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NORMALIZATION OF NON-SINUSOIDALITY INDICATORS OF MAGNETOELECTRIC GENERATOR UNDER AN AUTONOMOUS MODE OF OPERATION

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The object of this study is a magnetoelectric generator with an excitation system based on permanent magnets and an additional magnetic system in the form of ferromagnetic shunts.

This paper considers the task of non-sinusoidal voltage in a local electrical network with a magnetoelectric generator. This phenomenon negatively affects the operation of consumers and reduces the energy efficiency of the system. The work investigates the causes of harmonic distortion and proposes a method for reducing their impact. This helps ensure stable and high-quality operation of consumers in the electrical network.

The generated voltage was studied in terms of non-sinusoidality for a magnetoelectric generator at different load levels in isolated operation. The non-compliance of the generated voltage with the requirements of the current standard in terms of the relative voltage of individual harmonics and the total harmonic distortion factor (THD_U) was established. The dependences of the relative voltage of harmonics on the generator load level in the range from idle to nominal load were determined. The parameters of single-frequency resonant filters were calculated, which enable the normalization of the generated voltage according to the non-sinusoidality indicators under the conditions of isolated operation of the generator with a rated load.

A feature of the results is the design of adaptive voltage non-sinusoidality filters that take into account the specificity of operation of the magnetoelectric generator in the local network.

Analysis of the generator output voltage revealed that under an isolated operation mode, it is necessary to install filters of the 3^{rd}, 5^{th}, 9^{th}, 21^{st}, and 23^{rd} harmonics in the entire generator load range. The absence of harmonic resonance phenomena is shown if filters with fixed parameters are used in the generator load range from idle to rated load

Keywords: magnetoelectric generator, harmonic voltage, harmonic distortion factor, quality of electric energy

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1. Introduction

Under normal operating conditions, integrated power systems (IPSs) provide the function of reliable power supply to consumers connected to its network. At the same time, violations of the normal operating modes of IPSs, due to natural, man-made, military, or other reasons, lead to restrictions and long interruptions in the power supply of consumers. Under such conditions, there is a need for individual backup sources of electricity for industrial and domestic consumers, which are able to provide reliable power supply to consumers for a time sufficient for the distribution system operator to restore power. An obvious requirement for such backup sources is the absence of dependence of the volume of generated electricity on the time of day, weather conditions, etc.

For industrial and domestic consumers, backup sources can be diesel or gas generators and power plants. For people living in cities, there are systems for storing electricity based on various types of batteries, for the population living in the private sector, there are low-power (up to 10 kVA) gasoline or diesel generators. In the latter case, there is a need for simplicity of design and sufficient reliability of internal combustion engines and alternators (generators), which could enable the possibility of mass production and, at the same time, a moderate cost of a backup source of electricity.

These requirements are met by low-power generators with excitation from permanent magnets, which are characterized by high reliability of operation due to the absence of a moving system of rotor contacts with an electromagnetic exciter in the structure. At the same time, the absence of an excitation control system for such generators causes the problem of voltage regulation, the solution of which requires the use of additional means.

The structural features of a magnetoelectric generator with permanent magnets on the rotor poles and an additional magnetic system in the form of ferromagnetic shunts cause the occurrence of a wide range of harmonics in the generated voltage. This limits the possibility of using such a generator to

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power consumer electrical installations designed to operate in general-purpose electrical networks with non-sinusoidality of electrical energy quality indicators regulated in accordance with DSTU EN 50160:2023.

The relevance of research into this area is due to the need to determine the possibility of using a magnetoelectric generator to provide consumers with electrical energy of standardized quality in the absence of external power supply (under an isolated operation mode).

2. Literature review and problem statement

In [1], power losses in distribution networks are investigated, which leads to a decrease in the quality of service, an increase in electricity costs and losses of income for utilities. The authors argue that the integration of distributed generators into electrical networks leads to the minimization of losses. To do this, it is necessary to calculate the power and connection point of additional electric generators. The results of the study show that an increase in the number of distributed generators reduces losses by more than 56%. However, the work does not provide an analysis of the complex impact of generator parameters on the local network as a whole.

Another approach is proposed in [2], which considers conventional approaches and problems associated with the operational reliability of local electrical networks. The essence of the approach is that a new two-stage method of recovery after emergencies is proposed, which takes into account the ability of distributed generators to recover after short circuits. This two-stage approach promotes short-term rapid recovery of load power and increases long-term operational stability, improving both the resilience and reliability of distribution networks. However, it is unknown how the research results contribute to increasing the operational efficiency of modern energy systems, which is important for the integration of, for example, renewable energy sources.

An option for resolving this problem is reported in study [3]. Artificial intelligence-based controllers, in particular neural network controllers, are proposed. This makes it possible to monitor the state of the local power grid and promptly apply backup power generation systems with magnetoelectric generators, as well as using wind power plants. However, obtaining accurate data for training and tuning the artificial neural network model remains a significant problem in devising effective methods for monitoring, diagnosing, controlling, and protecting.

The principles of operation of autonomous power plants in remote regions from power plants are described in [4]. Many remote or isolated settlements rely on autonomous generators since connection to conventional power grids is either too expensive or technically impractical. In such situations, the most appropriate is the use of local power grids consisting of diesel generating sets and renewable energy sources. However, such systems are characterized by the presence of a significant number of higher harmonics on the one hand and a low overload capacity factor on the other. The authors investigate the dynamic processes in such a system. The impact of renewable energy sources and the issue of transient processes were not investigated in the cited work.

The study of dynamic processes in local distribution networks with autonomous power generators and wind power plants is reported in [5]. Such systems are the result of adding wind generators to a pre-existing diesel power plant located in a remote location, provided that wind resources are available. This makes it possible to reduce fuel consumption and harmful emissions. The impact of higher harmonics on dynamic processes and the magnitude of local network losses was not considered in the study.

Promising intelligent electricity distribution systems are considered by the authors of [6]. They use remote control of switches and advanced automation systems to operate under an autonomous mode of some parts of local networks in order to increase the reliability of such a power system. The authors developed a program code that is able to assess the reliability of electricity distribution using analytical methods. The shortcoming worth noting is that the results of such studies are difficult to use and build complex predictive models based on them.

A method for identifying parameters of a local network and power generators model using a genetic algorithm is proposed in [7]. Due to the increased integration of new electricity sources, the adaptability of conventional methods for analyzing and calculating emergency modes has decreased when applied to distribution networks. The proposed model accurately reflects the characteristics of poor-quality voltage and current during short circuits from the local network. However, this model does not take into account the influence of power quality from the power generator, which leads to relatively large calculation errors.

The integration of autonomous power generating units and renewable energy sources into the local power grid is studied by the authors of [8]. This makes it possible to increase the reliability of the network and prevent reverse power flow. The study focuses on the optimal distribution of electricity in local networks, taking into account the cost, network reliability, and environmental impact. However, the issue of reliability of the consumer's operation and the influence of higher harmonics on it remains unresolved.

The authors of work [9] study the impact of emergency operating modes on local networks. To analyze the negative consequences, the authors developed their own program code for modeling transient processes of the electrical network in the MATLAB environment. Transient overvoltage in electrical networks was studied using the developed code and software. The research results showed satisfactory agreement with the results of experimental studies. Given the high cost and complexity of such a system, its use in local electrical networks requires economic justification.

The analysis of existing methods for estimating parameters before designing local networks with autonomous electric generators under conditions of low-power consumers is considered in [10]. A method for determining the optimal power of substations and optimal sections of 0.38 kV power transmission lines is proposed, taking into account the probable nature of the applied load. However, the work does not investigate the influence of energy-saving systems, parameters of power supply systems, and higher harmonics of additional power sources.

To solve the problem of voltage regulation of a magnetoelectric generator with an excitation system with permanent magnets, the structure of which is similar to that proposed in [11], a number of possible approaches are considered. These approaches involve the use of semiconductor voltage converters [12], capacitors [13], and overexcitation for the generator [14, 15].

All allows us to assert that the issue of the possibility of using a magnetoelectric generator as a backup power source under an isolated mode of operation has not been considered in the literature, which necessitates such a study.

3. The aim and objectives of the study

The purpose of our work is to determine the influence of a magnetoelectric generator with permanent magnets on the rotor poles and an additional magnetic system in the form of ferromagnetic shunts on the quality of electrical energy in isolated operation. This will make it possible to increase the operational reliability of consumers under conditions of power supply restrictions and emergency modes, as well as reduce losses in the local electrical network.

To achieve this goal, it was necessary to solve the following tasks:

– to build a simulation model of a magnetoelectric generator with permanent magnets on the rotor poles and an additional magnetic system in the form of ferromagnetic shunts;

– to simulate the generator operating modes to determine the spectrum of harmonic voltage components at different levels of its load;

– to determine the parameters of harmonic filters based on non-sinusoidality for different levels of generator load under the condition of its isolated operation.

4. The study materials and methods

The object of our study is a magnetoelectric generator with an excitation system based on permanent magnets and an additional magnetic system in the form of ferromagnetic shunts.

The principal hypothesis of the study is as follows:

1. The non-sinusoidality of the voltage has a spectral structure characterized exclusively by components with a frequency multiple of the rated one and does not contain subharmonics.

2. Magnetoelectric generators, due to the specificity of their design, can introduce higher harmonics into the output voltage, especially when operating on an alternating load.

The assumptions adopted in the study:

1. The magnetoelectric generator is a power source for a local electrical receiver, and the active and inductive resistance of the generator windings remain unchanged.

2. The non-sinusoidality of the voltage in the network is caused mainly by higher harmonics, which are the result of the operation of the electric generator and the nonlinearity of the load, and the influence of external sources of distortion is neglected.

3. Passive or active filtering is used as a means of combating harmonics, as well as adjusting the parameters of the generator itself; the technique with an increase in short-circuit power is not considered based on the conditions of the isolated operation mode of the generator.

4. The influence of temperature and mechanical vibrations on the harmonic composition of the voltage does not affect or is considered insignificant.

5. The level of voltage distortion is characterized by generalized indices, in particular the harmonic distortion factor (THD_U), which makes it possible to quantitatively compare different correction methods.

Simplifications accepted in the study:

1. Symmetrical operating modes of the generator are considered.

2. It is assumed that the generator voltage regulation system provides support on its buses of a linear voltage of 400 V in the entire load range.

3. The active resistance of harmonic filters is neglected in the calculation model.

The research was conducted on the basis of a simulation computer model of a magnetoelectric generator, during which the harmonic spectrum of the generated voltage was obtained for the generator's idle mode, as well as for the 30%, 50%, 75%, and 100% load modes.

5. Results of investigating the non-sinusoidality of voltage of a magnetoelectric generator under an autonomous mode

5. 1. Simulation model of a magnetoelectric generator with permanent magnets and an additional magnetic system

The simulation model of a magnetoelectric generator was constructed in the COMSOL Multiphysics software environment. To estimate the magnitude and shape of the generator armature winding voltage, a circular-field simulation mathematical model was built. The peculiarity of this model is that a change in the generator load leads to a change in the nature of the electromagnetic field distribution and vice versa. That is, when the load changes, the magnitude of the current in the generator armature winding changes, the armature reaction changes, which affects the main magnetic flux and the generator output parameters: voltage and power. Therefore, this problem statement is considered multiphysical. To calculate the electromagnetic field, the data on the studied magnetoelectric generator are used, shown in Fig. 1.

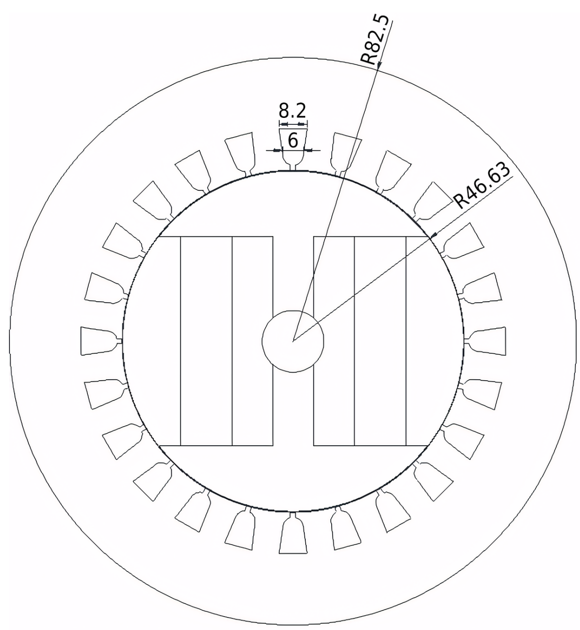


Fig. 1. Schematic of the studied generator

To calculate the electromagnetic field, a non-stationary nonlinear differential equation for the vector magnetic potential A in a moving conductive medium is used [14]

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

where V are the velocity vectors of the medium; ∇ is the differential Nabla operator.

The magnetic field of permanent magnets is calculated from the following equation [14]

$$\sigma\frac{\partial A}{\partial t}+\nabla\times\frac{\nabla\times A-B_r}{\mu_0\cdot\mu_r}=J_e, \quad (2)$$

where B_r is the residual induction of permanent magnets.

The вmagnitude of current in the armature windings, the induced EMF, and other winding parameters are determined from the following system of equations:

$$J_e=\frac{N\left(V_e+V_{ind}\right)}{S_c\cdot R_c},$$

$$R_c=\int_A\frac{N\cdot L}{\sigma_c\cdot a_c\cdot S_c}\mathrm{d}A, \quad (3)$$

$$V_{ind}=N\cdot\sum\frac{L}{S_c}\cdot\left(\int_{S_c}E_{zA}\mathrm{d}s-\int_{S_c}E_{zx}\mathrm{d}s\right),$$

where J_e is the value of the current density in the armature winding, which depends on the load and the nature of the generator; N is the number of turns in the armature winding; S_c is the cross-sectional area occupied by the winding with conductors; R_c is the active resistance of the stator winding phase; L is the average length of the stator winding phase turn; σ_c, a_c are the electrical conductivity of the stator winding material and the cross-sectional area of the elementary conductor; V_{ind} is the value of the induced EMF in the generator stator winding; V_e is the voltage characterizing the generator load; E_{zA}, E_{zX} are the electric field strength in the locations of the phase zones "A" and "x".

The distribution of the electromagnetic field and vector magnetic potential in the calculation area of the studied generator is shown in Fig. 2.

Based on the built mathematical model, the voltages and currents in the windings of the studied generator are calculated at different loads. Subsequently, the distribution curves of linear and phase voltages are used to design filters.

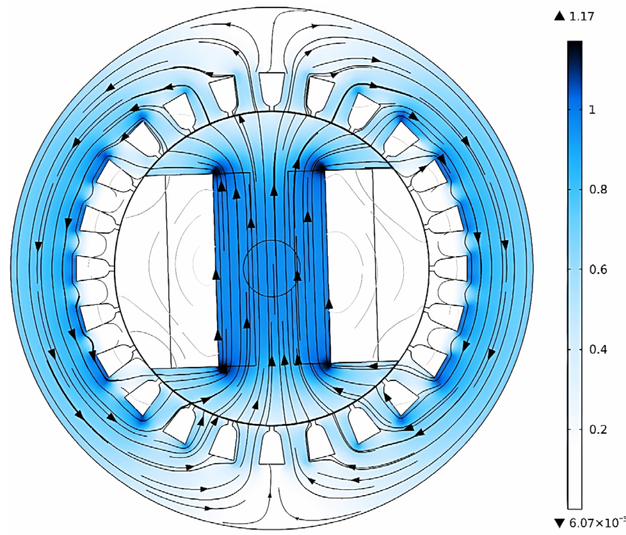


Fig. 2. Electromagnetic field distribution of the studied generator

5. 2. Studying the harmonic spectrum of voltage of a magnetoelectric generator for different load levels

In order to determine the harmonic composition of the voltage induced by the generator at different levels of its load, studies were conducted for the modes of idle operation, 30% (1.5 kVA), 50% (2.5 kVA), 75% (3.8 kVA), and 100% (5.0 kVA) generator load at a load power factor equal to 1. The voltage waveforms at the generator terminals for the modes of idle operation, 30%, 50%, and 75% generator load are shown in Fig. 3.

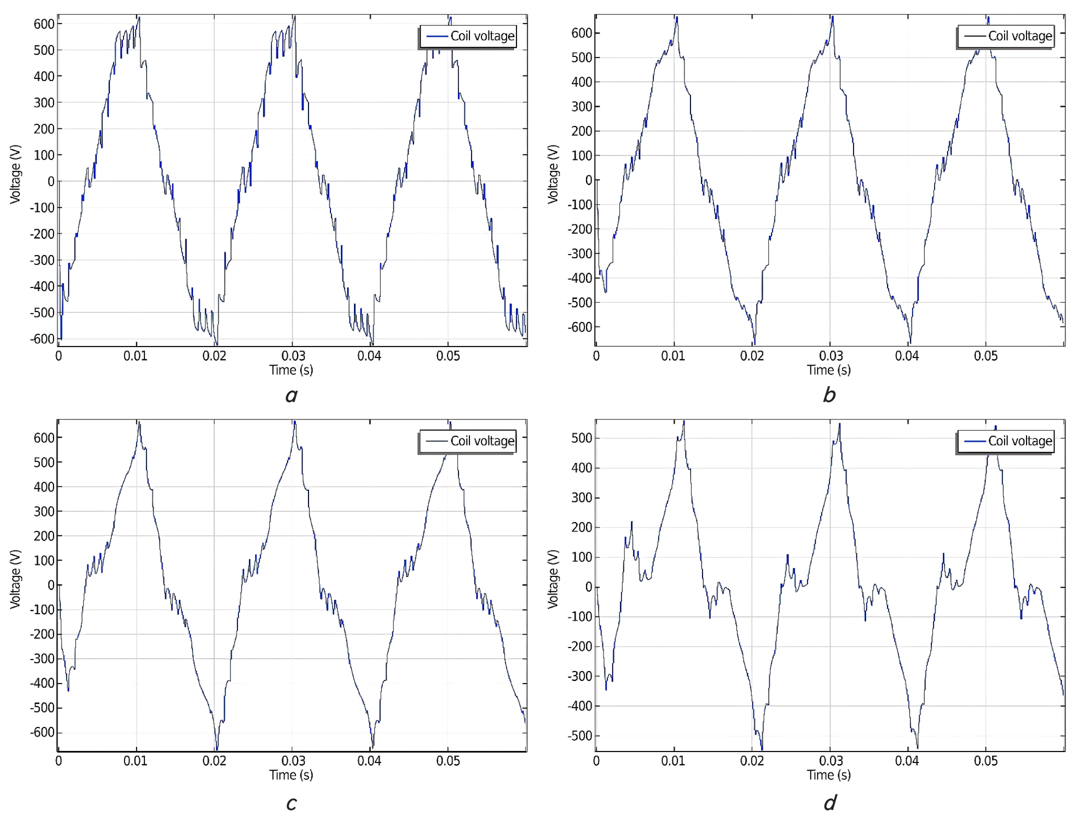


Fig. 3. Oscillograms of voltage at the generator terminals for loading: *a* – 0%; *b* – 30%; *c* – 50%; *d* – 75%

The results of determining the harmonic composition of the voltage generated by the generator at different levels of its load are given in Table 1.

Table 1

Harmonic voltage at the generator terminals

Indicator		Voltage of the h-th harmonic, % from the voltage of the principal harmonic							
		3	5	7	9	11	13	15	17
Generator load, %	0	8.9	5.2	0.8	3.2	1.3	0.8	2.0	1.0
	30	12.7	4.8	1.4	2.7	1.4	0.4	1.3	0.9
	50	21.0	5.8	1.4	2.7	1.8	0.6	1.0	1.0
	75	32.2	8.1	1.7	3.1	2.0	0.9	0.8	1.0
	100	44.2	11.3	2.9	4.1	2.3	1.3	0.8	1.0
Permissible harmonic voltage DSTU EN 50160:2023, %		5,0	6.0	5.0	1.5	3.5	3.0	1.0	2.0

Indicator		Voltage of the h-th harmonic, % from the voltage of the principal harmonic						THD_U, %
		19	21	23	25	27	29	
Generator load, %	0	1.1	1.7	5.0	2.8	2.6	0.9	12.9
	30	0.3	1.1	2.3	1.4	2.9	1.0	14.7
	50	0.6	2.0	2.0	1.1	3.3	1.0	22.6
	75	1.0	3.0	2.1	1.2	3.6	0.9	33.9
	100	1.2	3.8	2.5	1.4	4.0	1.0	46.5
Permissible harmonic voltage DSTU EN 50160:2023, %		1,5	0.75	1.5	1.5	n/a	n/a	8.0

The state standard DSTU EN 50160:2023, which defines the quality of electric energy in general-purpose electrical networks, regulates the need to measure the voltage of the first 40 harmonics to determine the total harmonic distortion factor (THD_U). At the same time, Table 1 gives measurement results only for harmonics whose relative voltage in the entire generator load range was not less than 0.5% of the principal harmonic voltage. The influence of harmonics with a lower relative voltage on the THD_U value within the framework of the study was recognized as insignificant.

It is obvious that determining THD_U and the need to filter a certain harmonic at a certain generator load level requires information about the harmonic voltages at this load level. Our studies have shown that the values of the harmonic voltage at generator load levels that differ from 0%, 30%, 50%, 75%, and 100% can be obtained with a sufficient degree of accuracy based on the quadratic approximation of the harmonic voltage values given in Table 1. The approximation was carried out by minimizing the quadratic error function taking into account the restriction on the values of the coefficients of the quadratic polynomial:

$$U_h\left(S_e\right)=\sum_{i=0}^{N-1}\left[U_{hi}-U_{hr}\cdot\sum_{j=0}^{N-1}a_j\cdot S_{ei}^{j}\right]^2, \tag{4}$$

$$R\left(a\right)=\sum_{j=0}^{N-1}a_j=1, \tag{5}$$

where $U_{h\,i}$, $U_{h\,r}$ – relative value of voltage of h-th harmonic, %, for i-th value of load factor S_e, a. u., and rated load of the generator, respectively; a_j – coefficients of the polynomial, which describes the change in voltage of a certain harmonic with changes in the load level at the corresponding powers of S_e; N – order of the approximating polynomial.

Minimization of the function of the total squared error of approximation $U_h(S_e)$ with a non-strict restriction (5) on the values of the coefficients of the quadratic polynomial $R(a)$ for each harmonic, indicated in Table 1, was carried out using the method of uncertain Lagrange multipliers. According to the results, the values of the coefficients of the approximating polynomials for the voltage of the corresponding harmonics and the values of the function of the total squared error of approximation $U_h(S_e)$ were obtained, given in Table 2.

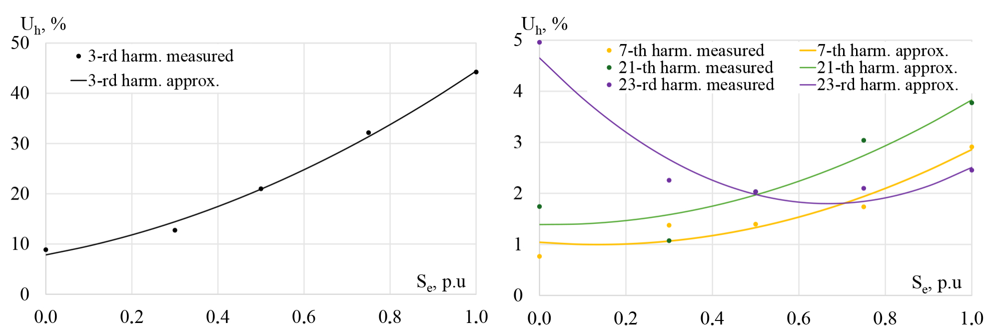
Plots of the dependence of harmonic voltage on generator load, constructed on the basis of quadratic approximating polynomials, and the values of the harmonic voltage obtained on the basis of simulation modeling, for which the values of the function of the total squared error of approximation $U_h(S_e)$ are the largest, are shown in Fig. 4.

Table 2

Determining the coefficients of a quadratic approximating polynomial

Polynomial coefficient	Value of the coefficient of the polynomial of the h-th harmonic						
	3	5	7	9	11	13	15
a_0	0.177	0.450	0.358	0.788	0.545	0.555	2.498
a_1	0.356	−0.286	−0.229	−0.752	0.357	−0.875	−3.501
a_2	0.471	0.839	0.853	0.962	0.101	1.332	2.003
$U_h(S_e)$, %^{2}	4.90	0.06	0.23	0.00	0.02	0.03	0.00

Polynomial coefficient	Value of the coefficient of the polynomial of the h-th harmonic						
	17	19	21	23	25	27	29
a_0	0.536	0.744	0.368	1.895	1.915	0.645	0.950
a_1	1.318	−1.200	−0.033	−3.483	−3.442	0.308	−0.034
a_2	−0.862	1.492	0.680	2.609	2.547	0.048	0.071
$U_h(S_e)$, %^{2}	0.01	0.18	0.40	0.30	0.06	0.01	0.01



a *b*

Fig. 4. Harmonic voltage values according to the results of simulation modeling and quadratic approximation depending on the generator load level: *a* — for the 3rd harmonic; *b* — for the 7th, 21st, and 23rd harmonics

A comparison of THD values with the data from calculated experiments is given in Table 3.

Table 3

THD values comparison

Harmonic voltage data	THD value, %, when loading the generator, %				
	0	30	50	75	100
Computational experiment	12.9	14.7	22.6	33.9	46.5
By quadratic approximation	12.0	16.4	22.5	33.1	46.6
Absolute error, %	–0.9	1.7	–0.1	–0.8	0.1
Modulus of relative error, %	7.0	11.6	0.4	2.4	0.2

The data given in Table 3 are calculated based on the values of the harmonic voltages by quadratic approximation polynomials.

5. 3. Determining the parameters of harmonic filters for normalizing the parameters of the generated voltage by non-sinusoidality indicators

The calculation of parameters for passive resonant filters was carried out for the isolated operation mode of the generator based on the values of the harmonic currents at the rated load of the generator when producing active power of 5 kW. The methodology for calculating the parameters of the passive resonant single-frequency filter of the *h*-th harmonic [16] involves determining its capacitance and inductance [17]:

$$C_h = \frac{k_s \cdot I_h}{2\pi \cdot f \cdot h \cdot U},$$

$$L_h = \frac{U}{2\pi \cdot f \cdot h \cdot k_s \cdot I_h}, \quad (8)$$

where U – phase voltage of the electrical network at the point of connection of the filter, V; f – rated frequency of the fundamental harmonic of the power supply voltage, Hz; k_s – safety factor; C_h – filter capacitance, F; L_h – filter inductance, Gn.

According to (8) for the value $k_s = 1.3$, which takes into account the possibility of short-term operation of the generator with overload, the parameters of the resonant filters of the 3rd, 5th, 9th, 21st, and 23rd harmonics were determined, the voltages of which, according to Table 1 and Table 3, exceed the values regulated by the DSTU EN 50160:2023 standard (filter connection scheme – "star"). The characteristics of such filters are given in Table 4.

In order to verify the impossibility of resonance phenomena during the operation of the generator with connected filters under conditions of load lower than rated, the operation of the generator with calculated filters was simulated. The results of the research are given in Table 5.

The simulation was performed for 50% load and generator idle modes.

Table 4

Higher harmonics filter parameters

Harmonic number	Capacity, μF	Inductance, mH	Power, kVAr
3	19.10	58.9	1.080
5	2.86	141.5	0.150
9	1.96	63.7	0.100
21	0.26	89.0	0.013
23	0.14	137.8	0.007

Table 5

Harmonic voltage spectrum with filter application

Indicator		*H*-th harmonic voltage, % of principal harmonic voltage							
		3	5	7	9	11	13	15	17
Generator load, %	0	0.0	0.0	0.8	0.0	1.3	0.8	2.0	1.0
	50	0.0	0.0	1.4	0.0	1.8	0.6	1.0	1.0
	100	0.0	0.0	2.9	0.0	2.3	1.3	0.8	2.0
Permissible harmonic voltage DSTU EN 50160:2023, %		5.0	6.0	5.0	1.5	3.5	3.0	1.0	2.0

Indicator		*H*-th harmonic voltage, % of principal harmonic voltage						THD_U, %
		19	21	23	25	27	29	
Generator load, %	0	1.1	0.0	0.0	2.8	2.6	0.9	4.9
	50	0.6	0.0	0.0	1.1	3.3	1.0	4.6
	100	1.2	0.0	0.0	1.4	4.0	1.0	6.3
Permissible harmonic voltage DSTU EN 50160:2023, %		1.5	0.75	1.5	1.5	n/a	n/a	8.0

6. Discussion of results based on studying the non-sinusoidality of voltage of the magnetoelectric generator under an autonomous mode of operation

Our study of the harmonic spectrum of voltage for different levels of generator load was carried out under the condition that the load power factor is equal to 1, since under a purely active load, the voltage amplitudes of the harmonics induced by the generator will be greater than under an active-inductive load. The reasons are as follows:

– the absence of a phase shift between the current and voltage does not lead to smoothing of the voltage curve and a decrease in the amplitude of the harmonics, which is observed, for example, under an active-inductive load;

– the absence of a damping (filtering) effect of the load inductance, which counteracts current changes, which leads to smoothing of current ripples, which are the source of voltage harmonics;

– the absence of the influence of the load inductance on the magnetic field of the generator, which can lead to partial compensation of the harmonics arising from the nonlinearity of its magnetic system.

Analysis of data in Table 1 reveals the following:

– the use of the studied generator in the entire operating power range for direct power supply of consumers under an isolated operation mode is impossible due to violation of the requirements of the DSTU EN 50160:2023 standard for the permissible THD_U value and the permissible voltage value of individual harmonics;

– the overestimated THD_U value is mainly caused by harmonics with numbers multiple of 3, in order to suppress which, it is advisable to change the connection scheme of the windings of the studied generator from "star" to "delta", which, however, will lead to a change in its rated voltage and cannot always be implemented;

– with the exception of harmonics with numbers multiple of 3, violation of the requirements of DSTU EN 50160:2023 for the permissible voltage of harmonics is observed for the 5th and 23rd harmonics, which requires the use of filters for these harmonics.

The increase in the relative level of harmonic voltage components with increasing generator load is due to the nonlinear properties of its magnetic system. With increasing armature current, the influence of the magnetic field of the armature winding increases, which leads to saturation of the magnetic core. This saturation causes an increase in the nonlinearity of the magnetic characteristic, which results in an increase in the content of harmonics in the generator output voltage.

Analysis of data in Table 2 and Fig. 4 allows us to conclude that the quadratic approximation of the harmonic voltage dependence data on the generator load level for harmonics from the 5^{th} and higher is sufficiently accurate since for them, the value of the total square error for the quadratic approximation does not exceed $0.4\%^2$ with the largest value of the linear deviation modulus of 0.5%. At the same time, for the 3rd harmonic, the value of the total square error for the quadratic approximation is $4.9\%^2$ with the largest value of the linear deviation modulus of 1.7%, which in certain cases can significantly affect the adequacy of the calculated THD_U value of the generator, which is confirmed by the data in Table 3 for low generator load levels, where the value of the relative error in determining THD_U can be up to 11.6%. For this reason, approximation of data for the 3rd harmonic under low generator load conditions may require the use of higher-order polynomials.

From the data in Table 1, it can be seen that ensuring the use of the generator in the entire operating power range for supplying consumers under an isolated operation mode requires the use of active or a group of passive filters. The rated power of active harmonic filters, as a rule, significantly exceeds the rated power of the generator under study, and their high cost makes the use of such filters to reduce THD_U and voltage harmonics induced by the generator economically inexpedient. Therefore, within the framework of our study, in order to ensure that the network powered by the generator meets the requirements of the DSTU EN 50160:2023 standard for harmonic voltage and THDU value, the use of only passive resonant filters was considered.

The total reactive power of the resonant filters of the 3^{rd}, 5^{th}, 9^{th}, 21^{st}, and 23^{rd} harmonics is 1.35 kVA or 27% of the rated power of the generator. Therefore, their impact on the voltage regime on the generator buses and the generator load level at full power is very significant and, under the condition of the isolated operation mode of the generator, requires mandatory consideration.

According to the simulation results, it was established that under the condition of isolated operation of the studied generator with a purely active load of 5 kW, the connection of the filters of the 3^{rd}, 5^{th}, 9^{th}, 21^{st}, and 23^{rd} harmonics reduces the THD_U value to 6.3%, which meets the requirements of the DSTU EN 50160:2023 standard.

Analysis of the data in Table 4 reveals that for the considered operating modes, the THD_U indicator meets the requirements of the standard. At the same time, under low generator load modes, in order to meet the requirements of the DSTU EN 50160:2023 standard, it is necessary to additionally use 15^{th} and 25^{th} harmonic filters.

Compared with similar studies [1, 16], our results take into account the peculiarities of operation of magnetoelectric generators under an isolated operation mode on the distribution network, which makes it possible to take into account their impact on voltage quality.

According to the results of our study, the parameters of active filters of higher harmonics, which are due to the operation of an autonomous generator, were obtained. This makes it possible to reduce losses and increase the reliability of consumers when the magnetoelectric generator operates as a backup power source under an isolated operation mode.

The limitations of this study are due to the dependence of efficiency of active filters on the characteristics of a particular magnetoelectric generator and the type of load, which may require their adaptation for other types of generators or networks. In addition, the results of our study are based on certain assumptions regarding the stability of network parameters, which should be taken into account both in practical implementation and in further theoretical studies.

The disadvantages of the study are the limited universality of the proposed methods, which require additional adjustment for different types of magnetoelectric generators and specific operating conditions of local distribution power networks.

This study in the future may consider the prospect of devising universal methods for reducing higher harmonics, which automatically adapt to different types of generators and variable operating conditions of power networks.

7. Conclusions

1. Simulation of the operation of a generator with excitation from permanent magnets showed that the values of the total harmonic distortion factor and the voltage of individual harmonics do not comply with the requirements of the current standard. The violation occurs with respect to the quality of voltage in general-purpose electrical networks in the entire load range.

2. Our studies of the generator simulation model have made it possible to establish that the use of quadratic polynomials to approximate the dependences of the harmonic voltage on generator load level provides sufficient accuracy with a total squared error of up to $0.4\%^2$ and the largest value of the linear deviation modulus of up to 0.5% for harmonics from the 5th and above. At the same time, for the 3rd harmonic at low generator load levels, the corresponding indicators are $4.9\%^2$ with the largest value of the linear deviation modulus of 1.7%, which requires the use of approximating polynomials of higher orders.

3. According to the simulation results, it was found that under the condition of isolated operation of the studied generator with a purely active load of 5 kW, connecting filters of the 3^{rd}, 5^{th}, 9^{th}, 21^{st}, and 23^{rd} harmonics with a total reactive power of 1.35 kVAr reduces the THD_U value to 6.3% (which meets the requirements of the DSTU EN 50160:2023 standard), but requires taking into account their impact on the voltage regime on generator buses and the generator load level at full power under an isolated operation mode.

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

The data will be provided upon reasonable request.

Use of artificial intelligence

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

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