UDC 621.3.013:669.165
DOI: 10.15587/1729-4061.2025.348152

DEVISING A METHOD FOR LARGE-SCALE MODELING OF NON-STATIONARY ELECTROMAGNETIC PROCESSES IN POWER TRANSFORMER EQUIPMENT UNDER SHARPLY CHANGING LOADS

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This study considers the sharply changing loads on powerful transformers and the non-stationary electromagnetic processes they excite, consisting of a set of parameters of different physical nature. The task addressed relates to the fact that powerful transformers used in modern electrical technologies fail almost twice as often as those operating in public networks. This encourages the design of special-purpose transformer equipment and requires establishing causal factors of accidents, their development, and new research methods.

This work reports a method for large-scale modeling of non-stationary electromagnetic processes in transformers.

The proposed criteria for the physical similarity of electromagnetic processes in the model and the original have been confirmed experimentally on a physical model and a real special-purpose transformer. A distinctive feature of the results is a method devised for the formation of sharply changing currents, which are characteristic of the electro-technological process in arc steelmaking furnaces.

The results of investigating additional losses and thermal overload of the transformer coincide, with reasonable accuracy for practice, with the experimental ones with an error not exceeding 5.7%. This makes it possible to compile project documentation for designing new types of special-purpose transformers. This is achieved by improving engineering methods for calculating additional losses and thermal overloads of inactive parts of transformer structures. In practice, the results allow for the correction of acceptance tests both at the design stages and under industrial conditions

Keywords: sharply changing loads, non-stationary electromagnetic processes, cumulative effect, magnetostriction, non-sinusoidal current, equivalence method, streamers, ferroresonance processes, skin effect

Received 30.09.2025
Received in revised form 10.12.2025
Accepted 17.12.2025
Published 31.12.2025

***How to Cite:** Zinovkin, V., Krysan, Y., Shylo, S. (2025). Devising a method for large-scale modeling of non-stationary electromagnetic processes in power transformer equipment under sharply changing loads. Eastern-European Journal of Enterprise Technologies, 6 (8 (138)), 6–23. https://doi.org/10.15587/1729-4061.2025.348152*

1. Introduction

In the power supply networks at arc steelmaking plants and other electrotechnological complexes with sharply changing loads, general-purpose transformers are used. Their electrical parameters are determined based on the power and voltage class. The failure rate of the latter in such networks is 50% higher compared to general-purpose networks. This encourages the development of new types of electrical equipment in accordance with the requirements of the standards IEC/EN60076, EN50160, IEC/EN60949, IEC/EN60287. Their rated load parameters are consistent with the corresponding voltage classes, mass and dimensions, levels of instantaneous overloads, depth of power regulation, as well as operating conditions, etc. When powering large arc steelmaking furnaces, rolling mill drives, lines and DC inserts, general-purpose electrical equipment is significantly overloaded. This is explained by the fact that in electrical technologies, currents and voltages change over time according to reliable laws, which are called rapidly changing loads in the literature [1]. This leads to a violation of the requirements of the EN50160 and [2] power quality standards. Therefore, the failure rate of powerful transformers in such networks is 50% higher than the failure rate of transformers operating in general-purpose networks.

When reconstructing transformer equipment after emergency failures, it is necessary to have appropriate methodologies and engineering methods for taking into account the impact of rapidly changing loads on its current technical condition in accordance with the characteristics of electrical technologies [3]. Numerous literary sources consider ways to solve individual causes or factors affecting individual parameters of electrical equipment. When trying to integrate them, to solve the impact of rapidly changing loads on the technical condition of powerful transformers, it is not possible to obtain even approximate reliable results regarding the parameters of non-stationary electromagnetic processes. This indicates the need to devise a methodology for simultaneous study of load parameters and electromagnetic processes occurring in the equipment. Therefore, it is a relevant task to carry out studies on modeling non-stationary electromagnetic processes in powerful electrical equipment under rapidly changing loads. Reliable results of such studies could contribute to establishing the causes and consequences of reducing the operating time of transformer equipment and developing new, more reliable standard designs.

2. Literature review and problem statement

At the current stage of development of the world scientific and technical community in the field of electrical engineering, there is a need for more efficient and economical use of electrical equipment when powering various technological devices. Issues of improving the quality of electrical energy in accordance with the requirements of the European standard EN50160 are becoming important. The characteristic features of the flicker effect, due to voltage fluctuations, are considered in work [1]. The connection of voltage fluctuations with other load parameters and the reasons for their formation are absent.

In [2], it is shown that higher harmonics in currents and voltages lead to overload of electrical equipment and methods of their compensation are proposed. Electromagnetic processes occurring in electrical equipment are not considered at all. They involve the development of special means of compensation and redistribution of individual power supply circuits of technological devices. The conditions of short-term overload of transformers in general-purpose power networks are considered in work [3], but the influence of sharply changing loads and other factors is not considered.

The separate issue of thermal overload during electromagnetic processes in power transformers under industrial operating conditions in general-purpose networks is addressed in [4]. There are no specific research methods here depending on the load terms, duration and specifics and characteristic features. Some specification of the influence of oscillations of electromagnetic processes in electrical equipment is considered in [5, 6]. At the same time, the issues of redistribution of the electromagnetic field of scattering relative to the excitation system and the influence of the magnetic system at standard equipment load parameters are considered. How the results were obtained and experimental confirmations are absent. Methodological approaches and theoretical ways of optimizing the power of general-purpose transformers in combination with the analysis of the current state are considered in [7]. When analyzing this work, no answer was found to the question of the influence of the redistribution of active and reactive power depending on the nature of the load, which is quite important for solving the task of our work. There are also no proposals for compensation of reactive power and higher harmonics.

For the first time, a methodological approach to multiparameter analysis of the current technical condition of transformers is proposed [8]; some results of experimental research are reported. This paper proposes a mathematical model of the mutual relationships between the electromagnetic parameters of transformers and provides the defining levels of experimental research. Adjustment of transformer power under load is proposed a theoretical model of taking into account the nonlinearity of the magnetic permeability of the electrical steel of the magnetic core [9]. The operating conditions of transformers under symmetrical load and at rated modes are considered.

The influence of the set of parameters of electromagnetic processes during load fluctuations in transformer equipment showed [10] that considering the influence of individual parameters on the equipment, obtained at different time intervals, will lead to an erroneous final result. How can such cases be prevented and methods for their experimental research are absent. Of particular importance are the technical means of developing an energy-saving power supply system for arc steelmaking furnaces [11] and planning the load distribution between transformers during parallel operation and other conditions [12]. The influence of the characteristic features of the electrotechnological modes of arc steelmaking furnaces (suddenly changing loads) on electrical equipment is not considered. The "evolutionary method" of assessing the conditions of transformer use is proposed in [13]. The operating conditions of transformers at rated load parameters and corresponding voltage classes are mainly considered. It is noted that when the rated load parameters are exceeded, non-stationary electromagnetic processes are formed in transformer equipment, which lead to a reduction in reliability terms. It is advisable to pay special attention to the overexcitation of the magnetic system due to the displacement of the main magnetic flux. The analysis of the nonlinear properties of reactive power depending on voltage fluctuations and deviations relative to the rated one is considered in [14]. It is shown that such cases are quite unfavorable and require compliance with optimal operating conditions. To ensure the normalized operating times of electrical equipment depending on various operating conditions, it is advisable to monitor the current technical condition of the equipment. For this purpose, it is advisable to use the synthesis and analysis of electromagnetic control of electrical equipment under three-phase asymmetric load, which is proposed in [15]. The mathematical model of the multiparameter optimization functional in combination with the determining criteria for the impact on transformers allows for a more thorough study of electromagnetic processes under variable loads [16]. It is advisable to adapt such a methodological approach to solving the problem of real research.

In the above cases, it is advisable to use the methodological approach of building a physical model of a special-purpose transformer [17]. This will allow for experimental studies on the set of parameters of non-stationary electromagnetic processes on a reduced copy of a special-purpose transformer. As noted in [18], it is possible to achieve special efficiency by using this method when improving the design of network transformers for electrometallurgical production taking into account asymmetric loads.

A comparative analysis of electromagnetic processes excited by non-sinusoidality and load asymmetry revealed that they lead to the gradual accumulation of cumulative effects and deterioration of the technical condition of electrical equipment [19].

Methods for simulating the load of electrical equipment in complex distribution systems of power supply of industrial enterprises [20, 21] deserve special attention. These results should be used in the absence of a reserve and in force majeure circumstances. At the same time, the lack of experimental confirmation of the practical use of the approach does not allow it to be used without appropriate analysis and research. In this case, it is advisable to use the method of experimental research of nonlinear properties of additional losses [22].

Using the proposed methodological approach, it becomes possible to coordinate and adjust individual methods of experimental research of individual parameters in terms of modeling their set on a physical model. Bringing these results to a real electrical object, which is subject to development or reconstruction, requires significant refinement.

It should be noted that the given research methods do not contain specific proposals for the formation of initial and boundary conditions in the development of mathematical models of non-stationary electromagnetic processes even with sinusoidal currents and voltages. They consider individual issues and provisions for the study of electrical equipment in load modes, operating conditions, power supply of various technical objects, reliability terms and use of experimental equipment. At the same time, it is not noted under which modes the transformer worked – no-load, short circuit, load.

Taking into account the influence of a single one of the many adverse factors will not lead to an improvement in the technical characteristics of the equipment. Therefore, solving one of the technical issues does not make it possible to improve the technical condition of the equipment as a whole.

The synthesis and analysis of existing methods for the study of powerful transformer equipment showed the following:

To solve the scientific and technical problem posed, to improve the technical condition of transformer equipment for powering technological devices, it is necessary to use a comprehensive approach to the formation of sharply changing loads and the adaptation of individual existing methods for the study of electrical equipment.

Thus, it is shown that the existing methods and research results consider the influence of individual single load parameters on the corresponding indicator in transformer equipment. Using these different research methods to solve the task – studying the influence of sharply changing loads on non-stationary electromagnetic processes with a set of parameters of different physical nature, was not crowned with success. Therefore, to meet the requirements of practice, it is necessary to form new methodological approaches and devise new methods of theoretical and experimental research. This indicates the feasibility of devising a method for large-scale modeling of non-stationary electromagnetic processes in transformer equipment.

3. The aim and objectives of the study

The purpose of our research is to devise a method for large-scale modeling of non-stationary electromagnetic processes in power transformers under rapidly changing loads, which lead to a reduction in the terms of reliable operation and emergency failures. This will make it possible to develop new typical designs of special-purpose power transformers based on the devised technical requirements and technical operating conditions and reconstructing existing general-purpose ones with significantly better reliability indicators.

To achieve this goal, the following tasks were set:

– to construct a generalized scheme for the formation of rapidly changing loads;

– to establish the causal factors and stages of their formation and influence on the operation of power transformers;

– to conduct modeling of non-stationary electromagnetic processes in special-purpose transformers;

– to perform experimental studies of non-stationary electromagnetic processes on physical models and a special-purpose transformer.

4. The study materials and methods

The object of our study is the sharply changing loads of powerful transformers and the non-stationary electromagnetic processes excited by them, which consist of a set of parameters of different physical nature. Such loads are formed in arc steelmaking furnaces and vary in time according to a reliable statistical law.

The principal hypothesis assumes that non-stationary electromagnetic processes can be reliably reproduced on a reduced copy if the following conditions are met:

– the model is a reduced copy of a real special-purpose transformer with the preservation of characteristic design features;

– active and inactive structural elements are made of the same structural steels and insulating materials;

– electromagnetic characteristics (electrical conductivity and magnetic permeability) of active nodes and inactive elements in the model and the original remain the same;

– experimental results obtained on the model are reduced to the original according to the determining similarity criterion.

The following assumptions and simplifications were adopted in the research process. The properties of the magnetic system and inactive structural parts remain the same since the working conditions correspond to the rated load parameters. The effect of overexcitation of the magnetic system on the displacement of the main magnetic flux was not taken into account. The electromagnetic field scattering diagrams in the space of the model and the original and on inactive elements remained similar. The integral indicator of the influence of non-stationary electromagnetic processes on the technical condition of the equipment are total and local additional losses.

The choice of the large-scale modeling method is due to the fact that powerful electrical equipment is a complex structural system with nonlinear relationships between parameters. Building a complete mathematical model that would take into account all these aspects is an extremely difficult task and often does not provide sufficient accuracy. Large-scale modeling on a reduced copy allows one to study a set of parameters of different physical nature (electromagnetic, thermal, electrodynamic) simultaneously, reproducing the real dynamics of processes, which is impossible to do when studying individual factors in isolation.

During experimental studies, special measuring devices with an extended frequency range were used, which were constantly verified in comparison with the exemplary ones.

When performing the work, the following research methods were applied: analysis and synthesis of complex systems, experiment and processing of the results, mathematical and large-scale modeling, mathematical statistics, electrodynamics of complex environments, random processes.

When constructing a method for large-scale modeling of non-stationary electromagnetic processes, a synthesis and analysis of existing methods for experimental research of individual parameters was used. During experimental research, the corresponding operating modes of the model and the real object were taken into account in the elements of the equipment design, which have the following features.

Under the non-working mode (idle operation), the following are studied: electromagnetic processes in the magnetic system; redistribution of the main magnetic flux along the rods; re-excitation and formation of balancing fluxes; losses in the first and subsequent packages of electrical steel; formation of local breakdowns between individual sheets of electrical steel and balancing currents; magnetostrictive processes that characterize the overall noise level and in the octave frequency spectrum and characterize the technical condition of the magnetic system.

Under short-circuit modes, the following are studied: distribution of the electromagnetic field of scattering in the cavity of the transformer, excited by the winding system; additional losses in inactive and active structural parts excited by scattering fields; electrodynamic processes in the electromagnetic field excitation system, leading to loss of electrodynamic stability of the equipment; thermal overloads of inactive structural parts formed by local losses; mutual influence of the current technical condition of active and inactive structural elements due to deterioration of dielectric and mechanical properties; conditions of accelerated aging of insulation in combination with the formation of electrical streamers, which contribute to breakdowns and subsequent emergency equipment failures.

Under load modes, all the processes listed above take place. At the same time, electrotechnological modes have a sharply changing nature, which changes in time according to a probable law.

When conducting research and interpreting the results of experiments, the requirements and provisions of international standards regulating the parameters and operating modes of electrical equipment were taken into account. In particular, the following standards were used: IEC/EN 60076 – for assessing the characteristics of power transformers, including thermal modes, losses, electrodynamic resistance and behavior under short circuit conditions; EN 50160 – for analyzing the quality of electricity supplied to arc steelmaking furnaces, taking into account voltage fluctuations, harmonics and asymmetry; IEC/EN 60949 – for modeling short-circuit currents and determining the boundary conditions of electrodynamic loading; IEC/EN 60287 – for calculating permissible currents and thermal modes of cable lines supplying transformers and furnaces. The use of these standards made it possible to ensure compliance of research methods with international requirements, as well as to increase the accuracy of modeling and the reliability of experimental results.

5. Results of investigating the formation of rapidly changing loads and their impact on non-transformer equipment

5. 1. Construction of a generalized scheme for the formation of rapidly changing loads

A scheme for combining electrical and electrotechnological equipment is proposed, which allows us to study the impact of rapidly changing loads on non-stationary electromagnetic processes (it is shown in Fig. 1).

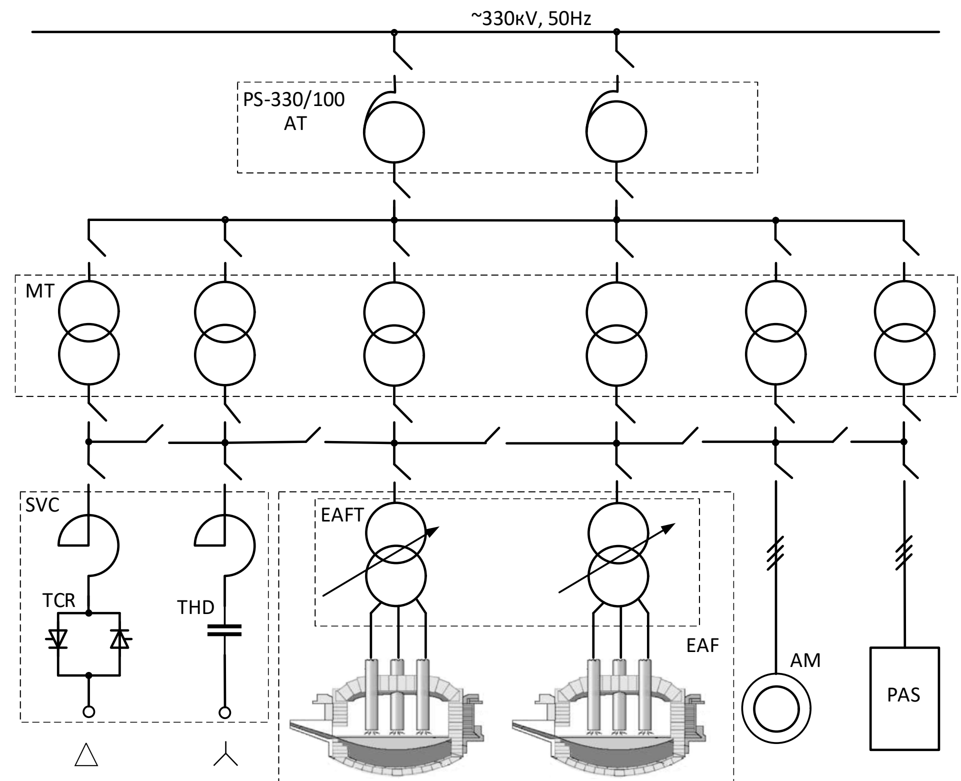

Fig. 1. Single-line power supply circuit DSP-100-N3A. SVC — thyristor reactive power compensator. PS-330/100 — network step-down substation; TCR — thyristor reactive power compensator; THD — filters of higher harmonics compensating links; EAF — electric steelmaking plant; AT — autotransformer; MT — network transformer; EAFT — electric furnace transformer; AM — electromechanical device; PAS — equipment for own needs

The obtained specific indicator of electric energy use in technological devices based on chipboard 50–150 is given in Table 1. It demonstrates that the voltage regulation limits are implemented within quite wide limits at rather high electric energy consumption per ton of produced products. This indicates the existence of ways to solve energy saving issues by reducing electric energy losses.

As an example, Fig. 2 shows the dependence of the power and productivity of an arc steelmaking furnace on the change in voltage. It demonstrates that the optimal productivity indicators V(t) and the electrical mode of the furnace change according to opposite nonlinear dependences and are achieved at different voltage values. The optimal operating conditions of the complex are achieved within 1.0–1.1 of the rated voltage. This indicates the expediency of searching for scientific and technical ways to find more effective operating conditions for electrical equipment, taking into account the influence of higher current and voltage harmonics, load asymmetry and a set of other characteristic features of sharply changing loads.

Table 1

Electrical parameters of the technological device as part of the corresponding arc steelmaking furnaces and electric furnace transformers

DSP type	Capacity, t.g.		Power of electric furnace transformer, mVA	Secondary voltage limits, V	Maks current, kA	Specific electricity consumption for scrap, kWh/t
	nom	max				
DSP-50	50	60	40	570–200	50	430
DSP-100	100	115	80	829–288	80	420
DSP-150	150	170	90	795–265	80	410

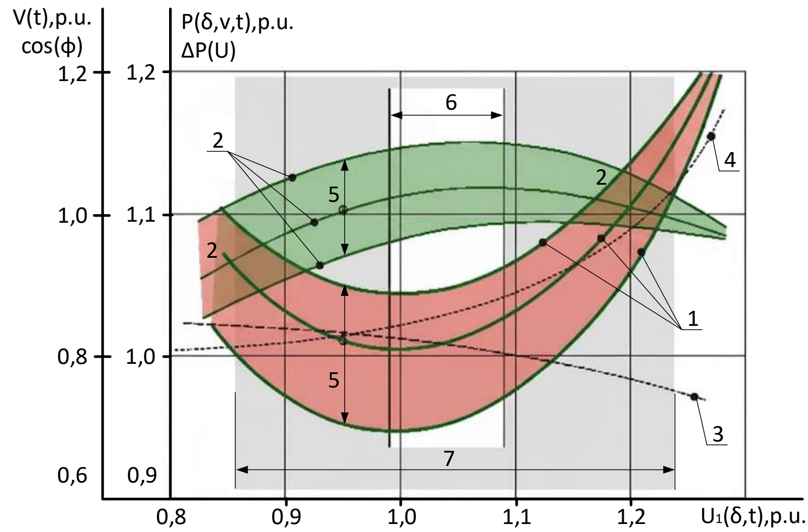

Fig. 2. Power (1) and productivity (2) of the technological device in the composition of the arc steelmaking furnace depending on voltage: 3 – cos(φ); 4 – ΔPE1(U1);
5 – boundaries of electrical and technological modes;
6 – optimal electrical technological mode; 7 – range of possible electrical modes

As an example, Fig. 3 shows a guideline power chart, and Fig. 4 shows an oscillogram of active and reactive power from a multi-channel loop oscilloscope, which was actually consumed by an arc steelmaking furnace of the DSP-150 type in different phases of the technological mode.

It demonstrates that at each stage of the technological process the power transmitted from the network to the furnace is significantly inconsistent with the directive task. This leads to a deterioration in the operating conditions of transformers and other electrical equipment. It is obvious that the choice of general-purpose electrical equipment is not appropriate for powering electrical technologies [17]. Under such modes, transformers are affected by numerous currents of technological and external short circuits, as well as surges and fluctuations of the load in total.

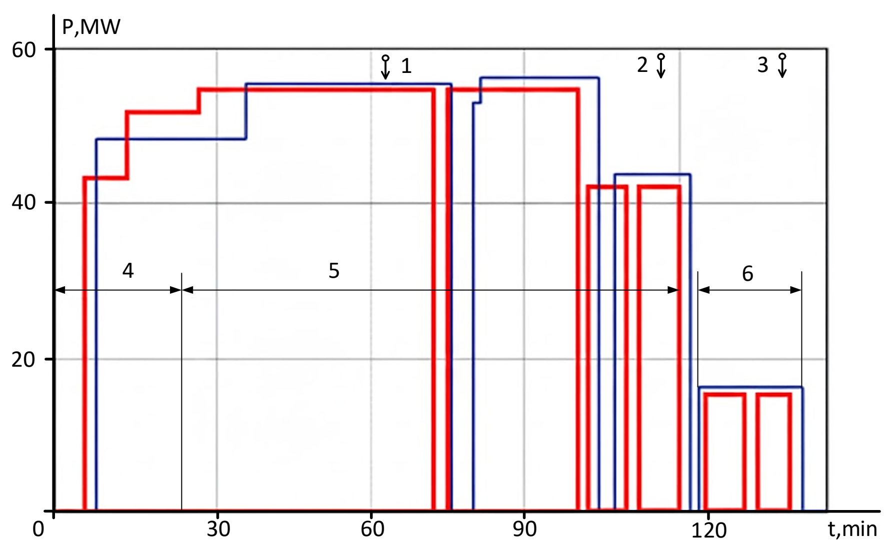

Fig. 3. Directive power chart of the electric arc steelmaking furnace DSP-150

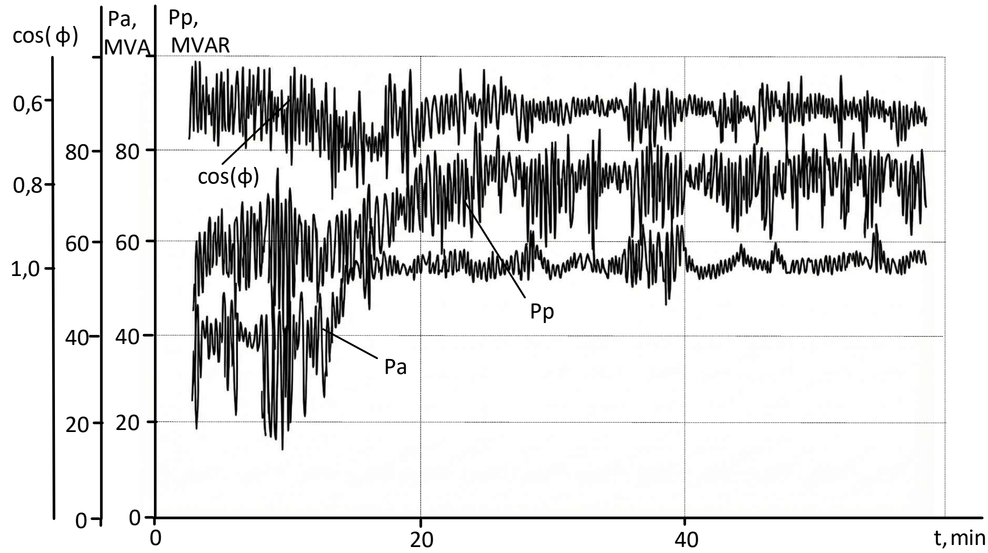

Fig. 4. Oscillogram of active (P_a), reactive (P_p), as well as power factor (cosφ) of the arc steelmaking furnace DSP-150 during the technological cycle

For example, according to the requirements from the IEC/EN60076 standard, testing of powerful transformers is allowed to be operated under the condition of no more than five external short circuits. In the power supply networks of arc steelmaking furnaces and rolling mill drives, powerful transformers operate with a significantly larger number of uncontrolled short circuits. This leads to irreversible phenomena that gradually accumulate and are the cause of emergency failures and reduced reliability periods.

5. 2. Causal factors and stages of their formation and influence on the operation of powerful transformers

The causal factors that lead to the deterioration of the reliable operation of transformer equipment under sharply changing loads have been established, and the sequence of their formation in combination with mutual relationships and cumulative effect. At the same time, analytical mutual relationships between individual parameters of different physical nature of non-stationary electromagnetic processes in transformer equipment make it possible to specify and increase the efficiency of the study in combination with the ability to correct their optimality. This was achieved on the basis of the performed analysis of the influence of a number of factors of different physical nature, leading to the deterioration of the current technical condition of electrical equipment.

The analytical relationships between individual parameters allowed us to establish the sequence of their formation and accumulation of adverse consequences.

Simultaneous study of all parameters of rapidly changing loads and non-stationary electromagnetic processes makes it possible to reproduce the real dynamics of their manifestation in the cavity of transformer equipment. Studies of individual indicators at different stages of the technological process of the furnace and time do not make it possible to establish real corresponding analytical dependences between external exciting and internal electromagnetic parameters

The constructed structural scheme of the influence of rapidly changing loads on electrical equipment and ways of solving the scientific and applied problem is shown in Fig. 5.

The multiplicity of currents exceeding the rated leads to switching processes, the formation of overvoltage circuits, cumulative and electrodynamic processes, and emergency protection testing. The multiplicity of currents of technological short circuits during the day is given in Table 2. It demonstrates that they are in the range from 2.0 to 2.3, and their number is in the range from 5 to 40 per day, which does not comply with the requirements of IEC/EN60076.

In three-phase transformers, such loads lead to the formation of balancing currents in the windings of different rods of the magnetic system. This worsens the electrodynamic stability of the excitation system of the electromagnetic field of the scattering and is the next reason for the reduction of the reliability of electrical equipment.

Table 2

Number of current overshoots under electrotechnological modes of DSP-100 in a network transformer

Current multiplicity of electrotechnological short-circuits	Number of overcurrents during the investigation		Number of current overshoots per day	
	pcs.	%	by IEC/EN60076, pcs.	Forecast, pcs.
to 0.5	8.0	7.6	–	4
0.5–1.0	45.0	43.0	–	23
1.0–1.1	7.0	6.6	to1000	4
1.1–1.3	9.0	8.5	to 10	5
1.3–2.0	29.0	28.0	to 3	15
2.0–2.3	7.0	6.7	unacceptable	4

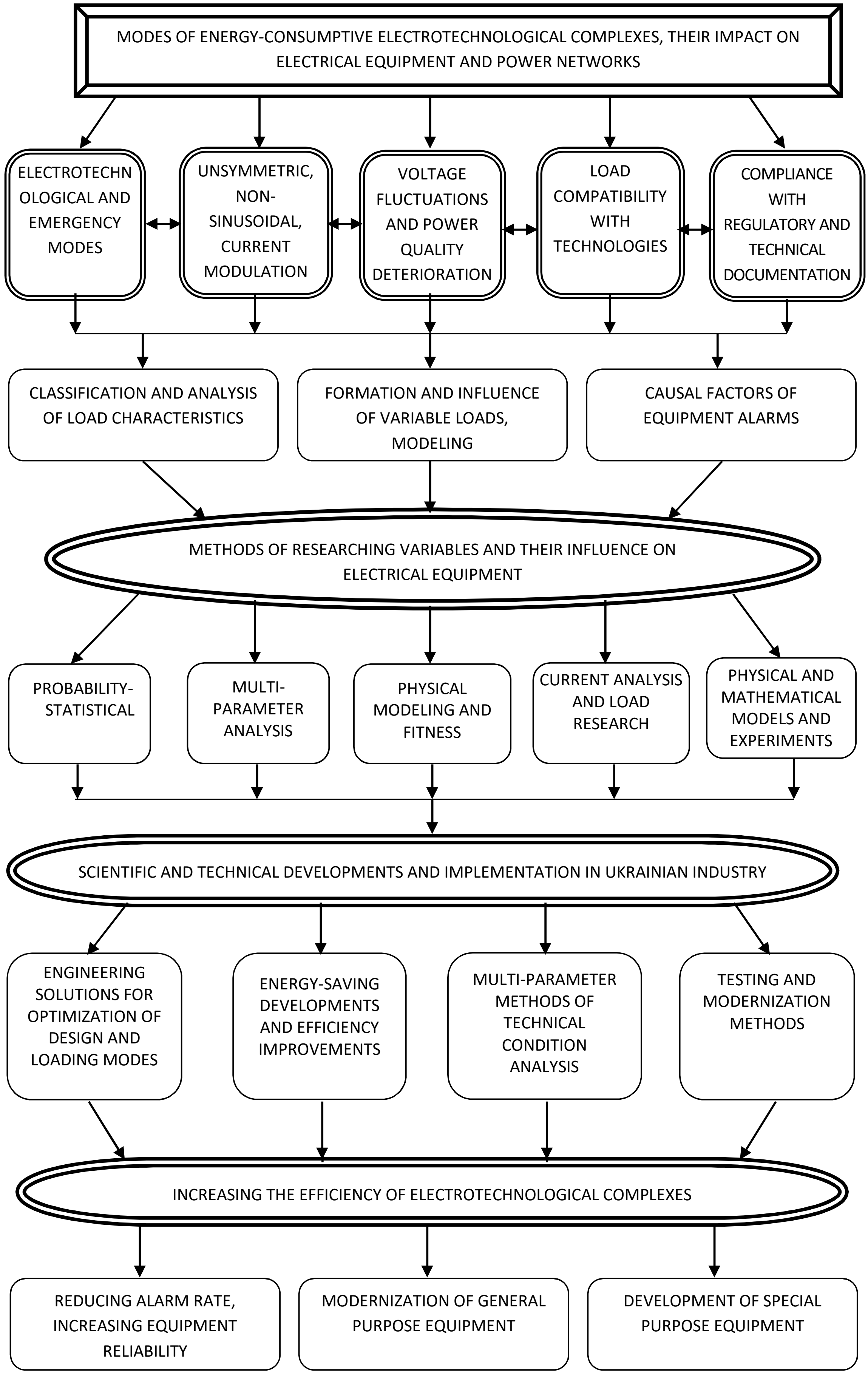

Fig. 5. Structural diagram of the influence of sharply changing loads on electrical equipment and ways to solve the scientific and applied problem

5. 3. Modeling of non-stationary electromagnetic processes in special-purpose transformers

The development of a method for large-scale modeling of non-stationary electromagnetic processes, consisting of a set of parameters of different physical nature and excited by sharply changing loads in the cavity of powerful special-purpose transformers, is based on the formation of sharply changing currents of different regulated non-sinusoidality in combination with mathematical models of the surface skin effect in ferromagnetic structural steels and equivalence.

Large-scale modeling makes it possible experimentally to reproduce the characteristic features of non-stationary electromagnetic processes in a physical model and bring them to the design of a special-purpose transformer. The influence of sharply changing loads was reproduced using the equivalence method.

Additional and local losses of electrical energy were used as an integral indicator of the influence of sharply changing loads on electromagnetic processes. This is explained by the fact that they reflect the mutual influence of both individual factors and all parameters of an electromagnetic nature, which are excited by electromagnetic fields of scattering in the cavity of the equipment relative to the windings. When the rated load of the equipment is exceeded, losses increase and lead to a deterioration of the dielectric properties of the insulation and its accelerated aging and charring. At the same time, a decrease in mechanical and compressive properties is formed in inactive parts of the structure, which contributes to the further development of negative and cumulative processes.

To solve current practical problems, it is recommended to evaluate electrotechnological parameters by voltage using the following expression

$$\Pi = k \times U^{p}, \quad (1)$$

where k, p are semi-empirical coefficients that take appropriate values for the relevant equipment, design, and electrical technologies. It is advisable to note that economic losses from electromagnetic processes range from 30 to 80% depending on the nature of damage to electrical equipment. Power supply of energy-intensive complexes in the composition of the DSP is carried out from networks of voltage classes 330, 220, and 154 kV.

The influence of the reactive power component on the increase in the voltage of the complex should be estimated from the following formula

$$\delta U = \left(\Delta Q \cdot S_k^{-1}\right) \cdot 100, \quad (2)$$

where ΔQ is the possible reactive power surge during the technological process; S_k is the short-circuit power at the measurement point; $\varepsilon = S_1 \cdot S_k^{-1}$ is the ratio of the power of one phase of the linear load to the total power.

Load asymmetry and higher harmonics of current and voltage of power supply systems of complexes with sharply variable loads, when exceeding the normalized indicators, should be evaluated in relation to the following conditions [17]

$$S_{nn} \cdot U_{nom}^{2} \leq 0{,}02, \quad (3)$$

where Snn is the power of the nonlinear load.

Load asymmetry leads to increased power losses, the formation of loop and balancing currents in the relevant circuits and equipment, overvoltage and the development of ferroresonance processes, and reduces the throughput of transformer equipment and networks. To ensure stable operation and efficient functioning of electrotechnological complexes, it is recommended to choose the largest possible short-circuit power of the network. Load asymmetry is accompanied by the formation of negative sequence currents [18, 19]. Such actions include parallel switching of network and electric furnace transformers.

Low-voltage windings with a large number of taps are used to regulate the voltage in combination with voltage regulation devices under load.

Voltage fluctuations in the network at the point of connection of low-voltage buses (for deep-input substations) are recommended to be estimated by active and reactive power from the following expression

$$\Delta U = \left(P \cdot R + X'\right) \cdot \left(10 U_{nom}^{2}\right)^{-1}, \quad (4)$$

where P and Q are the active and reactive components of power; R and X' are the active and reactive resistance of the network; U_{nom} is the rated voltage of the network

$$X' = U_{nom}^{2} \cdot S_k^{-1}. \quad (5)$$

The asymmetry of currents and voltages leads to the complication of the adjustment and reliable operation of protective devices under operating conditions, microprocessor devices of emergency signaling, etc. Despite the fact that the indicators of load asymmetry significantly affect the efficiency of the operation of electrical and electro-technological equipment, the solution to this scientific and technical problem in full requires further research. Long-term load asymmetry occurs during the technological process of the "melt" furnace and after the "basement" and significantly depends on the quality of "scraps" and other technical issues. Such processes occur in other electrical technologies, generating and converting devices. The analysis of electrical modes showed that the asymmetry of the load of individual phases in terms of current in electrical technologies can reach 50% relative to the rated value. Asymmetrical load leads to a deterioration in the quality of electrical energy and redistribution of the load of adjacent technological equipment and circuits of the enterprise's own needs. In turn, such modes lead to uneven phase resistances of short power supply circuits of arc steelmaking furnaces and the formation of ferroresonance processes in the higher harmonic compensation circuits.

As an example, Fig. 6 shows the oscillograms of the ferroresonance process in the circuits of compensation of higher harmonics of the electrotechnological complex, the scheme of which is depicted in Fig. 1. When the electric furnace transformer for powering the arc steelmaking furnace was turned on in one of the phases, the multiplicity of the switching current exceeded the permissible limits. This led to a change and redistribution of the inductive resistances of the electric furnace transformer – thyristor reactive power compensator and battery of capacitors circuit. This led to the formation and further development of the ferroresonance of the current in the second harmonic filter circuit and spread (at a frequency of 100 Hz) to the 35 kV buses of the factory distribution substation. The oscillograms show the formation of the resonant process, the increase in current, the operation of emergency protection devices, and the gradual attenuation of current and voltage.

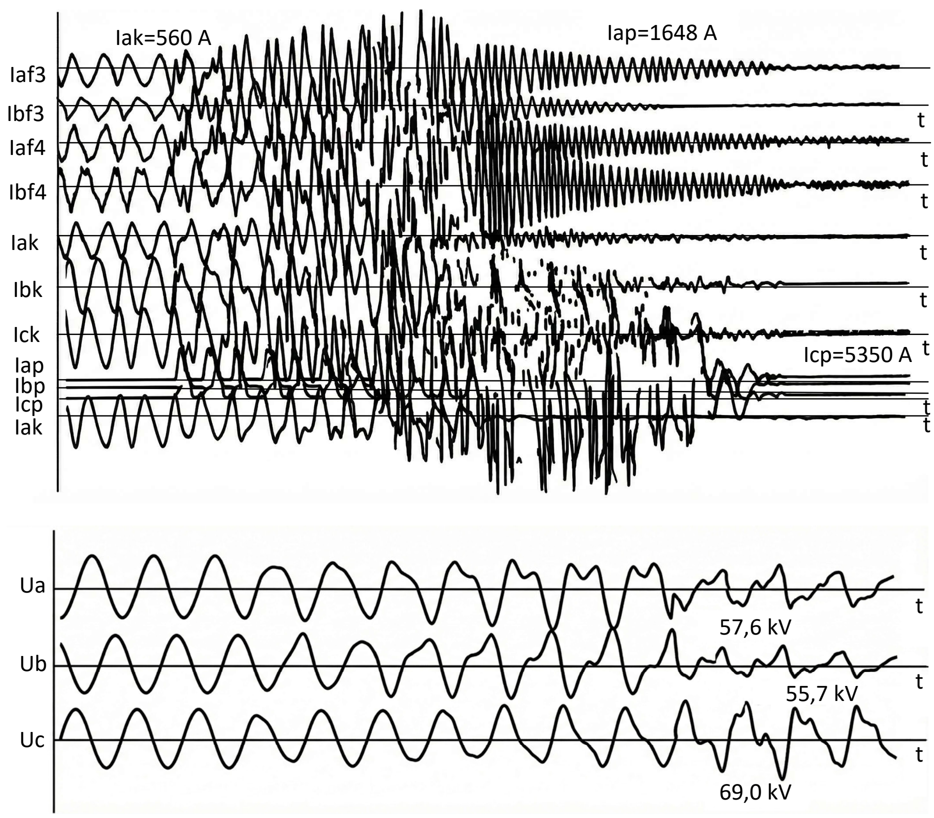

Fig. 6. Oscillograms of currents and voltages during the formation and further evolution of the ferroresonance process in the circuits of higher harmonic filters of the thyristor reactive power compensator: *a* — TCRP; *b* — voltage on the buses of network transformers

In Fig. 6, the following designations are adopted: TKRP – thyristor reactive power compensation; I – current; U – voltage; a–c – phases; f – filters of compensating circuits; p – electric furnace transformer.

This is explained by the fact that the asymmetry of the phases of the technological process leads to an increase in the voltage in the compensation circuits of higher harmonics, which leads to a redistribution of inductances and capacitances. Changes in the intrinsic inductances of reactors and capacitive batteries and the subsequent formation and development of the ferroresonance process. At the same time, such processes lead to the formation of subsequent undesirable electromagnetic phenomena and an emergency state of electrical equipment of the entire electrical complex. The complexity of studying this issue lies in the fact that such processes remain beyond the attention of operational and maintenance personnel, as well as the registration of emergency equipment. In the process of investigating such accidents at the enterprise, it is practically impossible to establish the primary cause that led to such consequences. The nonlinear properties of reactors significantly complicate modeling and numerous calculations of the parameters of compensating circuits and analysis of the impact of sharply changing electrotechnological modes.

When analyzing the impact of asymmetry on the operating modes of the equipment, it is advisable to use numerical calculations of reactive power without taking into account the probable nature of the load depending on the nonlinear properties. At the same time, in the mathematical model, at the first stage of the study, it is advisable to assume that the reactive power is symmetrical, varies in time according to a sinusoidal law and is determined by the full power according to the following expression

$$Q = \left(S^2 - P^2\right)^{0.5}. \quad (6)$$

In further steps, the total reactive power is found by adding up the individual phase reactance

$$Q = \sum_{i=1}^{a,b,c} Q_i. \quad (7)$$

It is worth noting that reactive power depends on the nature of the exchange of electromagnetic energy between the source, reactive network elements, load parameters and modes of adjacent equipment that have their own inductances and capacitances [20]. The solution to such a scientific and practical problem remains to be found.

With simultaneous voltage fluctuations in combination with non-sinusoidality, reactive power is advisable to use to characterize the influence of the exchange energy according to the following expression

$$Q = R_E \cdot Q_m, \quad (8)$$

where Qm – exchange reactive power; RE – parameter characterizing the resistance of the electrical network or a separate electrical circuit.

In this case, it is advisable to assume that the initial power corresponds to the directive (or rated), i.e., averaged over certain time intervals of the technological process. In practice, this corresponds to the modes of technological short circuits, stepped control angles of thyristor converters and other non-stationary and probable load modes of electrical equipment.

With short-term increases in power, it is possible to use the method of summing the influence of higher harmonics

$$Q = \sum_{\upsilon=1}^{n} Q_\upsilon,\ Q_\upsilon = I_\upsilon \cdot U_\upsilon \sin\phi_\upsilon, \tag{9}$$

where Q_υ – reactive power; I_υ and U_υ – current and voltage, respectively, of higher harmonics.

But it must be borne in mind that this will lead to an overestimation of the research results by 12–15% relative to the rated indicators.

Higher harmonics lead to overload of electrical equipment, an increase in general and local additional losses in inactive structural details, the development of electrodynamic processes in systems of excitation of the electromagnetic field of scattering, loss of electrodynamic stability, the formation and development of cumulative processes. And also higher harmonics lead to a redistribution of phase electrical parameters of electrical equipment and power supply networks, failures in the operation of automatic control and regulation systems of electrotechnological processes, protection of relay and control equipment [2, 21]. The solution of such problems in practice is carried out by neglecting non-stationary electromagnetic processes, sharply changing load, electrical losses, etc.

Higher harmonics in non-sinusoidal currents were studied using a spectrum and frequency characteristics analyzer as part of a specialized device for automated measurement, analysis, registration and visualization of a set of parameters of rapidly changing loads and storage of the information under study. Higher harmonics in rapidly changing currents of a network transformer in the power supply network of the complex as part of an arc steelmaking furnace in the electrotechnological mode “melt” are given in Table 3.

Table 3

Higher harmonics in the sharply changing currents of the network transformer when supplying an arc steelmaking furnace under the electrotechnological mode “melt”

Harmonic number	Multiplicity of higher harmonics in sharply changing currents, %				
	0.70–0.95	0.95–1.15	1.15–1.55	1.55–2.25	2.25–2.95
1	100	100	100	100	100
2	9.95	8.12	6.21	4.32	3.17
3	24.96	17.73	12.43	8.64	7.23
4	6.10	5.72	3.98	2.12	1.23
5	7.43	6.75	4.87	4.25	2.65
7	4.54	3.87	3.43	2.86	2.52
9	4.12	3.12	2.97	2.54	1.71

It is worth noting that the most unfavorable indicators of non-sinusoidality of the current occur during two-phase electro-technological short circuits in the phase of the technological process “melt”.

When choosing the optimal operating modes of electrical equipment, it is necessary to analyze the most characteristic features of the electro-technological loads of the complexes, their quantitative indicators, the spectral composition of higher harmonics, the degree of non-sinusoidality and load asymmetry [10, 17, 22].

The influence of voltage fluctuations on electromechanical devices is explained not only by the operation of the arc steelmaking furnace, but also by the modes of the adjacent electrotechnical equipment. During the studies, attention was paid to the fact that the mechanical parameters of electromechanical calibration devices in the composition of asynchronous motors change during voltage fluctuations. The results of the study are shown in Fig. 7, 8. In such cases, it is advisable to use the methods of equivalent sinusoids for voltage and current, respectively

$$U = \left(\sum_{\upsilon=1}^{n} U_0^2\right)^{0.5},\ I = \left(\sum_{\upsilon=1}^{n} I_0^2\right)^{0.5}. \tag{10}$$

Similar processes occur in other electrical equipment, but in practice they remain out of the attention of operational personnel.

So, for motors with a capacity of 20 ÷ 100 kW in the range of permissible voltage deviations by 1%, the reactive power consumed increases by 3%. Active losses in an asynchronous electric motor will be of the same order as in the network. At the same time, when calculating electrical energy losses, the non-stationary nature of electromagnetic processes is not taken into account. For synchronous machines, the increase in active power losses depending on the change in voltage in the network in combination with the reactive component can be estimated by the following expression

$$\Delta P = D_1\left(Q/Q_{nom}\right) + D_2\left(Q/Q_{nom}\right)^2, \tag{11}$$

where Q and Q_{nom} are the reactive power generated, the index “nom” means the rated value; D_1 and D_2 are semi-empirical coefficients that are constant for different types of electrical equipment.

The results presented indicate the need for further, more thorough, research into the influence of the set of parameters of sharply changing loads on non-stationary electromagnetic processes in electrical equipment and supply networks of energy-intensive industrial enterprises.

Falling on structural elements made of structural steels, they lead to certain levels of local losses of electrical energy. When the rated load of the equipment is exceeded, the losses increase and lead to an excess of the thermal load of the structural elements. At the same time, the dielectric properties of the insulation deteriorate and its accelerated aging and charring occur. In inactive parts of the structure, a decrease in mechanical and compressive properties is formed, which contributes to the further development of negative and cumulative processes.

Since electrical equipment is a rather complex structural system with nonlinear properties between parameters, its mathematical model is quite difficult to build. Therefore, we shall use a generalized representation of non-stationary electromagnetic processes occurring in special-purpose transformers by large-scale modeling using appropriate scale factors. The original should be understood as real powerful electrical equipment that must operate at rated load parameters.

Along with experimental studies of losses, it is possible to use the method of equivalence of non-stationary electromagnetic processes. They make it possible to reproduce the growth of losses depending on the spectral composition of higher harmonics in sharply changing loads.

The essence of large-scale modeling of non-stationary electromagnetic processes is described below. It was assumed that the electromagnetic scattering field in a complex system of active and inactive structural parts changes in time according to a complex periodic law

$$H_\xi^{(0)}\left(\delta,t\right) = H^{(m)}\left(\delta,t\right)\cdot m_e^{-1}\cdot k\omega_p = H_\xi\left(\delta,t\right)\cdot m_e^{-1}. \tag{12}$$

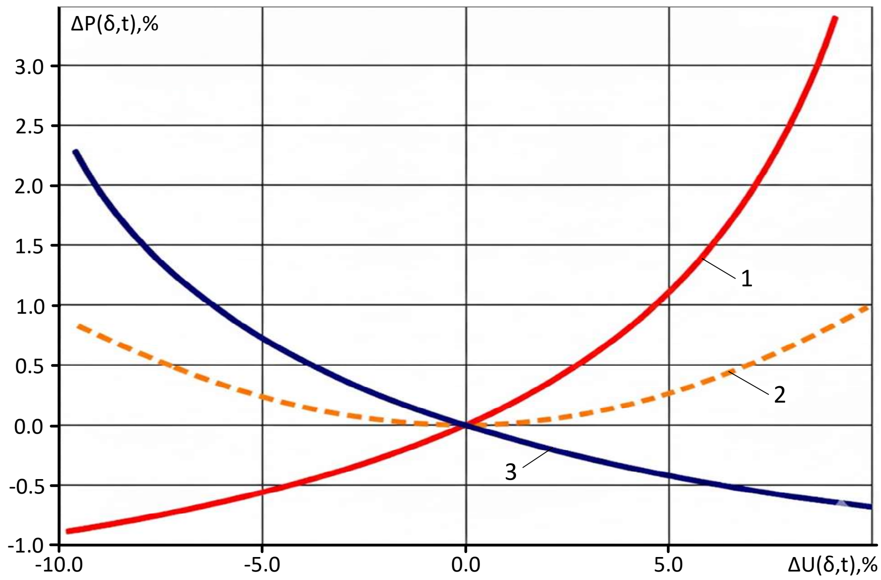

Fig. 7. Change in the active component of the power of an induction motor depending on voltage fluctuations relative to the rated value, as well as one equal to 0.75 and 0.5 (curves 3, 2, 1, respectively)

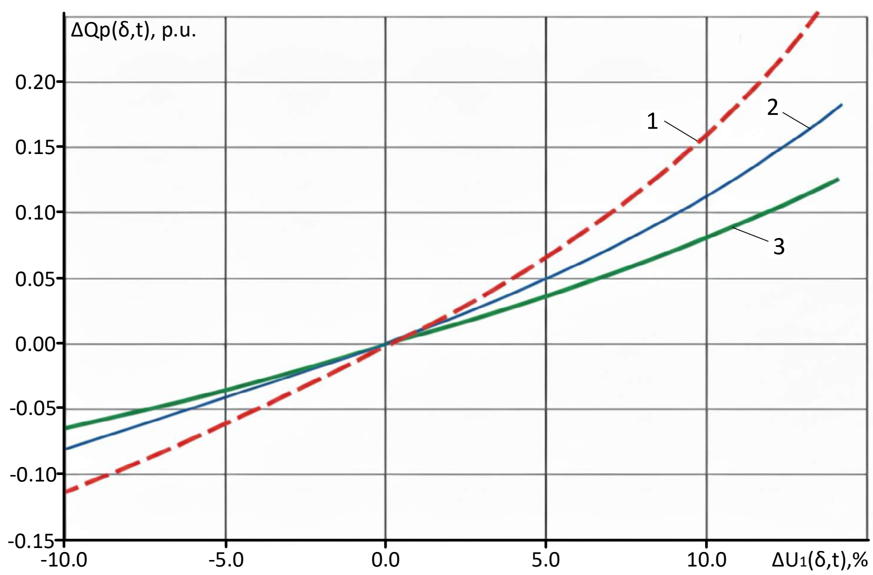

Fig. 8. Change in reactive power of an induction motor depending on voltage fluctuations at the rated value, and at a value equal to 0.75 and 0.5 (curves 3, 2, 1, respectively), (—) – theoretical

$$H_{\xi}^{(0)}(\delta,t)=H_{\ddot{Y}}(\delta,t)+H_{\breve{I}}(\delta,t)+H_{\Sigma}(\delta,t), \quad (13)$$

$$H_{\Sigma}(\delta,t)=\left\{T^{-1}\left[\sum_{\nu=1}^{H}H_{m,\nu}\cdot\cos\left(\nu\omega t+\phi_{\nu}\right)dt\right]^{2}\right\}^{-0.5}, \quad (14)$$

$$H(\delta,t)=\left\{T^{-1}\left[H_{m}\cos\left(\omega t+\phi\right)dt\right]^{2}\right\}^{0.5}, \quad (15)$$

where $H_{\xi(\delta,t)}$, $H_{\Sigma(\delta,t)}$ and $H_{(\delta,t)}$ are the averaged magnetic field over the period of the first harmonic, varying in time according to the sharply varying and sinusoidal laws, respectively; δ is the load parameter according to the characteristic features of the load; t is time; ω is the frequency of the first harmonic of the current; f is the industrial frequency; T is the period of the first harmonic; φ is the initial phase; m is the amplitude of the magnetic field; the indices (0) and (m) denote the nature of the field of the original and the model, respectively; kω is the equivalence coefficient.

The medium in which the scattering electromagnetic field propagates has linear electromagnetic characteristics. Under such conditions, the electric field for the original and the model can be represented in the following form

$$E_{\xi}^{(0)}(\delta,t)=E_{\xi}^{(m)}(\delta,t)m_{\gamma}^{-1}=E\left(\xi,t\right)m_{A}^{-1}k\omega\ . \quad (16)$$

The identity of the course of non-stationary electromagnetic processes in the original model is reproduced provided that they satisfy the following Maxwell's equation:

$$rotH_{\xi}^{(0)}(\delta,t)=rotH_{\xi}^{(m)}(\delta,t)\cdot m_{e}m_{H}^{-1}= =\sigma E_{\xi}^{(m)}(\delta,t)m_{E}^{-1}m_{\sigma}, \quad (17)$$

$$rotH_{\xi}^{(0)}(\delta,t)=rotH_{\xi}^{(m)}(\delta,t)\cdot m_{e}m_{H}^{-1}= =\left(\sigma E_{\xi}^{(m)}(\delta,t)+\varepsilon\frac{\partial E}{\partial t}\right)\cdot m_{\sigma}m_{e}m_{E}^{-1}. \quad (18)$$

Maxwell's second equation (18), according to the solution of the problem, is presented as follows

$$rotE_{\xi}^{(0)}(\delta,t)=rotE_{\xi}^{(m)}(\delta,t)\cdot m_e m_E^{-1}=$$
$$=-\mu\frac{\partial H_{\xi}^{(m)}(\delta,t)}{\partial t^{(m)}}\cdot m_t m_H^{-1}. \quad (19)$$

The systems of equations (17) to (19) fully reflect non-stationary electromagnetic processes and reflect the identity of their manifestation in the model and the original, provided that the conditions of equality of electrical conductivities and magnetic penetrations are observed.

The following notations are adopted in these systems of equations:

– scales of magnetic and electric field strengths:

$$m_H=H^{(m)}(\delta,t)\Big/H^{(0)}(\delta,t),$$

$$m_E=E^{(m)}(\delta,t)\Big/E^{(0)}(\delta,t); \quad (20)$$

– scales of electrical conductivity and magnetic permeability of inactive structural parts that are made of structural steels:

$$m_\sigma=\sigma^{(m)}\Big/\sigma^{(0)}, \quad m_\mu=\mu^{(m)}\Big/\mu^{(0)}; \quad (21)$$

– the scale of the circular frequency and the time of the electromagnetic process:

$$m_\omega=\omega^{(m)}\Big/\omega^{(0)}, \quad m_t=t^{(m)}\Big/t^{(0)}. \quad (22)$$

In the case when the design details of the model and the original are made of the same materials, then their electromagnetic characteristics are the same:

$$\sigma^{(0)}=\sigma^{(m)}=\text{const}, \quad (23)$$

$$\mu^{(0)}=\mu^{(m)}=\text{const}. \quad (24)$$

Dividing Maxwell's first equation by the second and taking into account the accepted conventions, we arrive at the conditions for the similarity of the electromagnetic field in the model and the original:

$$(m_e\cdot m_E\cdot m_\sigma)m_H=1; \quad (25)$$

$$(m_e\cdot m_\mu\cdot m_H)(m_E\cdot m_t)^{-1}=1.$$

Further transformations lead to the determining criterion for the similarity of electromagnetic processes in the model and the original in the following form

$$m_e^2\cdot m_t^{-1}\cdot m_\mu\cdot m_\sigma=1. \quad (26)$$

Thus, a determining criterion for the similarity of electromagnetic processes in the model and the original was obtained. It can be used for both electromagnetic and thermal and non-stationary, as well as for electrodynamic and electromechanical processes. At the same time, their use allows one to reproduce the influence of various factors simultaneously on the technical condition of the equipment.

Inactive parts of powerful transformers are massive structures made of structural steels. The latter have a nonlinear magnetic permeability depending on the intensity of the incident magnetic field, which complicates the study. Therefore, they were considered in the form of a massive half-space (skin effect) relative to the effective values of the non-sinusoidal magnetic field in the following form

$$\vec{I}_{í}(\delta,t)=\vec{I}_{î}(\delta,t)+\vec{I}_{ï}(\delta,t)+\vec{I}_{\Sigma}(\delta,t), \quad (27)$$

where I is the current; indices o, n, Σ mean constant, pulsating, and higher harmonics, respectively; δ is a parameter characterizing the degree of non-sinusoidality of a sharply changing load

$$\vec{I}_{\Sigma}(\delta,t)=\sum_{\nu=1}^{N}\vec{I}_{\nu}\cos(\omega_\nu t+\phi_\nu), \quad (28)$$

where ν – higher harmonics; ω – circular frequency of the first harmonic; φ – initial phase; t – time.

Based on the fact that the geometric parameters of inactive structural parts significantly exceed the depth of penetration of the electromagnetic field into them, they were considered as a ferromagnetic half-space – skin effect [3]. The electromagnetic field on the surface of half-space with conductivity σ and magnetic permeability μ(H) must satisfy the following differential equation

$$\frac{\partial^2 H_\Sigma(x)}{\partial x^2}-\frac{\sigma\partial B_\Sigma(H_\Sigma)}{\partial t}=0, \quad (29)$$

in combination with the equation

$$E_\Sigma(x)=-\frac{1}{\sigma}\times\frac{dH_\Sigma(x)}{dx}, \quad (30)$$

where $B_{\Sigma\{H(B\Sigma)\}}$ is the induction in the surface part; x is the direction of propagation of the electromagnetic wave in the ferromagnetic half-space.

As boundary conditions and boundary constraints, we used the tangential components of the magnetic and electric field strengths, respectively:

$$H_\Sigma(o,t)=H_o(t)+H_\Pi(o,t)+\sum_{\nu=1}^{\nu=\infty}H_\nu\cos(\phi_\nu-\nu\cdot\omega\cdot t), \quad (31)$$

$$E_\Sigma(o,t)=E_o(t)+E_\Pi(o,t)+\sum_{\nu=1}^{\nu=\infty}E_\nu\cos(\phi_\nu-\nu\cdot\omega\cdot t). \quad (32)$$

Under such constraints, the solutions to equations (29) and (30) are obtained as follows

$$H_\Sigma(x,t)=H_{\ddot{Đ}}+H\ +$$
$$+\sum_{\nu=1}^{\nu=\infty}H_\nu e^{\frac{-kx}{1\nu}}\cos(k_{2\nu}t+\phi_\nu-\nu\omega_\nu t), \quad (33)$$

where

$$k_\nu=\frac{\nu}{2}\omega_\nu\sigma\mu(H_\Sigma(t)). \quad (34)$$

After simple further transformations in combination with a comparison of surface losses at sinusoidal and non-sinusoidal current, the corresponding formulas for current and frequency equivalence coefficients were derived:

$$\left.\begin{aligned} Q_{\xi(0)}\left(H_{\xi(0)}\right)&=Q\left(H_{(0)}\right)\cdot\beta_{iQ}\Big|_{\omega=\omega_1,H_{\xi(0)}=H_{(0)}},\\ Q_{\xi(0)}\left(H_{\xi(0)}\right)&=Q\left(H_{(0)}\right)\cdot\delta_{EQ}\Big|_{\omega=\omega_Y,H_{\xi(0)}=H_{(0)}}.\end{aligned}\right\}\quad(35)$$

The current (V) and frequency (ω) equivalence coefficients are calculated from the spectral composition of the current, or one of the surface parameters of the electromagnetic field falling on the surface of massive structural parts of electrical equipment.

The non-sinusoidality of the current characterizes the number of higher harmonics relative to the first and is determined from the following formula

$$K_{FI}=\left[\sum_{\nu=2}^{N}H_{\nu}(0)/\sum_{\nu=1}^{N}H_{\nu}(0)\right]\cdot 100\%.\quad(36)$$

Thus, the equivalence coefficients of non-stationary electromagnetic processes make it possible to theoretically and practically reproduce the corresponding parameters excited by sharply varying loads. During the experiment, additional losses in inactive structural elements are automatically taken into account due to the nonlinearity of the magnetic permeability, which depends on the intensity of the incident non-sinusoidal magnetic scattering field.

5. 4. Experimental studies of non-stationary electromagnetic processes on physical models and a special-purpose transformer

The conducted studies of the set of parameters of non-stationary electromagnetic processes on a reduced copy and a real powerful special-purpose transformer are quite reasoned evidence of the effectiveness of implementing the proposed method of scale modeling in practice.

Using the determining criterion of similarity of electromagnetic processes in the model and the original (26) and taking into account that their structural elements are made of the same materials, the derivatives for building the model will be the scale factors of linear dimensions and the time of flow of the exciting current. This means that when a real transformer operates at an industrial frequency (50 Hz) the power supply frequency of the model will be 500 Hz, and the model is a reduced copy of a real transformer on a scale of 1 to 3.16. The appearance of the active part of the model and a single-phase special-purpose transformer is shown in Fig. 9 and Fig. 10, respectively.

Experimental studies on the model were performed in a specialized test room with sinusoidal and non-sinusoidal currents. The model was powered by a high-frequency generator with a frequency of 500 Hz. According to the results obtained, the corresponding design solutions were corrected, and, on their basis, the design of a real transformer was corrected. After manufacturing the final transformer structure, it was tested at the test station of the transformer enterprise also under two modes – with sinusoidal and non-sinusoidal currents. Thus, the current was used as a determining exciting parameter of electromagnetic processes. Total and additional losses are determining and, in turn, lead to thermal overloads of active and inactive parts of the structure, the development of electrodynamic processes and loss of structural strength. The obtained results of experimental studies on the model were converted to the original according to the determining similarity criterion (26) and scale factors.

The non-sinusoidality of the current was formed using special blocks of power thyristors by controlling the opening time, which led to a certain deterioration of the sinusoidality of the current. The non-sinusoidality of the current was determined by the spectral composition of the higher harmonics (36), which were measured by a spectrum and frequency characteristics analyzer from the Brüel & Kjær company.

The results of the experimental study on a physical model and a real powerful special-purpose transformer are given in Tables 4, 5.

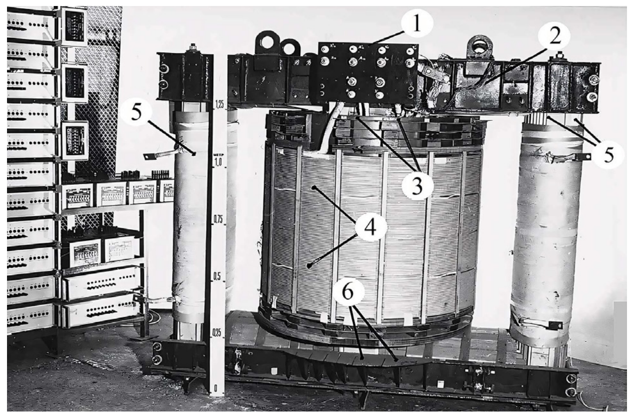

Fig. 9. Physical model of the active system of excitation of the electromagnetic field of the scattering of a single-phase powerful transformer of special purpose with a voltage of 750 kV: 1 – terminals of the terminals of the high and low voltage windings; 2 – pressing yoke beams; 3 – pressing rings; 4 – system of excitation of the electromagnetic field of the scattering (winding); 5 – side yokes of the magnetic system (magnetic circuit); 6 – shelf of the lower yoke beam

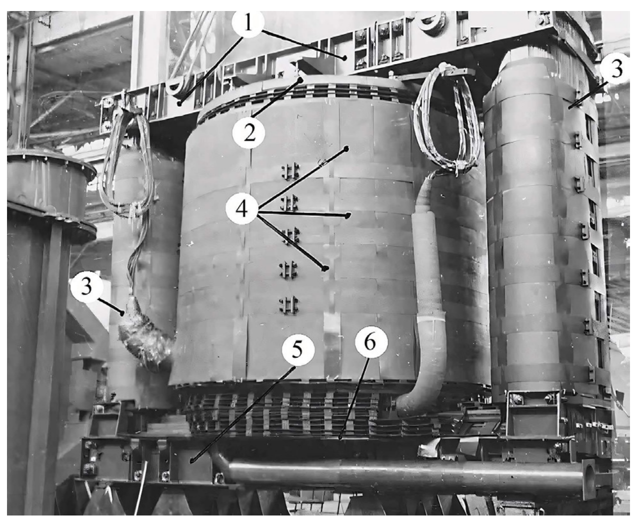

Fig. 10. Active system of a real single-phase special-purpose power transformer with a capacity of 175 MVA and a voltage of 750 kV: 1 – upper yoke beams designed for pressing the magnetic system; 2 – pressing rings designed to ensure the mechanical stability of the electromagnetic field excitation system; 3 – taps designed to connect the windings into the corresponding circuit; 4 – electromagnetic field excitation system (windings); 5 – lower yoke beam; 6 – insulating gaskets.

Since the original and its physical model are designed and manufactured with the preservation of characteristic design features, this allows one to obtain objective results of the influence of the set of characteristic features of the exciting parameters in combination with the processes occurring in real equipment. The most important nodes are the electromagnetic field excitation system and the magnetic system. They significantly determine the mass and dimensions of the transformer and affect the stabilization of electromagnetic processes of the equipment. Table 4 gives results of the study of additional losses and thermal overload of a single-phase special-purpose transformer under steady-state modes, the appearance of the active part of which is shown in Fig. 10.

Table 4

Results of large-scale modeling of additional losses in the core of the lower console of a powerful special-purpose transformer

Model		Original			
		Thermal overload, °C		Increasing losses, a. u.	
Model	Losses, W/m^2	Sinusoidal	Non-sinusoidal	Experiment	Theory
1	10.8	108.0	180.6	1.66	1.71
2	12.5	125.0	148.0	1.18	1.21

Table 4 gives surface losses in the lower console shelf (item 6 in Fig. 9) by the thermometric method. The most vulnerable places for the formation of surface losses (W/m^2) were determined by the plots of the magnetic field distribution of the scattering on the surface of the structure. Chromel-Kopel thermocouples were installed in these places, which were connected to a specialized thermoEMF recording device. The tests were carried out under short-circuit modes by instantaneous voltage supply using a powerful device. When the steady-state thermoEMF value was reached, the switch was triggered and the voltage was also instantly removed. The surface losses in the lower console shelf and thermal loads were determined by a comparative analysis of the increase and decrease in the thermoEMF.

To confirm the effectiveness of using theoretical provisions and the method of large-scale modeling of non-stationary electromagnetic processes, a study was conducted on simplified models of structural steels used in the practice of electrical engineering and the ST.3sp brand. The models were toroidal structures. The dimensions of the toroids were chosen so that the electromagnetic processes in them manifested themselves similarly to those in a ferromagnetic half-space. Magnetizing and measuring windings were wound on them. The first was used to form an exciting magnetic field, and the second for magnetic flux. These models were in transformer oil to prevent overheating. The tests were performed under two modes – with sinusoidal and non-sinusoidal currents. Under the first mode, power was supplied from a sinusoidal current source with a fundamental frequency of 50 Hz. Under the subsequent modes – with currents of different non-sinusoidality. Powerful thyristors were used as a current non-sinusoidality shaper. Non-sinusoidality was regulated by applying control pulses at appropriate times to the non-sinusoidality shaper. Losses were measured by the wattmeter method using special measuring instruments for current, voltage, losses, frequency, frequency spectrum, non-sinusoidality with an extended frequency range, as well as the temperature of the sample and cooling oil. The magnetic field was calculated from the current, and the magnetic flux and electric field from the voltage on the secondary winding.

The current non-sinusoidality coefficient was monitored by a digital analyzer of electrical energy quality indicators of the DIRIS A60 type. Current information was processed using the multifunctional CONTROL VISION software. The shape and spectral composition of the magnetizing current at the required effective value were corrected by the corresponding ratios of active and reactive resistance in the power supply circuits. Then the shape of the current, voltage and magnetic flux were visualized, and the indicators of the corresponding devices were measured and recorded.

At the same time, the shapes of the current, electric field $E(t)$ and flux $F(t)$ were recorded, as well as their numerical values and spectral composition.

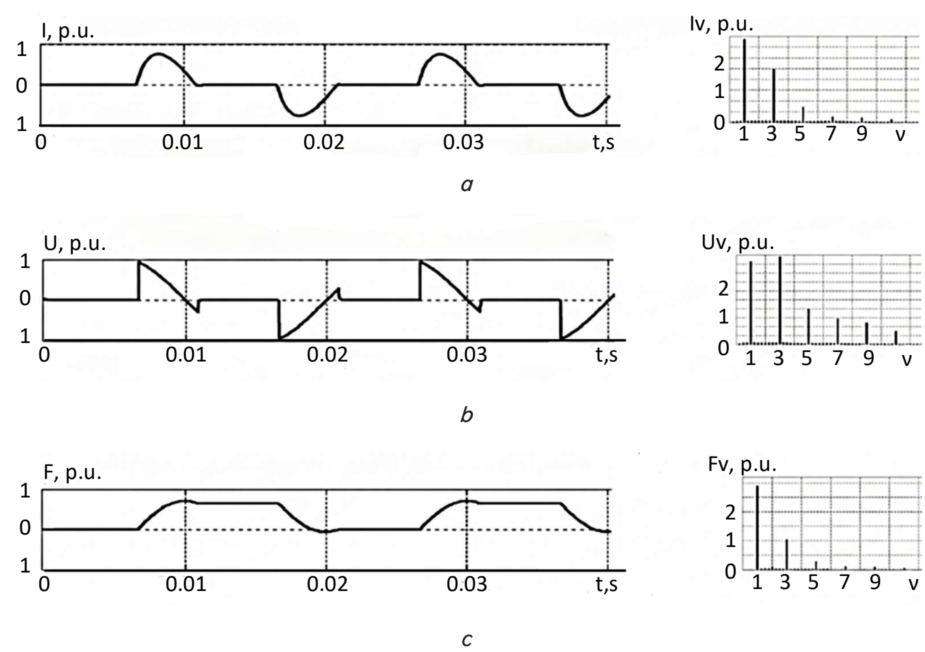

Fig. 11. Magnetizing current register graphs at a non-sinusoidal current coefficient (k_{fi}= 53%) (a), voltage (b), and in an integrating device (c) and the corresponding spectral compositions of higher harmonics

Samples from the corresponding structural steels with different non-sinusoidality coefficients were calculated from formula (36) and compared with those measured by the analyzer.

Fig. 11, 12 show the register and oscillograms of current $I(t)$, voltage $u(t)$ and flux $F(t)$ under one of the test modes at a non-sinusoidality coefficient of the current (k_{fi} = 53%) and their spectral composition of higher harmonics, respectively, and Table 5 gives the electrophysical characteristics of structural steels used in the practice of electrical engineering.

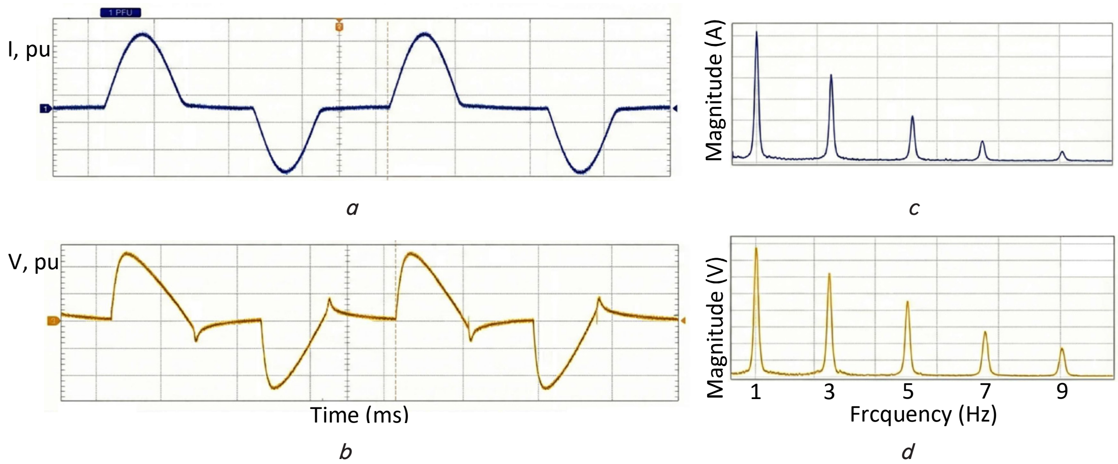

Fig. 12. Oscillograms of the magnetizing current at a non-sinusoidality coefficient (*kfi* = 53%) (*a*), voltage on the measuring winding (*b*), and their spectral compositions of higher harmonics (*c*, *d*)

Comparative analysis of the results depicted in Fig. 3, 4 revealed that the obtained results are consistent with each other. This indicates a very high reliability of the obtained experimental and theoretical data, as well as the methodology for modeling non-stationary electromagnetic processes in transformer equipment.

As can be seen from Table 6, the error between calculations and experimental studies of losses does not exceed 5.7% in the most unfavorable limits of the magnetic field – the region of weak magnetic fields. Within the limits of medium and strong magnetic fields, which is typical for transformer equipment, the error does not exceed 3.5%.

Table 5

Electrophysical characteristics of structural steels used in the practice of electrical engineering

Steel grade	$\mu_e(\lvert H_{(0)}\rvert)$, relative units	$H_{(0)}\times 10^2$, A/m	$\sigma\times 10^6$, Ohm $^{-1}$m $^{-1}$
St-2	1499	3.75	7.71
St-3sp	1362	3.92	7.12
St-14G2	822	7.23	3.83
St-09G2s	670	6.32	3.89
St-U8	490	9.53	5.31
Cast iron	360	5.84	1.38

Table 7

Experimental and theoretical coefficients of equivalence of surface losses in parts made of structural steel of grade St.3sp at non-sinusoidality of 70.2% of the exciting current

$H_{\Sigma(0)}$, A/m	Equivalence factors, relative units					
	Current		Frequency		Losses	
	Experiment	Theory	Experiment	Theory	Experiment	Theory
258.3	1.281	1.279	2.578	2.627	1.597	1.621
785.2	1.233		2.591		1.603	
1745.4	1.284		2.607		1.581	
3501.2	1.285		2.597		1.587	
5243.3	1.287		2.627		1.584	
6214.5	1.309		2.598		1.609	

Comparison of the results of theoretical and experimental studies given in Tables 6, 7 showed that the surface losses for sinusoidal and non-sinusoidal currents agree with each other with sufficient accuracy for engineering practice. This is the basis for the statement that the proposed modeling method is characterized by very high reliability, and it is advisable to use it in the design and reconstruction of powerful transformers.

Thus, we can note the rather high efficiency of the proposed methods for large-scale modeling of non-stationary electromagnetic processes in powerful special-purpose transformer equipment.

Table 6

Results of numerical calculations and experimental measurements of surface losses in structural steel St-3sp. at a current non-sinusoidality coefficient K*fi* = 35%

H_0, A/m	With sinusoidal current			With non-sinusoidal current		
	Q, W/m^2		Error, %	Q_Σ, W/m^2		Error, %
	Experiment	Calculation		Experiment	Calculation	
2000	571	582	1.9	662	686	3.6
3000	1070	1130	5.6	1242	1312	5.7
4000	1630	1703	4.5	1890	1979	4.7
5000	2230	2290	2.7	2587	2671	3.3
7000	3670	3698	0.8	4253	4378	2.9
9000	5203	5309	2.1	6032	6203	2.8

6. Research into the impact of rapidly changing loads on a powerful special-purpose transformer: results and summary

The constructed scheme of the combination of electrotechnological and electrical equipment, shown in Fig. 1, made it possible to experimentally study the influence of a set of sharply changing loads and a set of parameters of non-stationary electromagnetic processes of different physical nature (Fig. 2–4).

Comparative analysis of the directive task of power consumption by the complex (Fig. 3) with the experimentally obtained one (Fig. 4) made it possible to specify the limits of exceeding the load on powerful transformers and thyristor reactive power compensators. These include the obtained dependences of efficiency and power of the electrotechnological process, which are shown in Fig. 2. This made it possible to establish the most influential operating modes of transformers and electrical equipment. Directive graph (Fig. 3) of power and oscillogram (Fig. 4) that was actually consumed by the arc steelmaking furnace of the DSP-150 type in different phases of the technological mode. It demonstrates that during the "melt" period, the active component of power varies within the range from (–78.6) to (+21.9%), and during the "quiet melting" period – within the range from (–52.5) to (+71.6%). During the "melt" period, the reactive component of power varies within the range from (–86.4) to (+22.6%), and during the "quiet melting" period – within the range from (–56.6) to (+86.8%).

During the "fine-tuning" period, the fluctuation of active power relative to the directive varies within the range from (–9.4%) to (+10.2), and reactive – (–9.3) to (+10.3%).

The power factor in the technological process maps is set constant, but in practice it varies within (–34.5) to (+29.7%) during the "melt" period and from (–14.6) to (+9.2%) during the "quiet melting" period.

It can be seen that at each stage of the technological process the power transmitted from the network to the furnace is significantly inconsistent with the directive task. This leads to a deterioration in the operating conditions of transformers and other electrical equipment. It is obvious that the choice of general-purpose electrical equipment is not appropriate for powering electrical technologies.

Based on a thorough analysis of the research results, specific features of sharply changing loads of complexes in the composition of the chipboard were established, which are as follows:

– they lead to cyclical probable changes in electrical modes;

– they affect the quality indicators of electrical energy;

– they lead to significant consumption of reactive power;

– there is a large number of switching on and off of electrical equipment;

– electrical modes are accompanied by oscillations, asymmetry, non-sinusoidality of modes;

– there are thermal overloads of individual phases of network and electric furnace transformers and individual links;

– they lead to additional losses of electrical power;

– they excite non-stationary electromagnetic processes in electrical and electrotechnological equipment;

– there are no effects of iso- and exo- processes on the conversion of electrical energy into heat;

– the mechanisms of electromagnetic processes and their impact on the current technical condition of electrical equipment have not been sufficiently studied.

Large-scale modeling allowed us to establish that the thermal overload of the model under the first test mode and with a sharply changing load is 67.2% more compared to the sinusoidal one. At the same time, the powers differ by 26.8%. This is explained by the influence of higher harmonics on additional and local losses.

The thermal overload of the model and the original was determined in steady-state short-circuit modes. A comparative analysis of theoretical and experimental studies revealed that when testing under mode 1 at a power of 50 MVA, the thermal load increases by 25.0% compared to mode 2 – at a power of 67 MVA. Under each test mode, sharply changing currents were withstood, corresponding to a certain short-circuit mode. After analyzing numerical tests, it was found that the most unfavorable mode is the mode with a through-power of 67 MVA (Table 4). The error of taking into account the non-sinusoidality of the scattering field on surface losses in structural steels at non-sinusoidal currents does not exceed 3.1% under the most unfavorable conditions (Table 6).

In [2, 5, 8, 14, 17, 19, 22] it is proposed to consider the influence on the technical condition of electrical equipment of individual factors and operating conditions in combination with some other factors. In contrast, it is proposed to consider simultaneously the influence of a set of factors on electromagnetic processes of various physical nature occurring in powerful transformers under sharply changing loads.

Verification and validation confirm the reliability and effectiveness of the proposed method of large-scale modeling of non-stationary electromagnetic processes by comparative analysis of theoretical calculations and results of multi-stage experimental studies, the main ones of which are given in Tables 4–7 and Fig. 1–12.

According to the data given in Table 4, the losses in the shelf of the lower console are reproduced in the experiment with an error of 3.25% relative to the theoretical ones, and the smallest is 2.54%.

Surface losses in structural steel samples are experimentally reproduced with the largest error of 5.6%, and the smallest – 0.8% (Table 6).

Equivalence coefficients (increase in surface losses) with a non-sinusoidality of the exciting current of 70.2% are reproduced with errors: current – 1.54%; frequency – 3.4%; direct losses – 2.5%.

Thus, quite high validation indicators (comparison of experiment with theoretical calculations) have been proven, which is a fairly significant indicator of verification in accordance with the requirements of the international standard ISO/IEC 17025, which is adjusted by ISO technical committees. This Standard was developed in accordance with the editorial rules of the ISO/IEC Directives, Part 2.

The working capacity of the validated experimental research methods of non-stationary electromagnetic processes is confirmed by comparative analysis, which are given in Fig. 11, 12 and in Tables 4–6. The obtained dependences can be reproduced at different non-sinusoidalities of sharply changing loads in accordance with the IEC60076 research methodology of transformer equipment. Our results are confirmed by operational parameters in accordance with the conditions of real operation of the equipment under industrial conditions, which are illustrated in Fig. 2–4, 7, 8.

Validation of the obtained results of energy losses in the physical model, a real original transformer, and numerous experiments on structural steel samples confirms the verification (confirmation of the reliability of the declared research provisions). Comparative analysis of local losses in the most loaded structural elements, in particular in the shelf of the lower console, are consistent with experiments on samples.

Comparison of thermal overloads of the model and the original, under steady-state modes, confirmed the adequacy of the reproduction of temperature fields, which is the basis for further use in practice.

The correctness of the calculation of surface losses in structural steels and the electromagnetic parameters of the surface effect is quite effectively consistent with the experiment of non-stationary electromagnetic parameters with different spectral composition of the current.

The consistency between the theoretical and experimental results confirms the validation conditions, which is confirmed by the sufficiently high reliability of the reproduction of additional losses in inactive structural parts of special-purpose power transformers and is within the limits sufficient for engineering practice. The relative error of the proposed method does not exceed 5%, and the error of taking into account the non-sinusoidality of the scattering field in the most unfavorable conditions is no more than 3.1%. This indicates the feasibility of using the method in the design of new types of special-purpose transformers.

The method of large-scale modeling of non-stationary electromagnetic processes in combination with the equivalence of the influence of sharply changing loads should be implemented at the stages of development of new types of special-purpose power transformers and during the reconstruction of existing general-purpose ones operating under sharply changing loads. Neglecting the influence of sharply changing loads on power transformers and electrical equipment will lead to a reduction in reliability terms and subsequent emergency failures.

The shortcomings of this work include:

– lack of specific proposals and evidentiary results for other types of electrical equipment;

– the impact of violations of operating conditions and technical inspections has not been determined;

– lack of analysis of electromagnetic compatibility of adjacent equipment;

– lack of a mathematical model consisting of a system of nonlinear integral-differential equations that combine the characteristic features of structural parts, the system of excitation of the electromagnetic field of scattering, magnetic core and cooling oil.

In further research, it is desirable to take into account:

– uneven distribution of the magnetic field of scattering in the space of transformer equipment, which is formed by windings;

– nonlinear properties of magnetic permeability from the intensity of the incident magnetic field of electrical and structural steels from which the magnetic system and inactive structural parts are made;

– distribution of the thermal field in inactive structural parts of transformer equipment with increasing load and deteriorating indicators of the quality of electrical energy;

– conditions for shunting structural parts to reduce thermal overloads;

– consistency of dielectric properties of insulating materials with terms and conditions of operation and formation of partial streamers;

– influence of electrodynamic processes on pressing forces and devices.

7. Conclusions

1. It has been established that the real loads of transformer equipment in comparison with the directive task when supplying arc steelmaking furnaces exceed the rated ones and are characterized by the following indicators: during the technological phase of "melting", the active power is constantly redistributed within (–78.6)–(+21.9%), and the reactive power varies within (–86.4)–(+22.6%), respectively. Based on the comparative analysis, a generalized power supply scheme for powerful arc steelmaking furnaces was developed with the specification of the impact of sharply changing loads on transformers and electrical equipment.

2. The causal factors leading to the deterioration of the reliable operation of transformer equipment have been established. It was shown that the thermal overload of the transformer increases by 1.73 times with sharply changing loads, and the transformer failure rate under such load modes decreases by 51.0% compared to the rated mode.

3. Non-stationary electromagnetic processes have been considered in combination with parameters of various physical nature (additional losses, thermal overloads, electrodynamic processes, deterioration of dielectric properties of insulation, etc.). It is shown that the spectral composition of higher harmonics is as follows: 2nd – 9.95%, 3rd – 24.96%, 4th – 6.1, 5th – 7.41%, 7th – 4.54%, 9th – 4.15% relative to the first. At the same time, the non-sinusoidality coefficient (k_{fi}) reaches 70.2%, and surface losses increase by 41.1% within weak magnetic fields. This allowed us to adapt the method of large-scale modeling of non-stationary electromagnetic processes occurring in the cavity of special-purpose transformer equipment.

4. Comparison of theoretical and experimental data showed that under sharply changing loads, total and additional losses in transformer equipment can increase to 71.2% (in the first package of the magnetic system), and in inactive structural parts up to 67.2% and depends on the spectral composition of the exciting current. Large-scale modeling in combination with the equivalence of surface losses in inactive structural parts with ferromagnetic properties are consistent with sufficient accuracy for engineering practice and do not exceed 3.0%.

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.

Funding

The study was conducted without financial support.

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.

Authors' contributions

Volodymyr Zinovkin: Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition; **Yurii Krysan**: Writing – original draft, Writing – review & editing, Funding acquisition; **Serhii Shylo**: Writing – original draft, Writing – review & editing, Funding acquisition.

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