoelectric generator when operating in a local distribution network of low power.

3. The aim and objectives of the study

The purpose of our study is to determine the impact of work of a low-power magnetoelectric synchronous generator in parallel operation on the local distribution network. This will make it possible to determine the optimal ways to control the generator and reduce the impact of higher harmonics of the generator on the operation of the local network. In turn, this will reduce losses in the network, improve the shape of the voltage curve, and increase the reliability of consumer operation.

To achieve the goal, the following tasks have been set:

– to calculate the output parameters of the magnetoelectric synchronous generator under different techniques of switching the armature winding coils;

– to conduct a study of the magnetoelectric generator when the load changes using different control techniques;

– to analyze the impact of the shape of the output voltage curve under different control techniques on the operation of a local distribution network.

4. The study materials and methods

Object of research: synchronous magnetoelectric generator with a capacity of 15 kW. Synchronous generator with permanent magnets on the rotor is made on the basis of serial asynchronous motor 4A132M4U3. The stator of serial asynchronous motor was used, and the rotor was made with poles of rare-earth permanent magnets NdFeB with pole tips of magnetic soft steel. The stator design remained unchanged, all elements of the motor, including bearing shields, fan, etc. also remained from the prototype. The test results confirmed the calculated data [15].

For experiments with different implementations of the control system, a synchronous generator with the following parameters is used: $S=15$ kW, $2p=4$, $n=1500$ rpm, $U_l=560$ V, $I_l=16.3$ A, $\cos\varphi=0.95$. This technique assumes that using the proposed control schemes, the voltage is maintained within ±10 % of U_l, i.e., from 207 V to 253 V in accordance with DSTU EN 50160:2014 [16].

The basic hypothesis of the study: the operation of a synchronous magnetoelectric generator in the local distribution network is accompanied by the influence of the generator output parameters, namely:

1. The shape of the output voltage curve affects the operation of individual consumers and can cause their incorrect operation.

2. The output frequency of the generator depends on the nature of the load and requires strict stabilization, which is provided by the drive motor control system.

3. The output voltage is affected by the type of load and the technique of controlling the output voltage of the magnetoelectric generator.

Assumptions adopted in the study:

1. Since the generator is autonomous, there is no possibility of returning excess energy to the network.

2. It is assumed that there are consumers of both electrical and thermal energy. The generator is manufactured for its natural rated voltage, which is 20 % higher than the standard network voltage, and works mainly on an autonomous load.

Simplifications adopted in the study:

1. The shape of the output voltage in this case is sinusoidal and the generator can work partly on an autonomous load and partly on the network.

2. In case the autonomous load is less than 50 % of the rated value even under an idle mode, it is proposed to use simple, cheap standard circuits for "cutting off" excess voltage.

5. Results of research on the operation of a magnetoelectric generator in a local distribution network

5. 1. Output parameters of a magnetoelectric synchronous generator with different techniques of switching the armature winding coils

The connection scheme of individual coils of the armature winding of a synchronous generator makes it possible to obtain different output voltages at the generator terminals. Our work calculates the no-load characteristic for two options for switching the coils. All 8 coils of one phase are connected in series (Fig. 1, *a*) and 4 in parallel, when the coils of each phase are connected in series-parallel (Fig. 1, *b*). In this case, the active resistance of the winding phase $Rs=0.054$ Ohm.

When calculating parameters for the electric generator, its phases were connected to a diode bridge. Calculations of the idling characteristic were carried out for the stator phase connection option: "star" (Fig. 2).

Fig. 3 shows the dependence of voltage in the load on the frequency of rotation of the electric generator rotor (idle characteristic). The experiment is carried out for the "star" connection scheme of the generator armature winding coils for the 1st and 4th parallel groups.

Fig. 4 shows the calculated external characteristics for different rotation frequencies.

It is evident that for the drive from the internal combustion engine, it is necessary to use the data obtained for 1500 rpm.

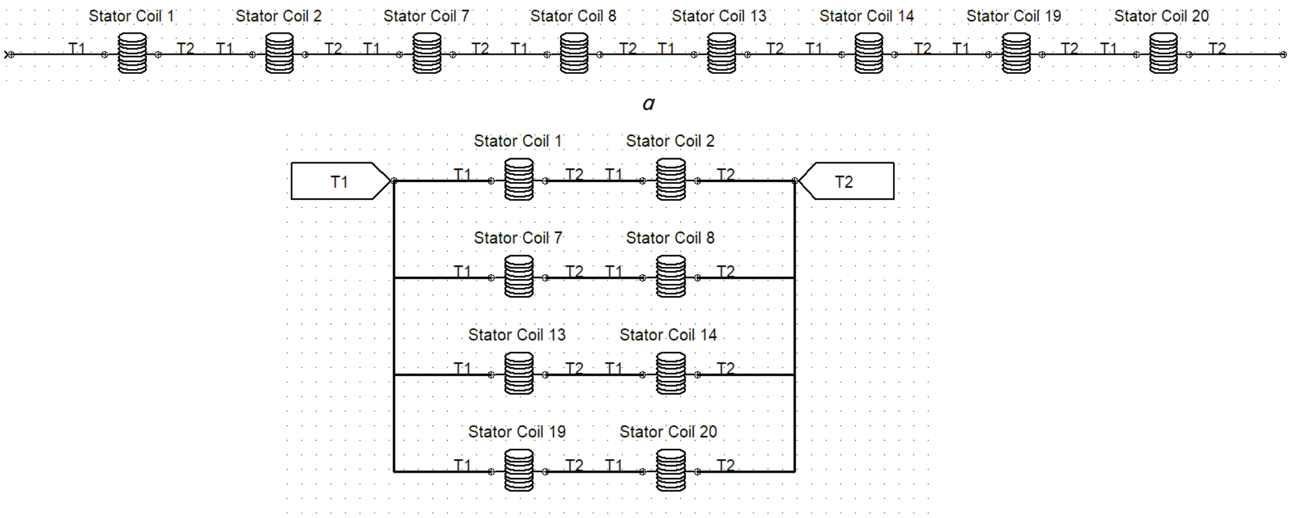

Fig. 1. Options for switching on coils of one phase: *a* — 1 in parallel; *b* — 4 parallel groups

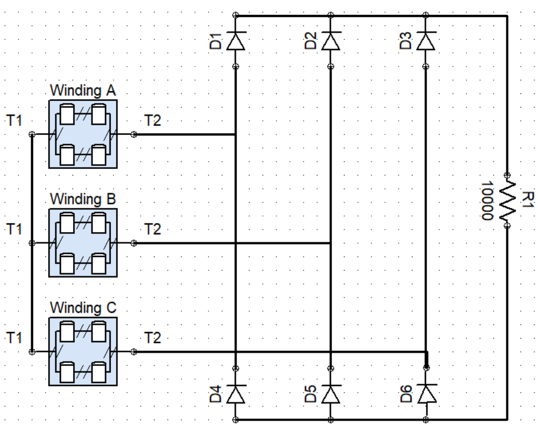

Fig. 2. Stator phase connection diagram: "star"

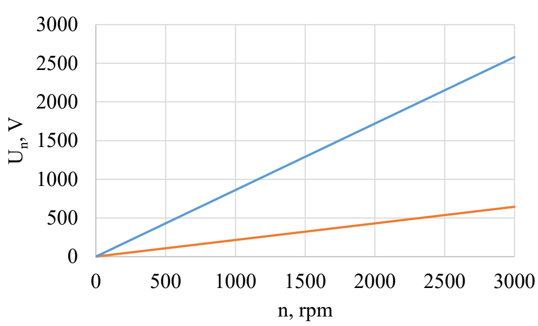

Fig. 3. Generator idle characteristics:
a — 1 parallel; *b* — 4 parallel groups

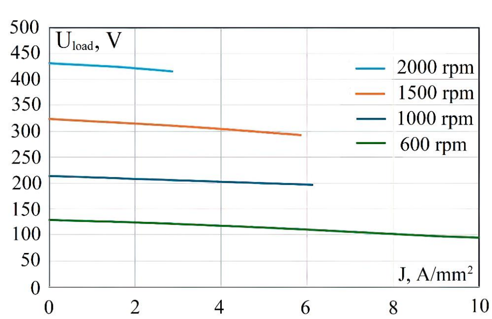

Fig. 4. Estimated external characteristics
for different speeds

5. 2. Research of the magnetoelectric generator when changing the load using different control techniques

Let us consider the simplest control system using triacs at the generator output. To study this version of the system, the circuit shown in Fig. 5, *a* was implemented. The best results in terms of the shape of the output voltage curve can be obtained using the circuit shown in Fig. 5, *b*. This is because the switching angle of the semiconductor valves was almost 0.

As a result of the tests, oscillograms of the generator output voltages were acquired using the proposed and implemented control scheme. The resulting voltage curve shapes are shown in Fig. 6.

For a typical local distribution network scheme, the following calculations of acceptable shapes of voltage curves that have distortions were performed.

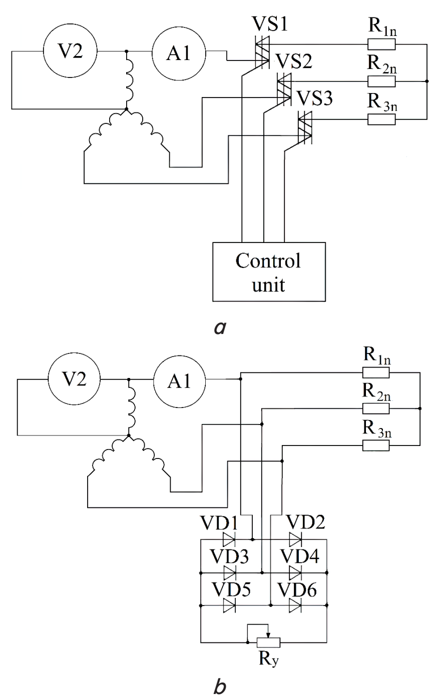

Fig. 5. Generator load schemes on variable resistances:
a — triac control scheme; *b* — voltage regulation scheme
with generator load on active variable resistance

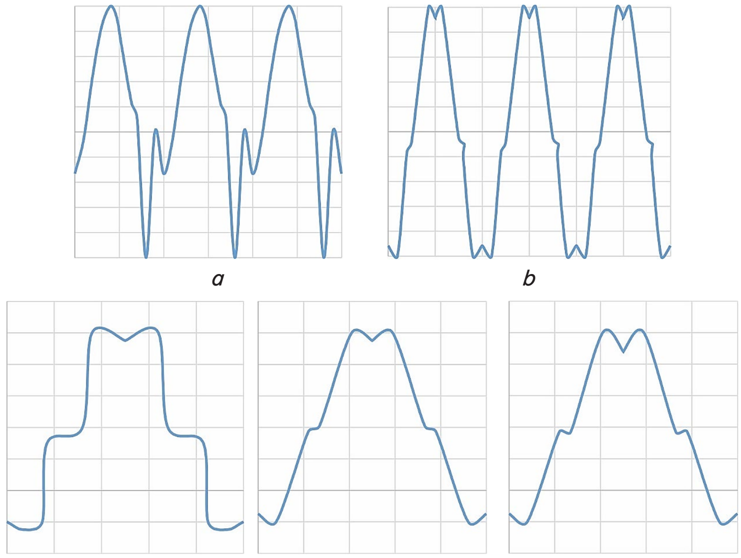

Fig. 6. Shapes of the voltage curve for a non-sinusoidal power source: *a* – control scheme for a semiconductor rectifier with controlled triacs; *b* – control scheme for a semiconductor rectifier with uncontrolled valves; *c* – control scheme for a semiconductor rectifier with uncontrolled triacs; *d* – control scheme for a semiconductor rectifier with controlled valves; *e* – control scheme for a semiconductor rectifier with controlled valves for an active-inductive load

Current regulatory documents regulate the voltage limits of higher harmonics in distribution electrical networks.

5. 3. Influence of the shape of the output voltage curve under different control techniques on the operation of the local distribution network

The study of the influence of a non-sinusoidal current source on the quality indicators of electric energy was performed for the test circuit of the 10/0.4 kV electric network, the circuit of which is demonstrated in Fig. 7.

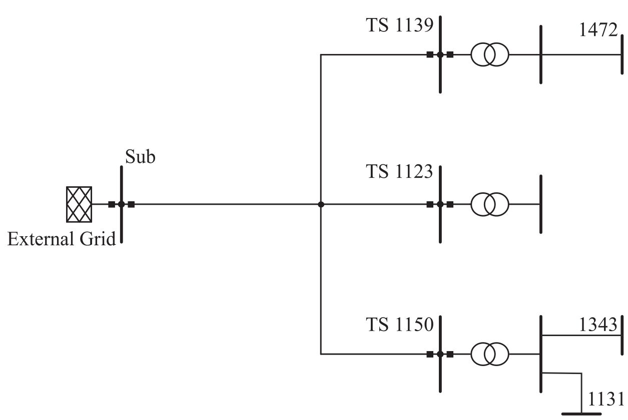

Fig. 7. Diagram of a 10/0.4 kV test electrical network

It shows: Sub – nodal feeding substation 110/10 kV; TS1123, TS1139, TS1150 – transformer substations (TS) 10/0.4 kV; 1131, 1343, 1472 – electric energy metering nodes. The non-sinusoidal current source is connected at the end of one of the 0.4 kV feeders of TS 1150 at point 1131. Harmonic analysis of the steady-state mode of the electric network was performed at the points:

1. At the connection point of the non-sinusoidal current source (p. 1131).
2. On the 0.4 kV TS 1150 busbars.
3. At the end of the adjacent 0.4 kV TS 1150 feeder (p. 1343).
4. On the 0.4 kV TS 1139 busbars.
5. At the end of the 0.4 kV TS 1139 feeder (p. 1472).
6. On the 10 kV busbars of the Sub.

Fig. 8 shows the result of analysis of the shape of the voltage curve demonstrated in Fig. 6, *a*. Fig. 8–12 show the Amplitudes of harmonics on the Y axis, and the numbers of harmonics on the X axis.

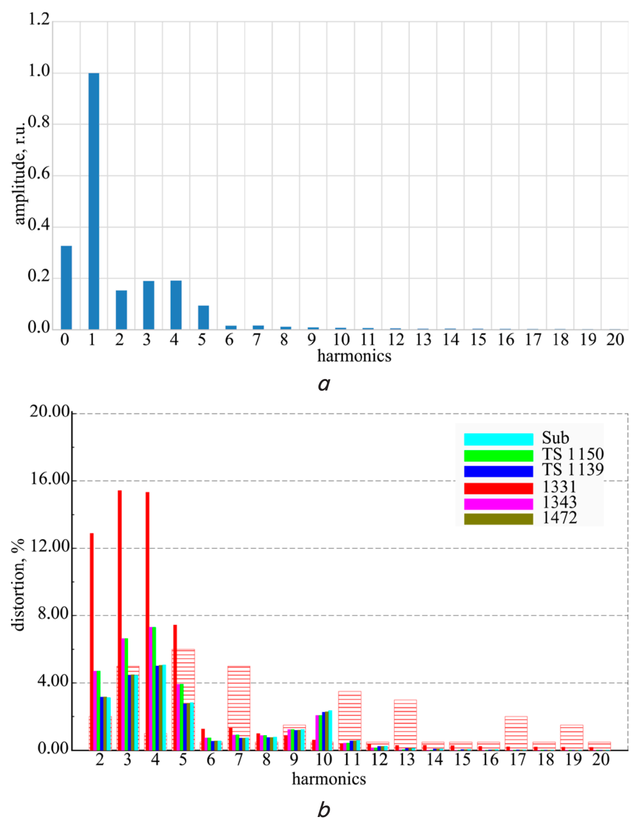

Fig. 8. Harmonic analysis of the electrical network mode for the voltage curve in Fig. 6, *a*: *a* – spectrum of harmonic components of the voltage curve; *b* – results of harmonic analysis

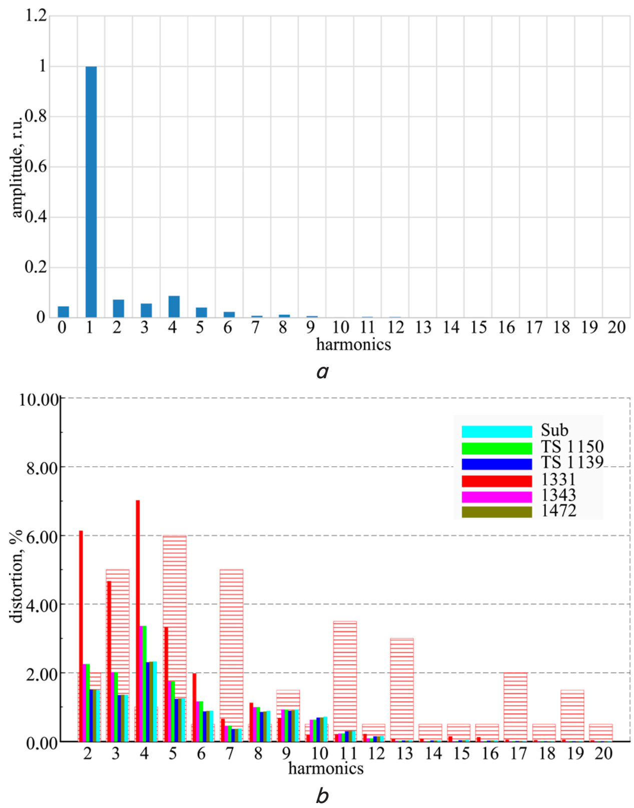

Fig. 9. Harmonic analysis of the electrical network mode for the voltage curve in Fig. 6, *b*: *a* — spectrum of harmonic components of the voltage curve; *b* — results of harmonic analysis

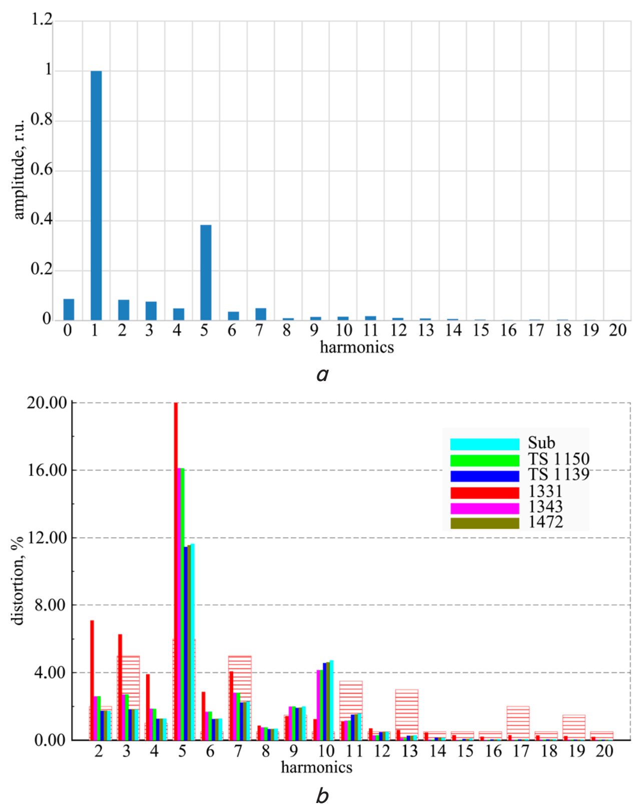

Fig. 10. Harmonic analysis of the electrical network mode for the voltage curve in Fig. 6, *c*: *a* — spectrum of harmonic components of the voltage curve; *b* — results of harmonic analysis

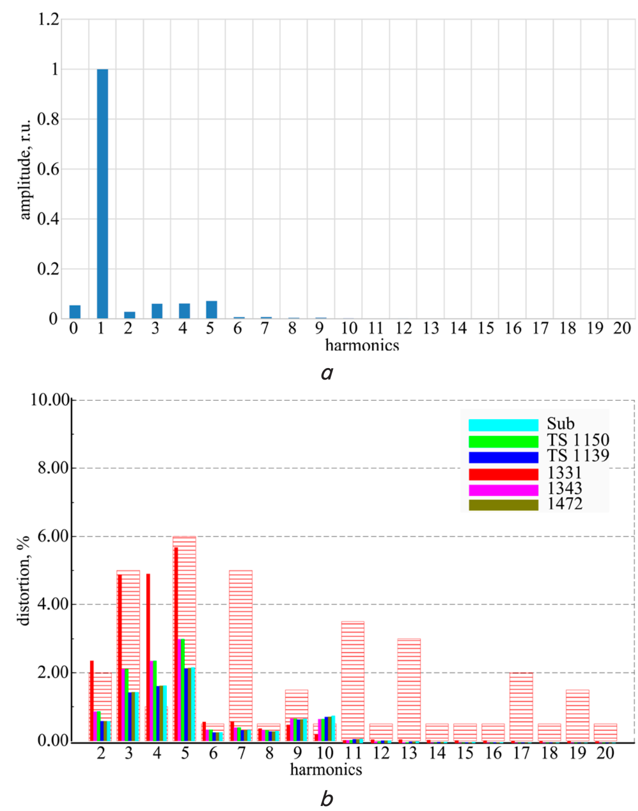

Fig. 11. Harmonic analysis of the electrical network mode for the voltage curve in Fig. 6, *d*: *a* — spectrum of harmonic components of the voltage curve; *b* — results of harmonic analysis

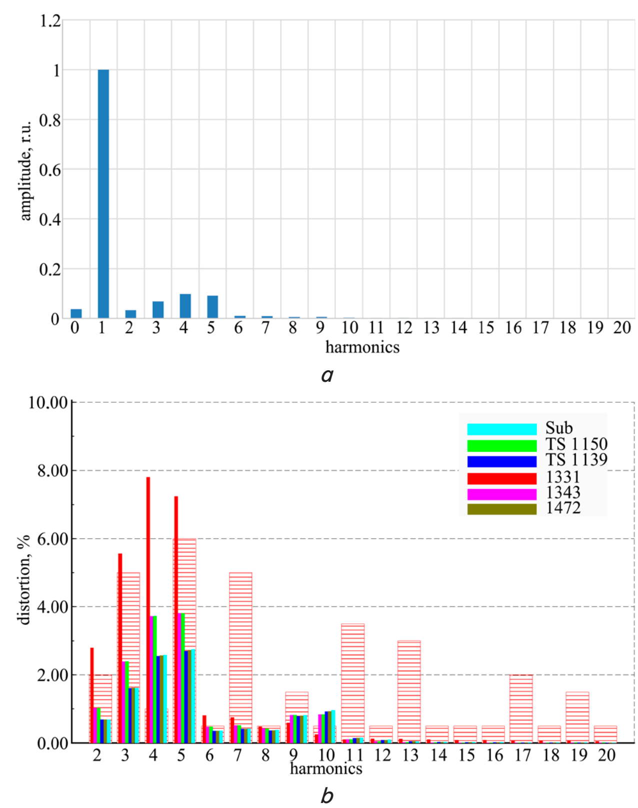

Fig. 12. Harmonic analysis of the electrical network mode for the voltage curve in Fig. 6, *e*: *a* — spectrum of harmonic components of the voltage curve; *b* — results of harmonic analysis

Fig. 9 shows the result of analysis of the shape of the voltage curve demonstrated in Fig. 6, *b*.

Fig. 10 shows the result of analysis of the shape of the voltage curve demonstrated in Fig. 6, *c*.

Fig. 11 shows the result of analysis of the shape of the voltage curve demonstrated in Fig. 6, *d*.

Fig. 12 shows the result of analysis of the shape of the voltage curve demonstrated in Fig. 6, *d*.

The presence of higher harmonics in the output voltage of a magnetoelectric generator does not limit its use in stand-alone installations and in parallel operation in a local network. It is worth noting that generators of classical design with electromagnetic excitation also have a non-ideal shape of the output voltage curve.

6. Discussion of results related to the operation of a magnetoelectric generator in a local distribution network

In the case of switching on 8 coils of one phase connected in series (Fig. 1, *a*) it is possible to obtain a higher voltage at the generator terminals. With a certain combination of such switching on, it is possible to choose a value at which ±10 % of the rated voltage is obtained at a load of 0.6–1.0 P_r. As for using the generator in the network at lower loads, it is proposed to use the scheme shown in Fig. 1, *b*, which provides the least voltage distortion.

To calculate the idle curve, the scheme shown in Fig. 2 is used. It is the simplest scheme built on the basis of the Larionov bridge. And it is used as a base for estimating the shape of the output voltage of the generator under study.

The obtained voltage values of the studied generator under an idle mode (Fig. 3, *a*, *b*) with different schemes of stator winding coil connections make it possible to obtain different voltage values at the generator output. The difference between the series and parallel connection of the coils makes it possible to obtain a voltage that is 4.05–4.15 times different from the series (classical, Fig. 3, *a*) connection of the coils.

In Fig. 4, at a frequency of 1500 rpm, the input voltage on the winding connected by a star is 480 V. When loaded from 50 % of the rated current to 110 %, the rigidity of the characteristic makes it possible to fit into the standards of –10 %...+5 % of the rated voltage.

The study of this circuit in Fig. 5, *a* showed that with a given voltage regulation range, an acceptable shape of the voltage curve was obtained, and the current curve has only minor distortions.

Using the circuit in Fig. 5, *b* shows minor distortions of the output voltage. The presence of higher harmonics is explained by the nonlinearity of semiconductor valves and switching processes in the valves.

The Fourier series expansion of the shape of the voltage curve of the power source determines the spectrum of harmonic components presented in Fig. 8, *a*. The results of harmonic analysis of the steady-state mode of the test electrical network are shown in Fig. 8, *b*. Also, Fig. 8, *b* indicates the maximum permissible voltage values of individual harmonics. Analysis of the obtained results indicates that the voltage curve of Fig. 6, *a* is characterized by significant non-sinusoidal nature. All even harmonics up to the tenth exceed the maximum permissible values at all control points of the test circuit. For the third harmonic, the maximum permissible values are exceeded at the point of connection of the non-sinusoidal voltage source. At point 1343 of the adjacent feeder and on the TP 1150 buses, that is, in the entire 0.4 kV local network to which the proposed magnetoelectric generator is connected. For the fifth harmonic, the excess is observed only at the point of connection of the power source with a non-sinusoidal voltage curve. For the seventh, ninth, eleventh, and higher harmonics, the requirements of the standards in the test circuit are not violated.

The Fourier series expansion of the shape of the voltage curve of the power source determines the spectrum of harmonic components presented in Fig. 9, *a*. The results of harmonic analysis of the steady-state mode of the test electrical network are shown in Fig. 9, *b*. Analysis of the obtained results indicates that the voltage curve of Fig. 6, *b* is characterized by moderate non-sinusoidal nature. For the second harmonic, the maximum permissible voltage values in the 0.4 kV local network, to which the non-sinusoidal power source is connected, are exceeded. For the remaining even harmonics, up to the tenth, the violation of the voltage limit values is observed at all control points of the network. For the remaining even and all odd harmonics, the curvature of the voltage curve at all points of the network is within normal limits.

The Fourier series expansion of the shape of the voltage curve of the power source determines the spectrum of harmonic components presented in Fig. 10, *a*. The results of harmonic analysis of the steady-state mode of the test electrical network are shown in Fig. 10, *b*. Analysis of the obtained results reveals that the voltage curve in Fig. 6, *c* is characterized by significant non-sinusoidal nature, especially at the fifth harmonic. For the second harmonic, the maximum permissible voltage values in the 0.4 kV local network, to which a non-sinusoidal power source is connected, are exceeded. For the remaining even harmonics up to the tenth, the voltage limit values are violated at all control points of the network. For the third and twelfth harmonics, the violation of the standard conditions is observed only at the point of connection of the non-sinusoidal power source. For the fifth harmonic, the permissible values of the voltage curve curvature are significantly exceeded at all control points of the studied network. Also, a slight excess of the permissible limits at all control points, except for the point of connection of the power source is observed at the ninth harmonic. For the seventh, eleventh, and the remaining higher harmonics, starting from the thirteenth, the voltage curve curvature at all points of the network is within normal limits.

The Fourier series expansion of the shape of the voltage curve of the power source determines the spectrum of harmonic components presented in Fig. 11, *a*. The results of harmonic analysis of the steady-state mode of the test electrical network are shown in Fig. 11, *b*. Analysis of the obtained results indicates that the voltage curve of Fig. 6, *d* is characterized by moderate non-sinusoidal nature. For the second, third, fifth, and sixth harmonics, the maximum permissible voltage values are exceeded at the connection point of the non-sinusoidal power source. For the fourth harmonic, the permissible values of the voltage curve curvature are exceeded at all control points of the studied network. For the tenth harmonic, the restrictions are violated at all control points, except for the connection point of the non-sinusoidal power source. For the remaining harmonics, the voltage curve curvature at all points of the network is within normal limits.

The Fourier series expansion of the shape of the voltage curve of the power source determines the spectrum of harmonic components presented in Fig. 12, *a*. The results of harmonic analysis of the steady-state mode of the test electrical network are shown in Fig. 12, *a*, *b*. Analysis of the obtained results indicates that the voltage curve in Fig. 6, *d* is characterized by relatively sufficient sinusoidal nature. For the second and sixth harmonics, a slight excess of the maximum permissible voltage values is observed only at the connection point of the non-sinusoidal power source. For the fourth harmonic, the permissible values of the voltage curve curvature are exceeded at all control points of the studied network. For the tenth harmonic, the restrictions are violated at all control points, except for the connection point of the power source. For the remaining even harmonics and all odd harmonics, the voltage curve curvature at all points of the network is within normal limits.

Existing autonomous sources of electricity operating in local distribution networks are based on the use of synchronous generators with electromagnetic excitation. They have a simple design and relatively lower cost compared to generators with permanent magnets and magnetoelectric generators. However, they require regular technical inspection and are less reliable. Magnetoelectric generators have higher energy performance, but they have a higher final cost for the consumer. Controlling the output parameters of such generators leads to the appearance of a non-sinusoidal output voltage, which negatively affects the operation of consumers and leads to additional losses. However, the use of the proposed control techniques makes it possible to solve this problem. At the same time, magnetoelectric generators do not require regular maintenance.

The use of a magnetoelectric generator, in contrast to [17, 18], makes it possible to reduce operating costs, increase energy performance, which contributes to increasing the reliability of autonomous power plants in general.

Based on our studies of operation of the magnetoelectric generator as part of the local distribution network, the reliability of autonomous power complexes has been increased.

The limitations of the proposed system with a magnetoelectric generator are associated with the saturation of the steel ferromagnetic elements of the magnetic system, which limits the limits of adjustment of the output parameters. The task of optimal design of such generators requires a balance between geometric parameters, minimal electromagnetic field pulsations, weight, and final cost.

The disadvantages of using magnetoelectric generators are due to the limitations of using permanent magnets since they are sensitive to mechanical influences and shocks, high temperatures, and demagnetization. There are also technological disadvantages associated with the complexity of manufacturing the elements of the magnetic system of the bias winding and ensuring its mechanical strength and cooling.

Our research may be advanced towards building a model of this control system and comparing data and predicting the behavior of generators of other capacities and different numbers of poles.

7. Conclusions

1. The use of different combinations of connecting individual coils of the generator armature winding makes it possible to change the output voltage at the generator terminals. This effect can be used both for systems with different rated operating voltages and for stabilizing the output voltage when the generator is operating in a certain load range (for example, 0.6–1.0 P_r). When connecting the generator armature winding coils in parallel groups, it is possible to obtain the least distortion of the output voltage. At a rated speed of rotation of 1500 rpm, the input voltage on the winding is 480 V. At a load from 50 % of the rated current to 110 %, the rigidity of the characteristic makes it possible to fit into the standards of –10 %...+5 % of the rated voltage.

2. When controlling the output voltage of the armature winding of a magnetoelectric generator using triacs at a given voltage regulation range, an acceptable shape of the voltage curve is obtained, and the current curve has only minor distortions. Using a load regulation scheme applying the generator's operation on a variable active resistance, minor distortions of the output voltage are observed. The presence of higher harmonics is explained by the nonlinearity of semiconductor valves and switching processes in the valves.

3. Connecting a generator with a non-sinusoidal voltage curve to the distribution electrical network causes a violation of the standards for the quality of electrical energy at the points of connection of consumers. The most significant distortion of the voltage curve is observed when a semiconductor rectifier control scheme with controlled and uncontrolled triacs is used. The least negative impact on the quality of electrical energy is exerted by a power supply with a voltage curve shape that corresponds to the control scheme of a semiconductor rectifier with controlled valves for an active-inductive load.

The magnitude of the 3rd harmonic of the voltage curve when using a circuit with controlled triacs is 19.6 %, the 5th – 8.4 %. The magnitude of the 3rd harmonic of the voltage curve when using a circuit with uncontrolled triacs is 7.9 %, the 5th – 39 %. The magnitude of the 3rd harmonic of the voltage curve when using a rectifier control circuit with controlled valves for an active-inductive load is 3.2 %, the 5th – 3.7 %.

When using a control circuit for the external characteristic of a generator with transistor switching, the range of output voltage changes is from 1.4 U_r to 0.4 U_r without significant distortion of its shape. Distortions of the voltage curve shape increase with increasing turn-on angle of thyristors and triacs, i.e., the expansion of the adjustment range should be limited to the user's requirements for the shape of the output voltage curve.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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