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MODELING OF STRUCTURAL ELEMENTS OF THE ENERGY-ECONOMIC MODEL «ELECTRIC NETWORK - ELECTRIC CONSUMER»

MONOGRAPH

2024

SWorld
Germany

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Included in International scientometric databases

MONOGRAPH

ScientificWorld-NetAkhatAV
Karlsruhe 2024

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Modeling of structural elements of the energy-economic model «Electric network - electric consumer» [Text] : Monograph / M. Tryputen, V. Kuznetsov, V. Kovalenko, V. Artemchuk, S. Levchenko. Karlsruhe, 2024. 138 p.

Early evaluation of the parameters of electric power quality and maintenance of the corresponding operating modes of electric facilities in work environment is the important scientific and practical task. In terms of real operating conditions, electric mains often demonstrate nonsinusoidal mode characterized by the available harmonics of voltage and current. Deterioration of the electric power quality in the electric supply systems for industrial enterprises results in the decreasing reliability and efficiency of the operation of energy consumers, i.e. asynchronous motors (AM).

The known methods to reduce negative influence of low-quality electric power on the AM operation differ with their integration costs and expected economic effect. Nevertheless, the available methods for the selection of protective means for asynchronous motors, operating in the electric mains with nonsinusoidal voltage, have no economic substantiation. Moreover, economic losses of an industrial enterprise due to the operation of asynchronous motors in terms of considerable deviation of the power quality values from the standard ones have not been analyzed to the full extent.

The chapter of monograph has shown that currently it is expedient to solve a task of the selection of AM protective means basing on the computational studies, which involve a simulation model representing the interaction of company electric main with the power consumers. There are following structural elements of a simulation model: a generator of linear voltages of the company electric main; a nonlinear electromagnetic and thermal model of an asynchronous motor; and a decision-making block. The chapter of monograph demonstrates the ways to increase reliability of the modeling of electric main parameters.

ISBN 978-3-98924-021-6
DOI: 10.30890/978-3-98924-021-6.2024

Published by:
ScientificWorld-NetAkhatAV
Lußstr. 13
76227 Karlsruhe, Germany
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Dedicated to ***Serhii Levchenko*** *– a colleague, a scientist. He perished for Ukraine in battles against the troops of the Russian Federation.*

Serhii Andriiovych Levchenko graduated from the Zaporizhzhia Industrial Technical School with a specialization in "Electrical equipment of industrial enterprises and installations" in 1984. After serving in the Armed Forces of Ukraine, he continued his education and obtained a higher education at the Zaporizhzhia Machine-Building Institute named after V.Ya. Chubarya (National University " Zaporizhzhia Polytechnic"), in the field of "Power supply of industrial enterprises, cities and agriculture". He worked as a design engineer of the Specialized Trust " Pivdenkolirmethazoochyshchennia".

In 1990, he started his scientific and pedagogical activities at the Zaporizhzhia Electrotechnical Professional College. Since 2003, he worked at the Zaporizhzhia State Engineering Academy. In 2009, he defended his PhD thesis at The Institute of Renewable energy of the National Academy of Sciences of Ukraine (Kyiv).

With the onset of Russian aggression, Associate Professor **Serhii Andriiovych Levchenko** volunteered to go to the front to defend his Motherland. During combat, he sustained a fatal wound in the temple. Serhii Andriiovych was respectfully buried at the cemetery of Saint Nicholas in the city of Zaporizhzhia.

Serhii Andriiovych Levchenko is the author of 50 scientific works and 60 methodological works.

Open, hardworking, honest, and kind – **Serhii Andriiovych** will forever remain in the memory of his loved ones, colleagues, and graduates.

CONTENT

INTRODUCTION

In today's context of growing global energy consumption and the drive towards more environmentally friendly and sustainable energy sources, the topic of modeling the structural elements of energy systems is gaining special importance. Electric grids form the backbone through which electricity is transmitted from generators to end consumers. This process is vital for ensuring the stable functioning of various sectors of the economy, infrastructure, and society as a whole.

During Russia's military aggression, starting in 2014 and especially with the full-scale invasion in 2022, Ukraine has faced serious challenges in ensuring the reliability of its power supply system. Targeted attacks on energy infrastructure, such as strikes on power plants, substations, transmission lines, and distribution networks, have led to significant power outages. These attacks not only deprive the population of electricity but also undermine the functioning of critical infrastructure, including hospitals, water treatment facilities, transportation, and communications.

One of the key factors is the vulnerability of energy facilities to precision weapons and drones, making them easy targets. Damage to networks and generating capacities significantly worsens the ability to promptly restore power supply, especially in active combat zones. In some cases, particularly during the winter, this leads to humanitarian crises related to the inability to heat homes and provide the population with basic services.

Another issue is the complexity of restoring energy infrastructure in the context of ongoing combat operations. The rapid mobilization of repair crews is often hampered due to the danger to workers' lives and the lack of access to damaged facilities. This increases the time needed to restore the power supply system and reduces its overall resilience.

Ukraine also faces the problem of electricity shortages caused by the destruction of large energy facilities. In response, energy-saving programs are being implemented, and integration with European energy systems is being strengthened, which helps partially offset the deficit. However, ensuring the sustainability of Ukraine's energy system requires significant investments in protecting critical infrastructure, modernizing networks, and utilizing distributed generation, including renewable energy sources.

Thus, the transition to new technologies for electricity generation and distribution, such as decentralized generation and smart grids, as well as the active implementation of renewable energy sources (RES), imposes additional demands on energy systems. These changes present the challenge of developing new economic models and management methods that will allow for more efficient use of energy resources, cost reduction, and minimization of environmental impact.

As is known, the electrical grid, a complex system consisting of generating, transmitting, and distribution capacities, is directly connected to electricity consumers. The latter can range from large industrial enterprises to small private households, creating diverse consumption scenarios and requirements for the reliability and quality of electricity supply.

Effective interaction between the electrical grid and consumers is a key aspect of energy system stability. In practice, this interaction involves many factors: forecasting electricity consumption, load management, resource allocation optimization, and accounting for dynamic changes in demand and supply in the electricity market.

The electricity sector serves as the primary energy supply source for most world economies. As technologies develop, the demand for electricity in the modern world is steadily increasing, particularly considering the digitization, development, and use of electric transportation, including electric vehicles, electric buses, electric bicycles, and other forms of electric-powered transport, as well as the infrastructure needed for their operation, including charging stations and management systems, and other energy-intensive innovations. The stability and reliability of power supply, as well as its economic efficiency, directly affect production processes, product and service costs, and the standard of living.

The modern power supply system, consisting of interconnected elements such as electricity generation, transmission, distribution, and consumption, must possess a high degree of resilience and flexibility to adapt to new economic and technological conditions. For example, the introduction of smart meters, the use of large databases for forecasting supply and demand, and the development of automated energy consumption management systems help improve the efficiency of power grids.

As is widely recognized, modeling electrical networks and consumption processes is becoming an important tool for analyzing and forecasting the functioning of energy systems. Modeling helps identify weak points in the structure of electric grids, optimize generation and distribution processes, and develop economically justified strategies for managing energy resources.

The modeling of structural elements of energy systems is based on various methods: mathematical models, data-based simulations, optimization problems, and the application of artificial intelligence (AI) and machine learning algorithms. These methods allow for more accurate forecasting of changes in electricity demand, optimizing network operations considering the time of day and season, and minimizing transmission losses.

Modern energy systems face significant challenges that need to be considered when developing and modeling the structural elements of an energy system.

The economic efficiency of energy system management is one of the key factors influencing the cost of electricity for end consumers, the profitability of energy companies, and the overall stability of the energy system. Modeling economic aspects in the context of the energy system includes:

Assessing capital and operational costs for modernizing grid infrastructure;

Analyzing the structure of electricity tariffs for various categories of consumers;

Modeling the impact of dynamic electricity pricing on consumer behavior;

Analyzing the impact of poor-quality electricity on the performance of electric consumers.

The effective functioning of the energy system requires a comprehensive modeling approach that considers multiple interrelated factors. This includes technical aspects (generation capacities, distribution networks), economic parameters (cost of generation and transmission, tariff policies), and environmental impacts (CO_2 emissions, use of renewable energy sources). Therefore, energy system development requires a multidisciplinary approach that includes technical, economic, and environmental aspects.

A major issue today is the complexity of integrating all these factors into a single model that provides accurate forecasts and can be used for management decisions. In practice, energy system models can range from simple linear models to complex nonlinear systems that involve optimization methods, artificial intelligence, and other tools.

Energy system modeling must consider not only the current state of the market and infrastructure but also future changes, such as:

The growth in electricity demand due to population growth and technological development.

Changes in the generation structure toward increasing the share of renewable energy sources.

The emergence of new consumers, such as electric vehicles, which can create additional loads on the grid but also serve as mobile batteries for storing energy.

Dynamic pricing and demand management that allow consumers to flexibly respond to electricity price changes, reducing peak loads and optimizing network performance.

In recent years, there has been rapid development in digital technologies that are increasingly applied in the energy sector. The introduction of the Internet of Things (IoT), big data, and artificial intelligence (AI) technologies allows for the creation of more accurate and flexible energy system models.

The digitization of power grids facilitates the transition to smart grids, which can analyze consumption data in real-time, manage loads, and optimize electricity distribution. Such systems can autonomously respond to changes in the grid, disconnect or connect consumers depending on the current load, thereby reducing energy losses and improving overall system efficiency.

Using big data and analytics allows energy system operators to gain a more comprehensive understanding of consumption patterns and demand changes. This opens up opportunities for more accurate forecasting of electricity needs and enables network operations to be adapted to changing conditions.

Another important aspect of energy system modeling is risk management and ensuring resilience. Energy systems must be prepared for unexpected changes, such as accidents, natural disasters, or equipment failures. The introduction of monitoring and early warning systems helps reduce risks and enhance the resilience of networks.

Special attention is paid to cybersecurity, as with the increasing level of digitization, energy systems become more vulnerable to cyberattacks. Energy system modeling also involves analyzing potential threats and developing protective mechanisms to prevent attacks.

Energy systems continue to evolve under the influence of technological, economic, and environmental factors. Modeling the structural elements of the energy system "Electric Grid – Electric Consumer" not only helps better understand the current state of the system but also offers solutions to future challenges. The introduction of renewable energy sources, the development of smart grids, energy storage, and adaptation to any changes require the integration of new models and approaches, making this research area one of the most relevant and promising in the energy sector.

As is known, electric energy is the most convenient type of energy, and it may be regarded as the basis of modern civilization. Due to the development of market relations in the industry of electric energy supply, electric energy is considered to be the product which should comply with certain quality and market demands. The Law of Ukraine “On electric energy market” as in force on 17.10.2020 defines clearly the legislative, economic, and organizational grounds of the energy supply market, regulate the relations in terms of production, transmission, distribution, purchase and sell, supply of electric energy to provide reliable and safe electric energy supply for consumers taking into consideration the consumers’ interests, development of competitive relations, minimization of costs for electric energy supply, and minimization of negative environmental impact. Article 18 “Quality of electric energy supply” of the Law of Ukraine “On electric energy market” makes it clear that:

1. The Regulator (the National Committee performing state regulation in the spheres of power generation and communal services) defines a list of quality coefficients for electric energy supply, characterizing the level of energy supply reliability (continuity), commercial reliability of the services as for electric power transmission, distribution, and compensation as well as electric energy quality, and approves their values;
2. The Regulator defines the procedure of compensations, if the electric energy supply does not meet the quality coefficients, and the amount of compensations;
3. The quality coefficients of electric energy supply, procedure, and amount of compensations for being not in compliance with them are subject to public disclosure in accordance with the procedure identified by the Regulator.

As is known, the electric energy quality is the complex of certain properties of electric energy according to the specified standards determining the degree of its suitability for its proper use.

According to the information from the official site of the National Committee regulating the activities in the spheres of power generation and communal services (http://www.nerc.gov.ua/): “Currently, the relations between the electric energy producers or suppliers and consumers, taking place during the electric energy purchase and sell in the electric energy market, are regulated by the “Rules of retail electric energy market (RREEM) approved by the National Committee regulating the activities in the spheres of power generation and communal services (NCRPGCS) of 14.03.2018 # 312.

According to point 5.1.2 of RREEM, an operator of the distribution system is obliged to follow the quality coefficients of electric energy supply, which characterize the level of reliability (continuity) of electric energy supply, commercial quality of the services concerning the electric energy distribution (transmission) as well as the quality of electric energy coefficient, which list and values are approved by the Regulator.

According to the provisions of point 11.4.6 of chapter 11.4 of division XI “Code of distribution systems” approved by the Order of the NCRPGCS of 14.03.2018 No. 310, parameters of the electric energy quality coefficients within the points of consumers' connections and in terms of standard operating mode should meet the parameters determined in DSTU EN 50160:2014 "Characteristics of electric energy supply voltage in general-purpose electric networks" (DSTU EN 50160:2014)".

Thus, the State Standard of Ukraine DSTU EN 50160:2014 "Characteristics of electric power supply voltage in general-purpose electric networks" is the current effective document in Ukraine; the Standard is developed by the Institute of Electrodynamics of the National Academy of Sciences of Ukraine.

As is known, electromagnetic compatibility (EMC) of technical means considers the processes occurring in electrical complexes and systems in terms of generating electromagnetic interference, their impact on electrical equipment, the degree of protection and correction of adverse effects. The emergence of new devices for conversion technology, the modernization of an increasing number of industrial electrical installations, in particular, the use of adjustable electric drive, lead to a decrease in the quality of electricity in the supply networks of enterprises. This necessitates the strengthening of electromagnetic compatibility requirements for industrial plants. Standardization of electricity quality indicators in such conditions is one of the main issues of this problem.

Electricity quality indicators (EQI), regulated by state standards, are the starting point in almost all areas related to electrical installations. This applies to the design of new facilities, and commissioning, research of electrical equipment, the decision to upgrade and others.

The international normative basis for the assessment of electromagnetic compatibility of electrical installations is the well-known European standard EN 50160: "Characteristics of voltage supplied by general purpose distribution systems" (1994), as well as the standard of the International Electrotechnical Commission (IEC) 1000-2 - 4: "Electromagnetic compatibility. EMC levels at industrial facilities for low-frequency conduction interference.

EQI in the power supply systems of industrial enterprises are determined by the mode of operation of electrical installations that introduce distortion, and therefore are constantly changing.

Therefore, in GOST 13109-97 "Electricity. Requirements for the quality of electricity in general purpose electrical networks" provides a comprehensive methodology for assessing the quality of electricity, based on the assessment of energy performance of the distortion. Normalized EQIs are integrated indicators that reflect the degree of negative impact of distortion of electricity on the technical and economic characteristics of electrical equipment. The maximum allowable values of the electricity quality indicator are selected for technical and economic reasons and the impact of distortion on the reliability of electrical equipment.

Thus, the main document in force in Ukraine regulates the following indicators of electricity quality: voltage deviation δU_y; the magnitude of the voltage change (or the amplitude of voltage fluctuations (VF)); intensity (dose) of flicker P_t; the coefficient of curvature of the sinusoid of the curve of linear (phase) voltage K_U; the coefficient of the n-th harmonic component of the voltage $K_{U(n)}$; reverse voltage asymmetry coefficient K_{2U} and zero K_{0U} sequence; duration of voltage failure K_{dv}; voltage pulse U_{puls}; temporary overvoltage factor K_{ov}; frequency deviation. Therefore, consider methods for calculating only the main indicators of electricity quality associated with the most common distortions of the network.

The asymmetry of voltages of a three-phase network is characterized by the coefficient of their reverse sequence K_{2U},%, which is determined by the ratio of the current value of the voltage of the reverse sequence of the fundamental frequency of the three-phase voltage system U_2 to the nominal value of the phase voltage U_{nom}:

$$K_{2U} = \frac{U_2}{U_{nom}} \cdot 100 \quad .$$

In addition, the value of the zero sequence coefficient is normalized K_{0U}, %, which is determined by the ratio of the voltage of the zero sequence of the fundamental frequency U_0 to the nominal value of the phase voltage U_{nom} :

$$K_{0U} = \frac{U_0}{U_{nom}} \cdot 100 \quad .$$

Non-sinusoidal voltage is characterized by the value of the curvature coefficient of its curve K_U, %, which is determined by the ratio of the current value of the higher harmonics U_n to rated voltage:

$$K_U = \frac{1}{U_{nom}} \sqrt{\sum_{n=2}^{N} U_n^2} \cdot 100 \quad ,$$

U_n – the effective value of the voltage of the n^th^ harmonic; N=22 – the number of the last of the considered harmonics. The permissible and maximum permissible value K_U depends on the voltage class.

In addition to the non-sinusoidal coefficient, the coefficients of each harmonic component up to the 22nd separately are also normalized. The latter are defined by the expression:

$$K_{U(n)} = \frac{U_n}{U_{ном}} \cdot 100 \quad .$$

And their allowable and maximum allowable values are also normalized depending on the voltage class.

Thus, the quality of electricity is determined by the set of its indicators, at which the electrical receivers can work properly and perform their functions. At deviations of their values from admissible, normal work of electromechanical converters is complicated or is possible only at considerable reduction of loading. It should also be noted that the reduction of the efficiency of this equipment often occurs at the values of EQIs in the ranges allowed by the standards.

Nowadays, the demand for electricity is much higher than the potential of electric networks; at the same time, consumers require much cheaper high-quality electric energy. That is why provision of high quality of electric energy is a topical problem and one of the main tasks of electric energy. Inappropriate electric energy quality is the main reason of interruptions in terms of power supply for consumers. Quality of electric energy is the degree of correspondence of electric energy characteristics at a specific point of electric system to a set of control parameters.

Broadly defined, electric energy quality is a set of its properties determining the influence on electric equipment, devices, and facilities. Quality of electric energy is connected with reliability since the standard mode of electric power supply is the one in terms of which consumers are provided with the electric energy of normalized quality, in the required amount, and without any interruptions. Due to the fact that the quality coefficients of electric energy may differ from the standard ones regulated by DSTU EN 50160:2014, some enterprises may face following negative consequences: disconnection and downtime of the equipment due to accidents and switching in the external networks; direct losses due to underproduction of end products; indirect losses due to possible operations to repair mechanical equipment as well as its maintenance expenses; decreasing reliability of electric energy supply systems; reducing production efficiency and increasing specific energy-output ratio of the end product unit; and reducing service life of electric equipment.

Annually, electric energy consumers bear direct and indirect costs.

Direct costs include the following:

- electric energy charge;
- costs for network operations;
- fee for fundamental electric energy loss;
- fee for additional electric energy losses stipulated by harmonic currents, asymmetry of voltages and currents;
- fee for low power coefficient taking into account a constituent of the increase in tariff for consumption (generation) of reactive power of extra specified boundary values of the reactive power coefficient.

As a result, direct costs of electric power consumers account for the considerable share of costs (81%). Indirect costs are related to interruptions in electric energy supply, overvoltages, transient processes, reducing voltages resulting in the loss of computer system data, underproduction, operating troubles, and equipment outage. Indirect costs of the electric energy consumers cover about 19%.

Topicality of the problem. Due to current problematic situation in energy power supply at Ukrainian industrial enterprises, more and more attention is being paid to the implementation of measures for providing main technological processes with considerable saving of energy resources. While organizing electric energy supply and consumption, there is one common and quite serious task – improvement and optimization of quality coefficients of electric energy to improve the efficiency of its use and provide reliability of electric equipment functioning.

To provide corresponding electric energy quality, we need continuous monitoring and control of the parameters of electric energy values. Currently, majority of the electronetwork companies do not have clear view of the parameters being expedient to control for the most efficient management of electric energy quality. Cooperation of power engineers, scientists, and specialist dealing with electric energy quality control is the possible solution of that problem.

As is known, functioning of electric equipment in the networks with low-quality electric energy results in negative consequences, i.e.: increasing temperatures of its windings; reducing period of its service life; decreasing technical and economic indices of the latter such as power coefficient and coefficient of efficiency; increasing losses and growing volume of the consumed reactive power. Analysis of the previous studies makes it possible to conclude that the operation of any electrical receiver in terms of low-quality electric energy results in the reducing performance and reliability of that equipment class.

However, the published research findings do not contain economic evaluation of the resulted loss. The considered effect of low-quality electric energy on the electric receiver operation does not touch upon the main thing – financial aspect of the problem. Up to now, the monetary issues have not been studied yet; as a result, there is no possibility to have comparative evaluation of economic damage due to low-quality electric energy and the costs required to provide the relevant quality.

A share of costs for electric energy is the dominating component of the total monetary means necessary for the electric equipment operation. According to different estimations, the share is 75-80%. Thus, even inconsiderable growth of losses due to deteriorating quality coefficients of electric energy (QCEE) causes significant increase in the annual costs for electric equipment maintenance. As a result, enterprises have to implement measures for preventing from losses due to low electric energy quality in their intra-factory networks.

Along with that, implementation of the corresponding technical means should be economically expedient; they should take into account the specificity of both production and the involved equipment. In this context, currently there are no corresponding instruments providing economic substantiation of the expediency of measures against negative effects of electric equipment operation in terms of low-quality electric energy. First of all, that is due to impossibility to have accurate forecast of damage being the exact result of low-quality electric energy.

Thus, the topical scientific task is to develop a new universal toolset helping the enterprise staff evaluate promptly the economic performance of electric receivers, operating within the low-quality electric power networks, and select the appropriate means for improving their energy efficiency taking onto account accidental changes in QCEE in the workshop network as well as features of specific technical and technological equipment.

The objective and task of the research. The research objective is to develop the methodological basis for selecting efficient and economically expedient means to improve energy efficiency of electric receivers operating in the specific networks with low-quality electric power.

The research object is represented by methods and means of evaluation as well as provision of energetic and economic indices of electric receiver operations in terms of its functioning in a network with low-quality electric energy.

The research methods. Solution of the research tasks involved theory of probability, mathematical statistics, theory of differential calculus, numerical integration, and fundamental provisions of electrical engineering and theory of automated control.

Practical implications of the obtained results. The theoretical developments represented in this research have made it possible to do the following:

– to develop and recommend for implementation a joint energetic and economic model of the substantiated selection of technical means to reduce negative influence of low-quality electric energy on the efficiency of electric equipment operations;

– to elaborate and recommend for application an algorithm for complex evaluation of the damage stipulated by low-quality electric energy in the workshop networks of enterprises, allowing to forecast technical and economic records of operations of electric energy consumers.

Approbation of work results. The main results of the chapters were presented at the International scientific and technical conferences: *«5th IEEE International Conference on Modern Electrical and Energy System, (MEES 2023)*, Kremenchuk, Ukraine, *on* September 27 – 30, 2023 “*4th International Conference on Modern Electrical and Energy System, (MEES 2022)*” Kremenchuk, Ukraine on October 20-22, 2022, *«The Third International Conference on Computer Science, Engineering and Education Applications» (ICCSEEA2020)* 21-22 January 2020, Kiev, Ukraine; *«2019 IEEE 6th International Conference on Energy Smart Systems, ESS 2019»*, (Kyiv, Ukraine on April 17 - 19, 2019); *«International Conference on Modern Electrical and Energy Systems, MEES 2019»*, (September 23-25, 2019 Kremenchuk Mykhailo Ostrohradskyi National University, Ukraine); *«International Conference on Modern Electrical and Energy Systems»* : Kremenchuk Mykhailo Ostrohradskyi National University, Ukraine, 15-17 November, 2017; *"2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON)*, Lviv, Ukraine, 2019; *«IEEE 3rd International Conference on Intelligent Energy and Power Systems»* (IEPS). – September 10 - 14, 2018 Kharkiv, Ukraine.

Practical use. The results of the studies were adopted for the educational process:

- for students of the Ukrainian State University of Science and Technologies with a master's degree, who study under the educational-professional program « Engineering of industrial electromechanical systems and electrical technology complexes » of the second level of higher education in the specialty 141 - "Electric power, electrical engineering and electromechanics» of knowledge 14 – «Electrical engineering» in the discipline «Non-sinusoidal modes in electrical networks of enterprises» and for students of the Ukrainian State University of Science and Technologies with a master's degree, studying in the following specialties: «122 - Informational-control systems and technologies», «174 - Automation, computer-integrated technologies and robotics» and 141 - "Electric power, electrical engineering and electromechanics» in the discipline «Electromagnetic compatibility of technical means and quality of power supply»;

- for students of the Dnipro University of Technology of educational level – bachelor of specialty - «174 - Automation, computer-integrated technologies and robotics» of discipline – «Identification and modeling of technological objects of automation» and for postgraduate students: educational level - Doctor of Philosophy of specialty - 174 «Automation, computer-integrated technologies and robotics» of discipline – «Modeling of objects and control systems»;

- for students of Zaporizhzhia National University educational level – bachelor of specialty - 141 – «Electric power, electrical engineering and electromechanics» of knowledge 14 – «Electrical engineering» in the discipline «Simulating of electromechanical systems».

CHAPTER 1
EVALUATING THE EFFECT OF ELECTRIC POWER QUALITY UPON THE EFFICIENCY OF ELECTRIC POWER CONSUMPTION

It is common knowledge [1] that any electromagnetic environment is formed as a result of a certain technological process. In the context of electric power process, power supply systems are distribution of electric energy, its transmission, and consumption. Every stage of the process is characterized by definite changes being a result of deviations from the determined operation mode, principle of electric equipment action etc. Electric energy characteristics (EECs) are the levels of electromagnetic compatibility of electric grid providing adequate performance of any electrical means connected to the grid if the EECs do not exceed permitted values.

In the context of the general idea of electromagnetic compatibility of consumers within power supply grids, power quality represents one of the most pressing and critical issues in the modern electric power supply industry. Ensuring high-quality power supply is not merely a technical challenge but a fundamental requirement for enhancing the overall efficiency of electric energy utilization across a variety of applications and industries. The successful resolution of power quality issues has far-reaching implications, significantly influencing the improvement of energy efficiency at both the micro and macro levels. As the demand for energy continues to grow globally, the development of effective strategies and basic tendencies aimed at improving energy efficiency in electric power supply grids has become a top priority. Achieving this goal largely depends on the accurate identification and understanding of the root causes that lead to the degradation of electric energy quality. Without a clear grasp of these underlying factors, efforts to address power quality issues may lack precision and efficacy, thereby limiting the potential benefits of such initiatives.

Electric energy quality is a pivotal factor that directly affects not only the operational performance and reliability of power systems but also the efficiency of the connected consumers. In other words, the quality of electric energy acts as a critical determinant of the functionality, durability, and energy consumption patterns of various electrical devices and systems. Poor power quality can lead to numerous adverse outcomes, including increased operational costs, reduced lifespan of equipment, heightened risks of failure, and inefficiencies in energy utilization. Consequently, addressing power quality issues is essential to optimize the overall performance of power systems and to ensure that consumers receive reliable and efficient energy supplies that meet their needs.

The challenge of ensuring high-quality electric energy within power grids has gained increased importance in recent years, particularly as technological advancements have introduced a wide range of new, progressive processes and systems. These innovations, while beneficial in many respects, have also introduced complexities into the power supply landscape. For instance, the growing prevalence of nonlinear and unsymmetrical energy consumers—such as variable frequency drives, electric vehicle chargers, and renewable energy sources—has posed significant challenges to maintaining power quality. These devices often generate harmonic distortions, voltage imbalances, and other disruptions that can compromise the stability and performance of the entire power grid. Such challenges underscore the need for advanced methodologies and tools to monitor, analyze, and mitigate power quality issues effectively [2].

The objective of this study is to identify and analyze the fundamental causes of deviations in key electric energy quality indices from their specified values. By pinpointing these causes, it becomes possible to develop targeted solutions and interventions that address the root of the problem, rather than merely mitigating its symptoms. This approach ensures that power quality improvements are sustainable and impactful, paving the way for enhanced energy efficiency, reduced operational costs, and greater reliability across the power supply network. Identifying these fundamental causes also provides valuable insights into the design and implementation of future technologies and processes that are more resilient to power quality challenges, ensuring that advancements in the electric power industry contribute to a more efficient and sustainable energy future.

1.1. Basic reasons of deviation of electric energy quality indices from the specified ones

While selecting measures to improve the efficiency of electric equipment in the context of inadequate electric energy, it is first required to determine reasons of the situation; to identify actual values of the specified quality indices; and to compare the latter with the permitted ones. It should also be mentioned that despite the great consequence of the problem, information concerning integral assessment of electric energy quality within grids of Ukrainian industrial enterprises is not available.

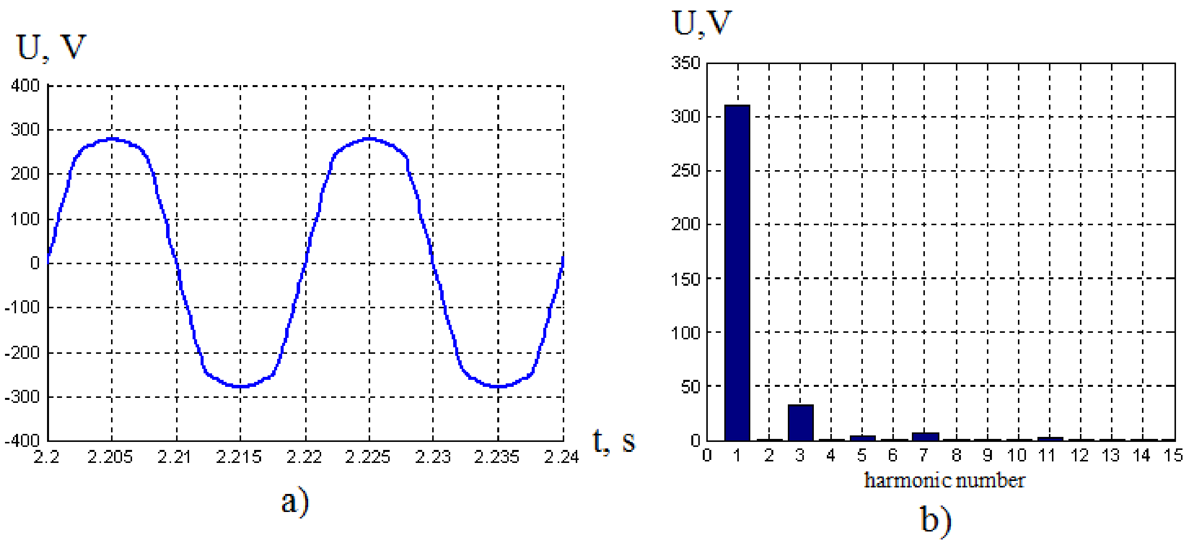
The above does not concern studies of electric energy quality within workshop grids of Alchevsk Metallurgical Integrated Works [3]. Electric drives of rolling mills of roughers and semifinished mills are basic consumers at the enterprise as well as the other similar ones. Power of such drives may be up to 13 MW; it concerns the electric drive of blooming operating at ArcelorMittal OJSC (town of Krivoi Rog). Despite the fact that its upgrading, connected with generator-motor (G-M) system substitution for thyristor converter-motor (TC-M), resulted in the improved control characteristics of the latter, TC-E systems stipulated significant deterioration in the electric energy quality within the enterprises.

Paper [3] shows that the use of TC-E systems by the main drives of rolling mills results in significant distortion of workshop voltage. High harmonics (up to 23-38 order) are available within a grid; moreover, they are even harmonics and odd ones. Coefficients of certain harmonic components are 5-7 times more than permitted values.

Notwithstanding that the problem of TC-E systems effect on the electric energy quality has been under thorough analysis since the moment of the drives extensive use (i.e. since the 1970s) [4, 5, and 6], it is still topical although being one of the reasons of poor quality of electric energy in workshops of Ukrainian enterprises. Unfortunately, paper [3] considers TC-E systems only, and “classic” publications (for example, [5, and 6]) are turned to be old substantially since new processing plants have already been introduced and a structure of energy consumption by enterprises has varied. Hence, more detailed study is required to analyze typical electric energy distortions as well as their qualitative and quantitative characteristics. It is the only basis for methods to select rational measures aimed at the improvement of electric energy quality.

The authors believe that additional research [7-12] helps formulate basic reasons of the considered distortions.

For example, core saturation of line transformers of workshop substations is one of the common anharmonicity reasons; it especially concerns low-power systems to be typical for small enterprises as well as for agrarian processing facilities. Core saturation of such transformers may result from operation of heating elements, welding equipment, and other high-powered consumers. In this context, characteristic curve of supply voltage is of truncated type; harmonic three is seen obviously in its spectral structure (Fig. 1 a, and b).



a) b)

Fig. 1 Characteristic shape of a voltage curve if cores of line transformers are saturated (a) and its spectral structure (b)

As it is known, the latter is risky for AM and transformers which primaries are of triangle connection. The matter is that they form zero-sequence, and resistance of electric coils on them is minor (leakage inductance is determined); the connection provides circuit for harmonic three current flow. As a result, current losses increase; coil temperature rises; and output capacity of the equipment drops.

Availability of powerful semiconductor converters within a grid is another common reason of harmonicity distortion [9, 10]. When such devices are commutating, consumed current is of peak values; consequently, voltage falls are observed within inputs of other consumers (Fig. 2, a).

The curve shape is typical for workshop grids of such large industrial enterprises as metallurgical integrated works, oil-refining integrated works, and mining-and-processing ones where powerful controlled electric drives with rectifiers or frequency converters are available. Practices show that despite steps, taken to increase electromagnetic compatibility, in such cases, quality indices of supply voltage exceed ultimate levels of the permitted values.

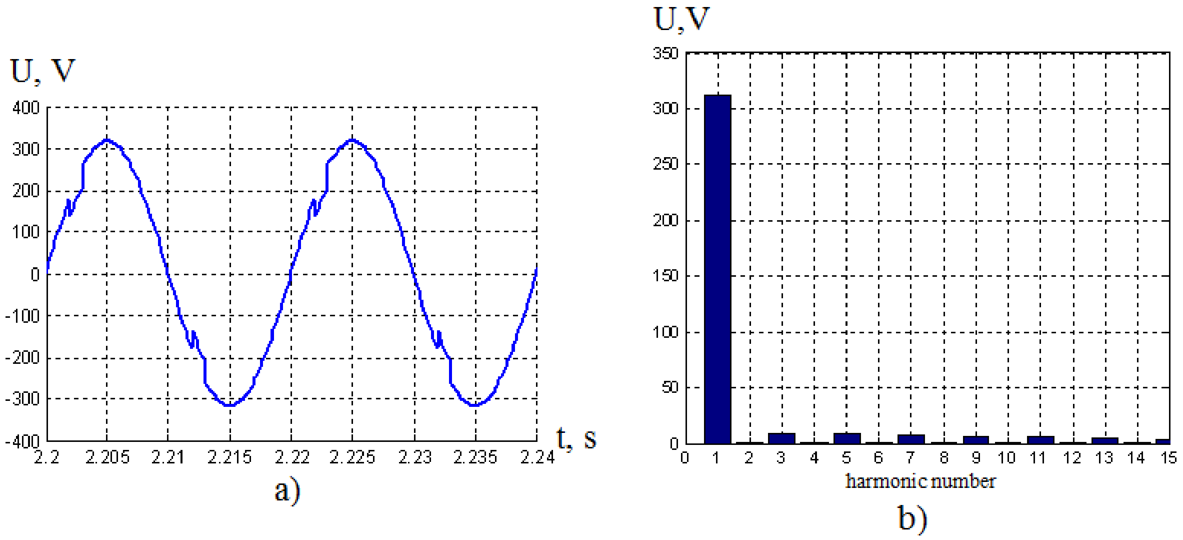
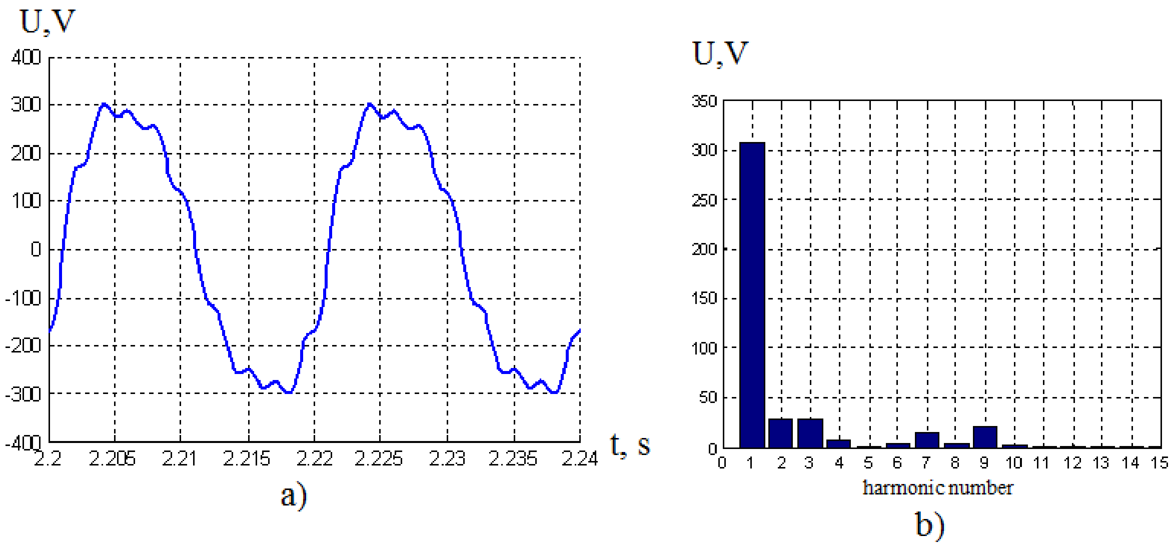


Fig. 2 Shape of a voltage curve if switching noise is available (a) and its spectral structure (b)

As it is understood, almost all high harmonics are available within spectral structure of voltage distorted by semiconductor converters (Fig. 2, b). They effect torque pulsation of asynchronous motor weakly [3, 9, and 10]; however, the process results in additional losses in the steel of the motors and converters stipulating their excessive heating which decreases energy efficiency of the electric equipment as well as its reliability. If workshop grid involves powerful consumers, supplied by the converters with pulse-phase control (i.e. plating tanks or arc furnaces), asymmetric distortion of voltage sinusoidal wave takes place and second harmonic is seen within the structure (Fig. 3 a, and b). It is known that the latter stipulates negative-sequence current flow while forming braking electromagnetic torque on the motor shaft.

Moreover, vibrations within its mechanical portion experience their intensification; depreciation is accelerated; and the equipment reliability drops.



a)

b)

Fig. 3 Voltage curve shape if harmonic two is available (a) and its spectral structure (b)

1.2. Quantitative evaluation of electric energy quality indices within workshop grids of an enterprise

Voltage oscillograms [13], recorded during the operational processes at various industrial enterprises, serve as clear and undeniable evidence of the widespread presence of poor-quality electric energy within their workshop grids. These oscillograms provide a visual representation of the voltage waveforms, revealing distortions, fluctuations, and other irregularities that deviate from the expected standard parameters of electric energy quality. Such deviations are indicative of significant issues within the power supply systems of these enterprises, reflecting the broader challenges faced by modern industrial facilities in maintaining the desired quality of electric energy.

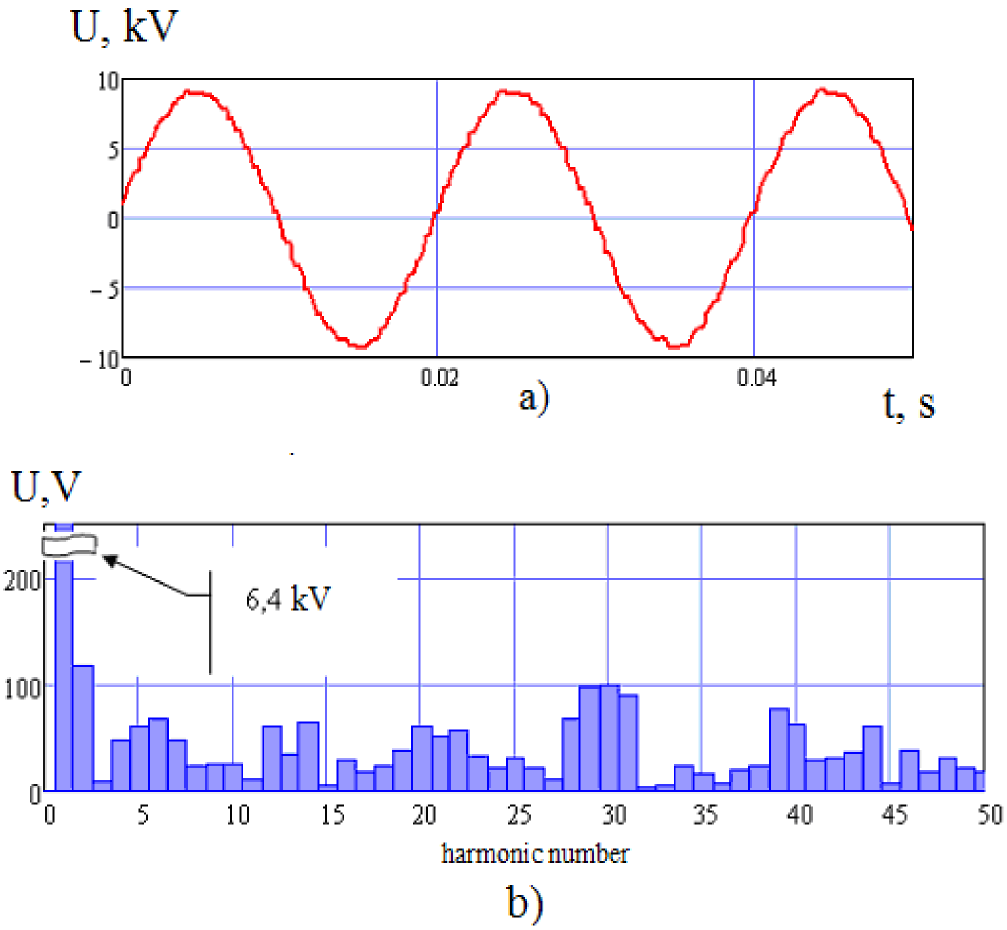
The analysis of these voltage oscillograms often reveals a range of common problems, such as harmonic distortions, voltage sags, swells, flickers, and phase imbalances. These irregularities not only compromise the stability and reliability of power supply systems but also have a detrimental impact on the performance and longevity of electrical equipment operating within these grids. For example, harmonic distortions can lead to overheating of transformers and motors, increased losses in power lines, and erratic behavior of sensitive electronic devices. Voltage sags and swells can cause equipment malfunctions, downtime, and even permanent damage to critical components. Flickers, resulting from rapid voltage fluctuations, can create a noticeable nuisance for both human operators and automated systems, reducing productivity and operational efficiency.

The availability of poor-quality electric energy within workshop grids is often linked to a variety of factors inherent to industrial environments. One major contributor is the widespread use of nonlinear loads, such as adjustable-speed drives, arc furnaces, and electronic converters, which generate harmonics and disrupt the sinusoidal nature of voltage waveforms. Additionally, the integration of renewable energy sources and distributed generation systems, while beneficial for reducing carbon emissions and diversifying energy supply, introduces new challenges in maintaining voltage stability and quality. The lack of adequate filtering, balancing, and compensation mechanisms further exacerbates these issues, leading to persistent problems with power quality.

The implications of poor-quality electric energy extend beyond the immediate technical challenges. For industrial enterprises, the presence of substandard electric energy within workshop grids translates into increased operational costs, reduced equipment reliability, and frequent maintenance requirements. Downtime caused by power quality issues can result in significant production losses, missed deadlines, and reputational damage, particularly in highly competitive markets. Furthermore, the inefficiencies associated with poor power quality contribute to higher energy consumption and environmental impact, counteracting efforts to achieve sustainability goals and improve overall energy efficiency.

To address these challenges, the study of voltage oscillograms plays a crucial role in diagnosing and understanding the specific issues affecting power quality in industrial workshop grids. These oscillograms serve as a valuable diagnostic tool, enabling engineers and technicians to pinpoint the sources of disturbances and assess their severity. By analyzing the recorded waveforms, it becomes possible to identify patterns and correlations between voltage irregularities and specific operational conditions, equipment, or processes. This information provides a solid foundation for developing targeted solutions, such as the installation of harmonic filters, voltage stabilizers, and power factor correction devices, tailored to the unique needs of each enterprise.

Fig. 4, a demonstrates a curve of linear voltage in a cracking workshop of oil refinery (OR) Ukrtatnafta; a number of high harmonics are available (Fig. 4, b). To make the displaying more convenient, amplitude of harmonic one (i.e, basic harmonic) is not represented in full.



a)

b)

Fig. 4 Oscillogram of linear voltage of substation in a cracking workshop at Ukrtatnafta oil refinery (a) and its spectral structure (b)

Table 1 represents the values of the regulated voltage quality index (i.e. coefficient of harmonic components of supply voltage $k_{U(n)}$) in phases in the context of the case under analysis. Bold type shows the excess of permitted values. Quality requirements are not met in terms of a coefficient of harmonic components of 6th, 8th, 10th, 12th, 14th, and 16th harmonics.

Table 1

Values of the regulated quality index of electrical energy in a cracking workshop of OR

Harmonic number	Standard permissible value of $k_{U(n)}$ coefficient for 6 kV supply chain, %	Rated value of $k_{U(n)}$ coefficient for 6 kV supply chain, %	Actual values		
			"AB" phase $k_{U(n)}$,%	"BC" phase $k_{U(n)}$, %	"CA" phase $k_{U(n)}$, %
4	0.7	1.05	**0.87**	0.32	0.55
6	0.3	0.45	**0.91**	**0.91**	**0.55**
8	0.3	0.45	**0.49**	0.19	**0.60**
10	0.3	0.45	0.28	**0.66**	0.23
12	0.2	0.35	**0.60**	**0.55**	**0.52**
14	0.2	0.35	**0.60**	**0.31**	**0.50**
16	0.2	0.35	**0.48**	0.07	**0.35**

In the context of the case under analysis, a value of voltage waveform distortion factor, overall K_U for the three phases was not more than 3.6% to be satisfactory from the viewpoint of power quality demands (standard permissible value is 5%).

Figure 5 illustrates the oscillograms of linear voltages recorded in the machine workshop of Zavod Montazhnykh Izdeliy Ltd, located in the city of Dnipro. Additionally, the figure provides their corresponding spectral structures, offering a detailed insight into the composition of voltage waveforms observed during the workshop's operation. The shape of these oscillograms can primarily be attributed to two significant factors: the overload conditions of the workshop's substation and the presence of a powerful inductive hardening plant within the facility. These elements introduce distortions and irregularities in the voltage waveforms, affecting their overall quality and stability.

Analyzing the case in more detail, it becomes evident that, in comparison with previously examined instances, the level of high harmonic components remains within the permissible range established by relevant standards and regulations. This indicates that the harmonic content of the voltage waveforms is not excessive or disruptive. However, a critical issue is observed with the voltage waveform distortion factor, which is measured at 8.4%. This value exceeds the standard permissible threshold, highlighting a deviation that requires attention. Such a distortion level can adversely affect the performance and efficiency of electrical equipment and systems connected to the workshop's power grid.

The elevated voltage waveform distortion factor indicates a need for further investigation and potential corrective measures to bring it within acceptable limits. Addressing this issue would involve identifying the specific sources contributing to the distortion and implementing appropriate solutions, such as harmonic filters or load balancing techniques. Overall, the oscillograms and spectral analysis presented in Figure 5 provide valuable data for understanding the electrical conditions within the workshop and for planning interventions to improve power quality.

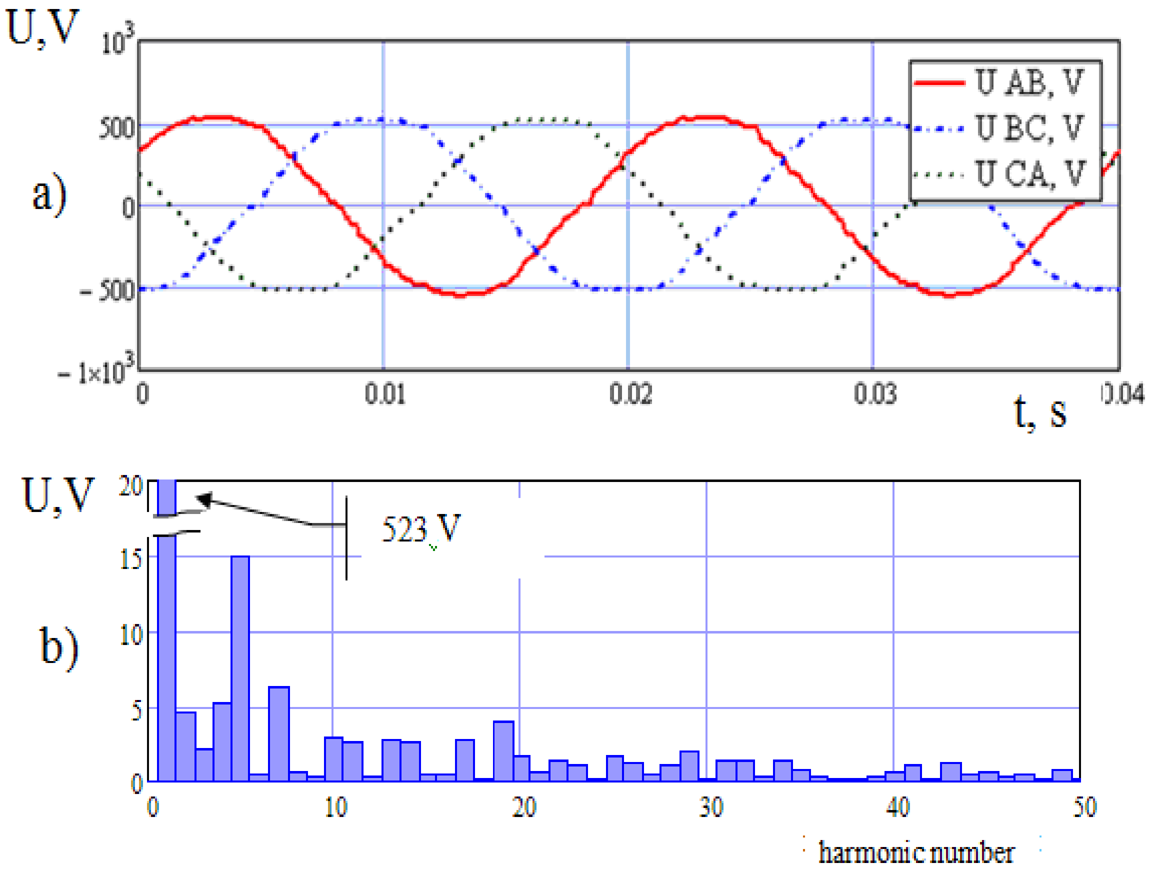


Fig. 5 Oscillograms (a) and spectral structure (b) of linear voltages of mechanical workshop substation of *Zavod Montazhnykh Inzdeli* ltd, city of Dnipro

Consider workshop supply systems of Zaporozhie Transformer Works as following example. Its process loads are supplied by two transformer substations (6 kV/0.4kV) through distributing 124 km system. Processing of statistical data, obtained at the enterprise input, has shown that there are no significant deviations as for the UPQI. Maximum value of the unified power quality index and its minimum value are 0.75% and 0.32% respectively. As for the coefficients on the negative sequence (K_{2U}), they are 0.9% and 0.38%.

Those supply lines where the majority of different consumers are concentrated have been selected as the considered workshop grids of the enterprise including those worsening UPQI invariably, i.e. mechanical workshop, welding workshop, and casting one. Table 2 demonstrates a structure of consumers as for the rated power in the listed workshops of *ZTW* Ltd making it clear which of them are responsible for UPQI deviations.

Table 2

A structure of consumers as for the rated power in the listed workshops of *ZTW* Ltd

A workshop	% of the rated power				
	Consumers having no effect on UPQI		UPQI effecting consumers		
	Machine tools with AM	Burning furnaces	Welding facilities	Metal coating tanks	Induction furnaces
Mechanical	92.5	5	2.5	-	-
Welding	27.3	2.7	70	-	-
Casting	5.9	34.4	-	50	9.6

Analysis of power consumption of the enterprise has shown that electric loads of a welding workshop, where bridge-connection rectifiers are installed, effect power quality significantly; metal coating tanks, locating in a casting workshop, supplying by direct-current valve inverters, increase UPQI.

Table 3 presents the quality indices of the supplying voltage for the enterprises under consideration. These indices provide a detailed overview of the voltage parameters, enabling a comprehensive analysis of the power quality in these facilities. The table highlights specific values for each index, offering a clear comparison against the standard permissible limits defined by relevant regulations and guidelines.

Values that exceed the standard permissible limits are indicated in bold type, drawing attention to areas where the voltage quality does not meet the required standards. This formatting helps to quickly identify problematic parameters, such as excessive voltage distortion, harmonic levels, or imbalances, which may negatively impact the performance and reliability of electrical equipment at the respective enterprises.

The data in Table 3 serves as a critical reference for diagnosing power quality issues and planning corrective measures to ensure compliance with established standards and improve the overall stability and efficiency of the power supply systems.

Table 3

Values of power quality indices in workshops of the analyzed enterprises

Enterprise	**Workshop**	**Power quality indices**			
		k_U, %	**$k_{U(\upsilon)}$ %**	**δU,%**	**$К_{2U}$,%**
ZTW Ltd	Mechanical	2…4	0.07...0.14	-5…+4	1.7...1.9
	Welding	8…12	0.07...0.15	**-9**…+5	1.5...**3.6**
	Casting	7…**11**	0.07...0.15	**-7**…+5	2…3.5
Oil refinery	Cracking	2.6...4.6	0.35...0.91	-1…+1	0.5...1.2
	Rectification	2.3...4.3	0.01... 0.02	-1,2…+1	1…1.5
	Filtration	0.1…0.3	0.01...0.02	-1…+1	0.2...1.8
Assembly facilities works	Mechanical treatment	7.4...9.4	0.01...0.02	-0.5...+0.5	1…1.5
	Maintenance	0.9...2.9	0.01.. 0.02	-1…+1	0.3...1.7
	Tool	1.8...3.8	0.01.. 0.02	-1.2…+1	1…2

Hence, in the context of *ZTW* Ltd, the greatest deviation of power quality indices from the permissible ones have been registered in welding workshop, and in casting one which impacts operation of electric consumers, available in them. Significant UPQI effects negatively technical state of machine tools with asynchronous drives. Total power losses also increase; quality of rectified current of converter installations required for electroplating decreases. Imbalance between asymmetry coefficient on negative sequence and standard permissible value results in origination of magnetic fields, rotating towards AM rotor and causing vibrations as well as failure of bearings.

Consequently, analysis of typical distortions as well as quantitative evaluation of power quality indices within workshop grids of the considered industrial enterprises helps conclude that quality of electric energy within similar grids of many Ukrainian enterprises cannot meet the specified requirements. They involve distortions resulting from operation of semiconductor converters, transformer core saturation etc.

Following fact should also be mentioned: if UPQI corresponds to GOST, then significant excess in coefficients of certain harmonic components of supply voltage is observed. It speaks for preferable use of the latter while analyzing electric facilities operating within grids with poor-quality electric power.

Finally, principal conclusion of the experiments is as follows: electric power quality differs at an enterprise input and within its workshop supply lines. Thus, similar consumers in different workshops are characterized by different energy efficiency involving individual approach while selecting means to increase it.

1.3 Power quality within grids of non-traction railway consumers

Electric supply of non-traction railway consumers from electrified railway lines is of specific interest from the viewpoint of power quality. They are components of large railway stations and junctions including engine-houses, carhouses, cultural and general objects as well as outside consumers connected to traction substations. In this context, certain consumers within railroad hauls and stations, located in areas between substations (lighting, autoblocking devices etc.) are connected generally to the lines of so-called longitudinal power supply with 6, 10, and 35 kV voltages.

If the main signalling, centralization and blocking (SCB) facilities as well as connection are supplied from individual lines of autoblocking power lines, then backup power supply is either from two wires-rails (TWRs) lines with nominal 25 kV voltage or from longitudinal power supply (LPS) with 6 and 10 kV voltages. Single-phase mini-substations (MSs) applied in this context, are mounted on the railway support bearings [15].

The mentioned LPS and TWRs also power such outside consumers as industrial enterprises and population; during the last five years the electrical supply increased by 15% (as of 01.01. 2015, it was almost 8 mln kWh) [16]. Loading conditions vary as well: a share of domestic equipment (i.e. personal computers, servers, printers, uninterruptible power supply units, microwaves etc.), using single-phase supply, increases as well as controlled electric drives of conditioning systems and ventilation systems. Luminescent lamps with electron ballast are used for lighting. Share of nonlinear load far exceeds linear component for the consumers.

As a rule, power sources of office equipment use bridge-circuit rectifiers with capacitor smoothers. Within the rectifiers, used by the current power sources, circuit voltage is supplied right to a diode bridge. In this context, the rectified current is transformed into high-frequency alternative current with the help of a commutator, and then becomes rectified again. Such power sources provoke significant distortions of the current being consumed; components with the frequency of harmonic three are its weighty share [17]. Emergency of high harmonics effects negatively the performance of power equipment, protection equipment and control relays initiating accelerated insulation aging [18].

Thus, addressing the issue of efficient power utilization within the grids of non-traction railway consumers remains a highly relevant and pressing task. As in similar cases, the foundation for resolving this challenge lies in conducting a thorough evaluation of power quality directly during its transmission and consumption within the grids under consideration. This approach ensures a detailed understanding of the specific conditions and factors influencing power quality, enabling the development of targeted and effective solutions.

The complexity of this problem is multifaceted, encompassing both theoretical and practical dimensions. On the theoretical side, it requires a deep analysis of the mechanisms and processes that affect power quality and efficiency in such systems. On the practical side, it involves implementing appropriate measures and technologies to improve energy utilization while ensuring reliability and compliance with established standards. Given these intricacies, the issue demands a comprehensive and multidisciplinary approach to achieve meaningful and sustainable improvements in power use within these specialized grids.

Since modern measurement techniques (MTs) implement flexible algorithms to process and analyze highly complex experimental data, they provide sufficient measuring accuracy. In this context, both quality control of electromagnetic processes within alternative current circuits and its recording are performed mainly by such portable analyzers as EDL-175xr or PNA-296 manufactured by SATEC Company and based upon a device of energy accounting PM175.

Fig. 6 explains a scheme to measure power quality indices in terms of a modern electrified alternative-current area within TWR line.

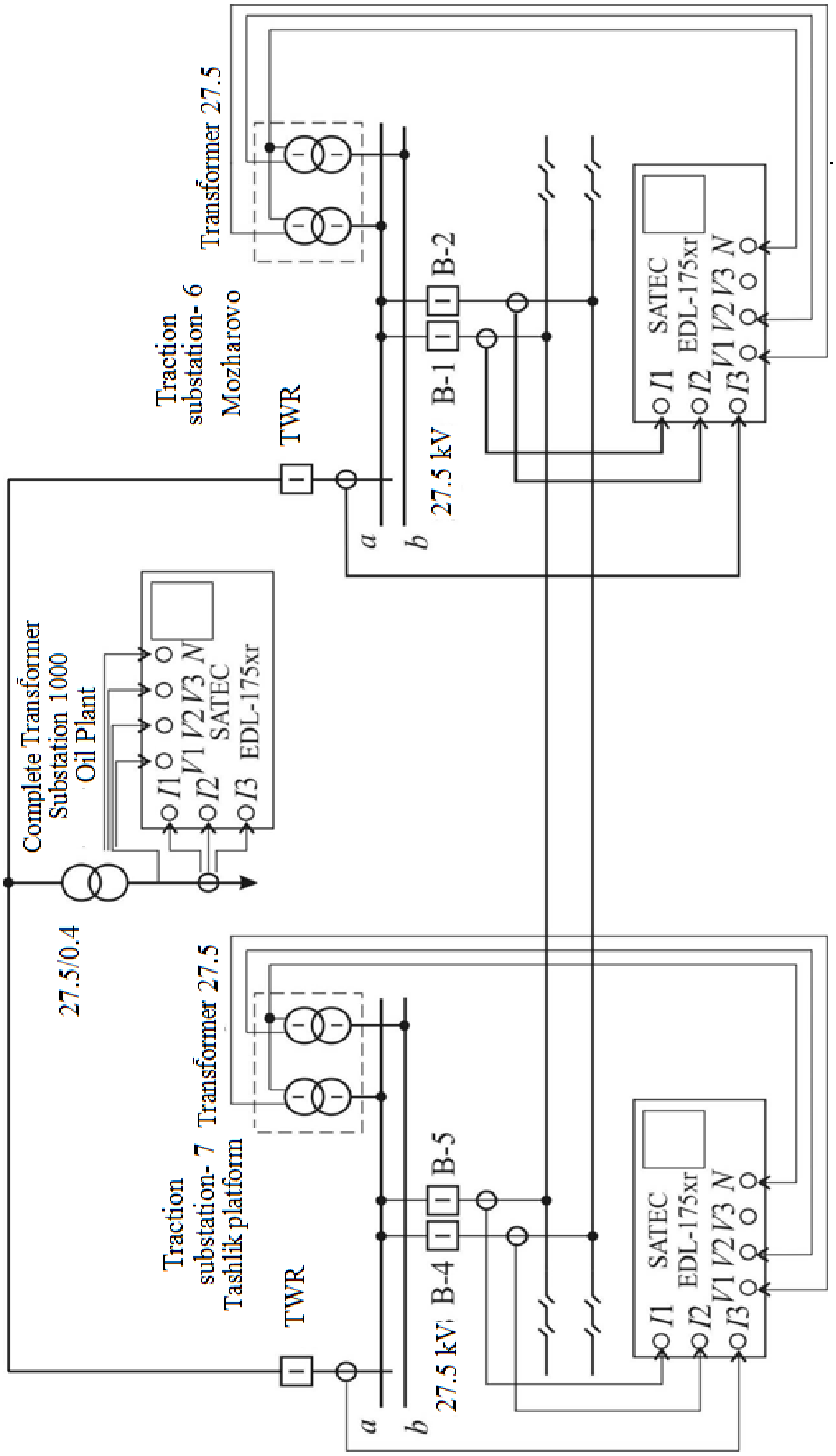


Fig. 6 Measurement plan for industrial object supplied by TWR

It helped evaluate such power quality indices as:

- voltage level and its deviations;
- negative-sequence asymmetry coefficient; and

- harmonic factor of reactive power.

In addition, reactive power coefficient has been evaluated.

As an example, Fig. 7 demonstrates fragments of the indices recording within a line of non-traction TWR consumers with 27.5 kV voltage. Table 4 shows the results of their statistical processing. Lines with 10 and 0.4 kV voltages have also been analyzed similarly.

Analysis of the obtained results, concerning power quality within TWR line, makes it possible to conclude that at large, statistical characteristics of the voltage deviation in 27.5 kV circuit are in the range of the permitted values; they varied insignificantly during the observations.

Voltage asymmetry coefficient on the negative sequence within 27.5 kV buses of traction substations varied from 0 to 3.63%; the value exceeds standard permitted value while remaining within the rated values. As for the voltage waveform distortion factor within buses of the listed substations, it varied from 0 to 10.5% exceeding both standard permitted value and the rated one.

Within 10 kV line, statistical characteristics of voltage deviation are also in the prescribed limit; they varied insignificantly during the observations.

Negative-sequence voltage asymmetry coefficient varied from 0 to 1.58% to be within standard permitted value as well. However, voltage waveform distortion factor varied within greater limits (i.e. 0…14.4%) exceeding all the permissible rates.

At the same time, within 0.4 kV connections K_U coefficient value is 1.4…10.3% exceeding standard permitted value while remaining within the rated value. In this context, the voltage deviation varied from – 2.66% up to + 7.42% exceeding standard permitted values.

Negative-sequence voltage asymmetry within 0.4 kV connections varied significantly (i.e. from 0 to 3.43%); however, standard permitted value was exceeded at some instants.

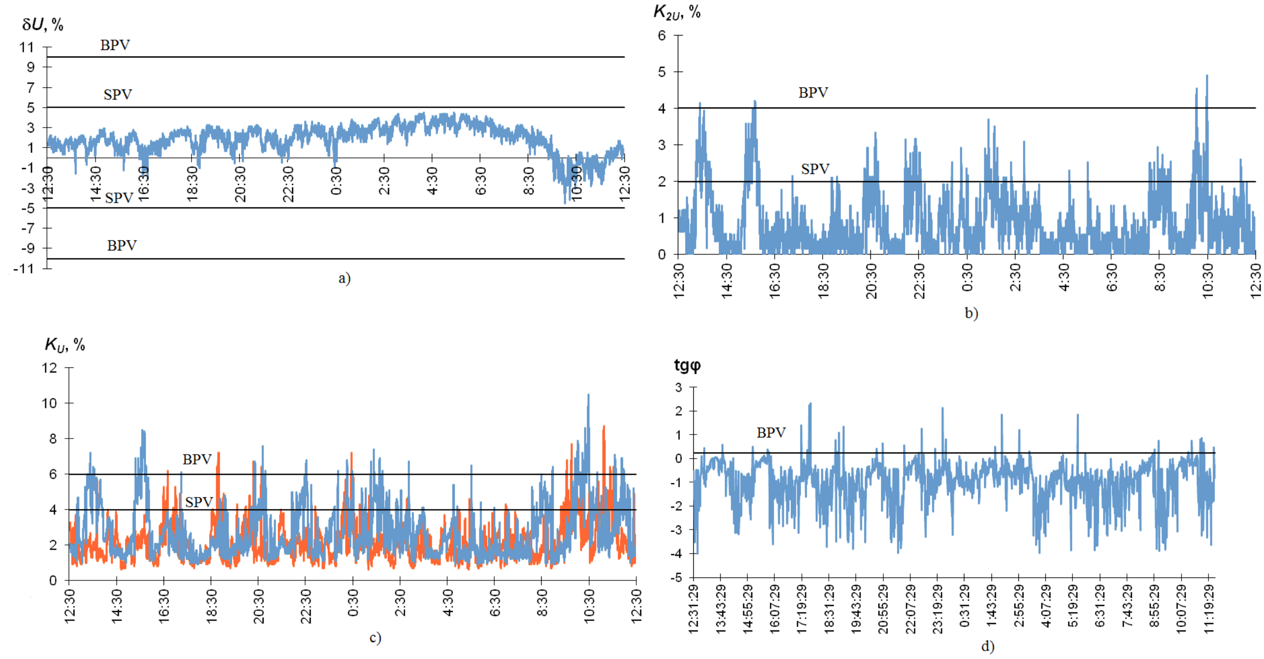


Fig. 7 Changes in power quality indices within 27.5 kV TWR line: a) voltage deviation; b) negative-sequence asymmetry coefficient; c) distortion coefficient of voltage harmonicity; and d) reactive power coefficient

Table 4

Statistical characteristics of power quality indices within 27.5 kV TWR line

Index	***U***			**δ*U***	***K_{2U}*, %**	**K_U, %**			**tgφ**	**K_i, %**
	U_A	**U_B**	**U_C**			**U_A**	**U_B**	**U_C**		
1	2	3	4	5	6	7	8	9	10	11
M	27844.55	28179.63	28016.05	1.86	0.83	2.76	2.14	0.0	-0.97	
Mo	28034.00	28401.00	28122.00	2.61	0.03	1.40	1.20	0.0	0.00	
Me	27938.00	28305.00	28074.00	2.09	0.56	2.30	1.90	0.0	-0.78	
D	208507.75	166606.06	139821.9	1.87	0.588	2.14	1.18	0.0	0.80	

ContinuationTable 4

1	2	3	4	5	6	7	8	9	10	11
S	456.63	408.17	373.93	1.37	0.767	1.46	1.09	0.0	0.89	
As	-0.93	-0.94	-0.89	-0.89	1.41	1.25	1.60	0.0	-0.88	
Ex	1.67	0.87	0.93	0.96	1.93	1.37	3.74	0.0	1.36	
min	25259.00	26393.00	26313.00	-4.50	0.03	0.90	0.60	0.0	-3.99	6.4
max	28799.00	28974.00	28743.00	4.52	4.90	10.50	8.70	0.0	2.35	41.7

It is also interesting to observe changes in reactive power coefficient in the analyzed lines. Thus, in the context of TWR, reactive power is oscillated almost during the whole period. The process may depend upon significant capacitive susceptance of the line under minor load level. In the context of 10 kV, modes of reactive power oscillation and consumption alternate owing to a cycling nature of technological process of the non-traction consumer. Only reactive power was consumed almost during the whole observation period when 0.4 kV was connected. tgφ value exceeds the rated 0.25 level in the context of all voltages being analyzed.

Current distortion coefficient is of specific importance. Current Ukrainian regulations, controlling the problem of power quality provision, consider derivative of voltage power quality indices [18]. However, European countries use IEEE 519-1992 Standard [19] which determines maximum current values of odd harmonics percentagewise to load current. According to the Standard, current waveform distortion factor depends upon the ratio between short-circuit current within common connection point and load current. As a result, if grid is a high-power system (take into consideration the fact that traction substation power is much higher than non-traction load power), then maximum current waveform distortion factor should not be more than 15%. Current of harmonics, which sequence numbers are n<11, should be less than 12% of load current. According to the calculations, current distortion factors within the analyzed lines are quite higher than the normalized ratios. In this context, intervals of current distortion changes are of greater values within TWR line and within 0.4 kV consumers powered by it.

1.4. Enhancing power quality within the context of industrial enterprises: strategies for improvement

1.4.1. Optimizing Power Quality in Industrial Environments: Key Improvement Strategies

Essentially, active filters for three-phase consumers are autonomous converters with a condenser installed in the direct current link. Action of the device is as follows: voltage is redistributed between phases at the expense of energy accumulated within its capacitor element. To do that, control system of converter keys is added by sinusoidal reference signal in each phase and a feedback signal on the current within phases of the supply mains.

Fig. 8 demonstrates the simplified circuit schematic of the device.

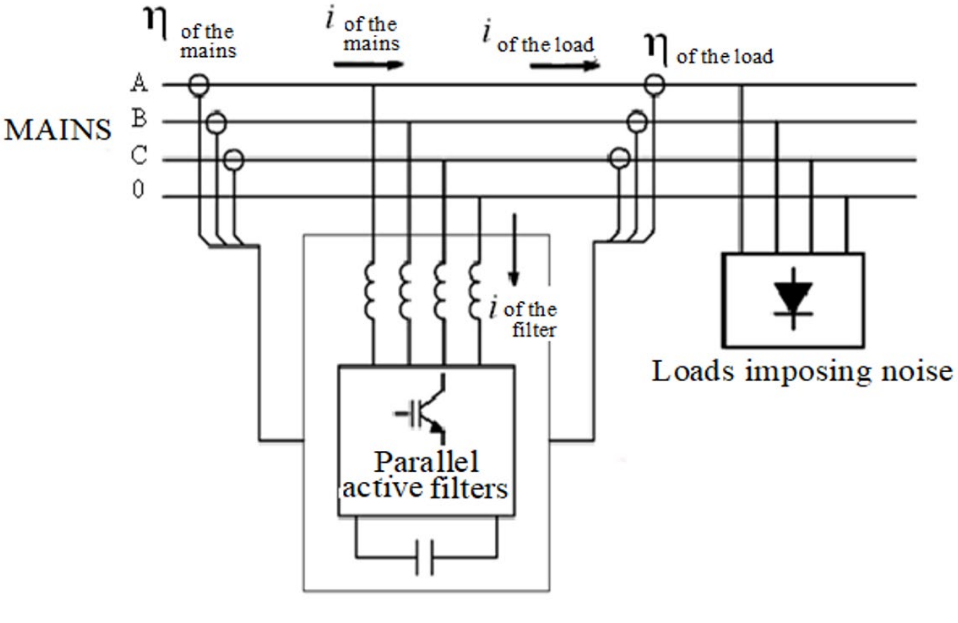


Fig. 8 – Simplified circuit schematic of a power active filter

The following can be considered as absolute advantages of the active filters:

– possibility to be adapted to the current forms of phase voltage curves;

– independence of performance capability of the active filter on the consumer load level;

– compensation of anharmonicity as well as asymmetry of phase voltage;

– capability of the active filter use to compensate distortions of supply voltage by several consumers; and

– correction of consumer power coefficient.

Maybe, high cost is the only disadvantage of the active filters. If it is required to compensate reactive power components (for instance, during start-up), power keys should be selected based on the voltage of the same order as the consumer voltage. The abovementioned makes cost of such a device comparable with frequency converter cost.

Meanwhile, modern frequency converter solves the problems of noisy supply voltage relative to AM; moreover, it offers numerous additional advantages which cannot be provided by an active filter.

They are: smooth start with the controlled current and torque; control of production mechanism speed; implementation of feed-back and protection in terms of operational parameters etc.

Hence, rather often active filters turn out to be a reasonless engineering solution. Integration of active filter functions in the powerful frequency converters is a promising tendency. In such a way it is possible to control simultaneously speed of one of themechanisms and perform “group” correction of the supply voltage.

Passive filters [20] are electrical components typically designed as series and parallel LC-circuits, which are commonly tuned to operate in resonance modes. These filters are widely used in power systems for their ability to mitigate harmonics and improve power quality. Figure 9 illustrates a connection diagram of individual passive LC-filters specifically designed for the protection of asynchronous motors. These filters are strategically placed to ensure the safe and efficient operation of motors by reducing the impact of harmonic distortions and other undesirable voltage or current fluctuations.

One of the most notable advantages of passive filters is their low cost, making them an economical solution for many industrial and commercial applications. In addition to their affordability, passive filters are highly durable and reliable. Once installed, they require minimal to no maintenance, as they are inherently robust and do not involve complex components that are prone to frequent failure. This durability eliminates the need for regular adjustments, servicing, or repairs, which is a significant advantage in environments where operational continuity and cost-efficiency are critical.

As a result of their simplicity, cost-effectiveness, and longevity, passive filters are a practical choice for harmonic filtering and voltage stabilization in a wide range of applications, particularly in scenarios where high reliability and minimal maintenance are prioritized.

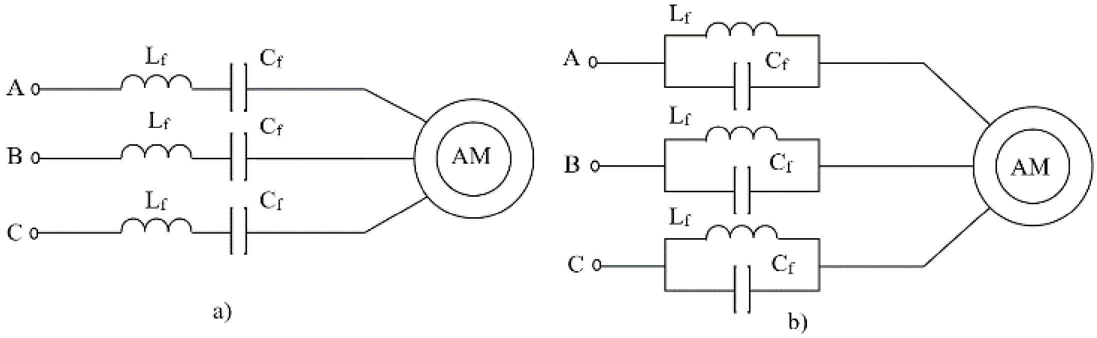


Fig. 9 – Connection diagrams for series (a) and parallel (b) passive LC-filters

The following can be considered as disadvantages of passive filters: impossibility to correct supply voltage asymmetry; and instability of resonance modes for certain filter types due to field-assisted motion of the consumer parameters.

As a whole, efficient use of individual passive filters should involve solution of the problems: selection of a filter type to correct AM input voltage in the best way; determination of the filter parameters (i.e. inductance and capacitance) in terms of which the ideal AM performance is provided; and reaching a compromise between specifications (inductance, capacitance, and component power) and cost of the engineering solution; i.e. make cost-benefit analysis.

Consider the basic methods to improve power quality under the conditions of an enterprise or its workshop [17]. The methods are classified in terms of the quality indices providing by them: asymmetry, distortion of harmonicity etc.

Voltage asymmetry, stipulated by nonuniform distribution between phases of consumers, can be limited down to the rated values with the help of circuitry or by using specific balancer set [20]. The latter helps compensate equivalent current of reverse sequence of asymmetrical load as well as voltage stipulated by it. Individual, sectional, centralized, and combined symmetrization methods are recognized.

Individual balancer sets are installed directly at a consumer. In the context of sectional symmetrization, several considered devices are installed within different points of the mains. Each of the devices is responsible for certain mains area with a group of asymmetrical consumers, connected to it. In the context of the centralized symmetrization, one of such devices is installed within the distribution mains. The combined method is the combination of two or three balancer sets.

Individual method makes it possible to neutralize asymmetry right in the consumer; however, in this context the capacity of power elements of such protective devices is used irrationally. The centralized method needs less capacity of balancer set elements. However, current asymmetry continues within the mains where loads are distributed irregularly. Sectional method combines pluses and minuses of both individual method and the centralized one.

Mainly, symmetrization method selection depends upon the mains parameters and load conditions. Balancing sets can be either uncontrolled or controlled depending on the generation schedule features. There are many circuits of such devices having electric and electromagnetic element connections. Consider some of them. Fig. 10 demonstrates the simplified circuits of balancing sets.

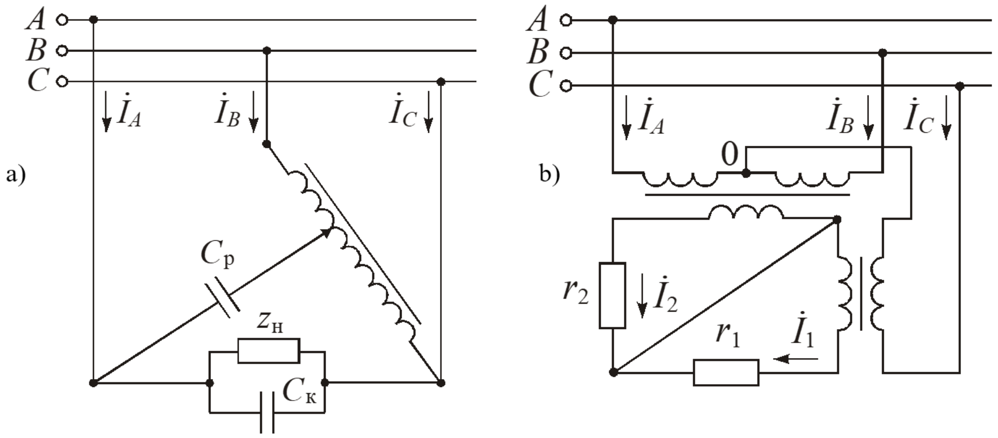


Fig.10 – Simplified circuits of autotransformer (a) and transformer (b) types

Compensating devices are also used [20]. They are higher harmonic filters assembled on the basis of Capacitor Battery (CB) of a balancing set; asymmetrical filters. Fig. 11 demonstrates a simplified circuit schematic of the filter compensating device. Its operating principle is to provide voltage resonance on the frequencies of higher harmonics. In such a way, series LC-chains are short circuits for the latter.

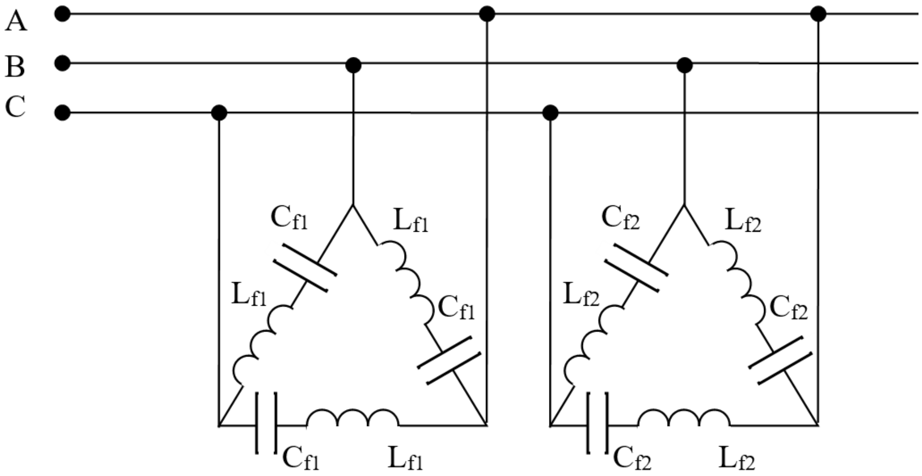


Fig. 11 – Simplified circuit schematic of the filter compensating device

Lowered level of higher harmonics within electric mains is a part of the general problem to minimize the effect of nonlinear loads on supply mains and to improve power quality within the electrical power systems of enterprises. Complex solution of the problem, based upon the use of multifunction devices, turns out to be more expedient economically to compare with, say, measures to improve a shape of line converter current. Resonance filters, called filter compensating devices, are the examples of such multifunction devices. They generate reactive power for supply mains while decreasing the levels of higher harmonics.

In terms of parallel connection of LC circuits, adjusted to frequencies of single harmonics, a chain filter compensating device originates. In such a case, reactive-power shortage on the substation busbars may be compensated with the help of capacitor banks; moreover, 80–90% of the rated condenser power is applied. Hence, filter compensating devices are the simplest and the most economical filters; that has popularized them so much.

1.4.2. Evaluation of the effectiveness of employing existing methods to enhance the energy efficiency of asynchronous motors.

Section II of this chapter (1.1.4) provided a detailed overview of the currently available methods and technologies used to ensure power quality, along with an analysis of their respective advantages and disadvantages. Among the discussed topics, it was highlighted that asymmetry compensation of supply voltage is commonly achieved using symmetrical devices, often referred to as "sectional" methods. These methods involve dividing the electrical load into sections and applying compensation techniques tailored to each. The design and parameter calculation of such symmetrical devices constitute a key challenge in the development and optimization of electric power supply systems.

One of the most complex issues in this domain is the local compensation of frequency variations in the supply mains, as such changes are dynamic and often unpredictable. Despite the difficulty of this task, it is equally important to address the distortion of sinusoidal voltage waveforms, which is a common problem in workshop environments at many domestic enterprises. These distortions are typically caused by the specific characteristics of power loads, such as nonlinear or unbalanced consumption patterns. This issue requires the implementation of specialized equipment, such as individual protection devices for asynchronous motors (AM), to safeguard them against potential damage and performance degradation.

Given these challenges, it becomes necessary to examine in greater depth the specific features of electric drive operations when integrated with devices designed to improve power quality. One effective approach involves the use of individual passive filters, which are particularly suitable for mitigating the effects of harmonic distortions and voltage asymmetries in local grids. These filters can be designed and configured to address the unique requirements of each application, ensuring optimal protection and efficiency for asynchronous motors and other equipment.

In this context, the results of the parameter calculations play a critical role in the development of a comprehensive technique for determining both the type and the specific parameters of the required filters. This includes identifying the most appropriate individual and sectional filters to achieve the desired level of power quality improvement. By applying these calculations, it is possible to tailor the filter designs to the operational characteristics of the target electrical systems, thereby ensuring reliable and efficient performance while minimizing disruptions caused by power quality issues.

Active filters and filter-compensating devices

Section II of this chapter considered pluses and minuses of active filters. Below you can find the illustrated features of operation of the devices under the conditions of noisy power.

Paper [Fujita, H., Yamasaki, T., Akagi H. A hybrid active filter for damping of harmonic resonance in industrial power systems (2000) IEEE Trans. Power Electron. – vol. 15. – no. 2. – Mar. 2000. – pp. 215–222.] describe series-parallel active filters making it possible to compensate partly asymmetry of supply voltage, and high frequency distortions to a greater degree. Fig. 12 demonstrates voltage oscillograms within a workshop main before active filter connection and after it.

Authors of [Fujita, H., Yamasaki, T., Akagi H. A hybrid active filter for damping of harmonic resonance in industrial power systems (2000) IEEE Trans. Power Electron. – vol. 15. – no. 2. – Mar. 2000. – pp. 215–222] mention that the devices, analyzed by them, are efficient to suppress high-frequency interference (7th, 11th harmonics and higher), and compensate some asymmetry degree. That depends upon the limited power amount accumulated with the active filter capacity. As it is seen in Fig. 12, low-order harmonics are still represented in the curves of phase voltage. Moreover, active filters are complex devices which cost is comparable with the converter cost.

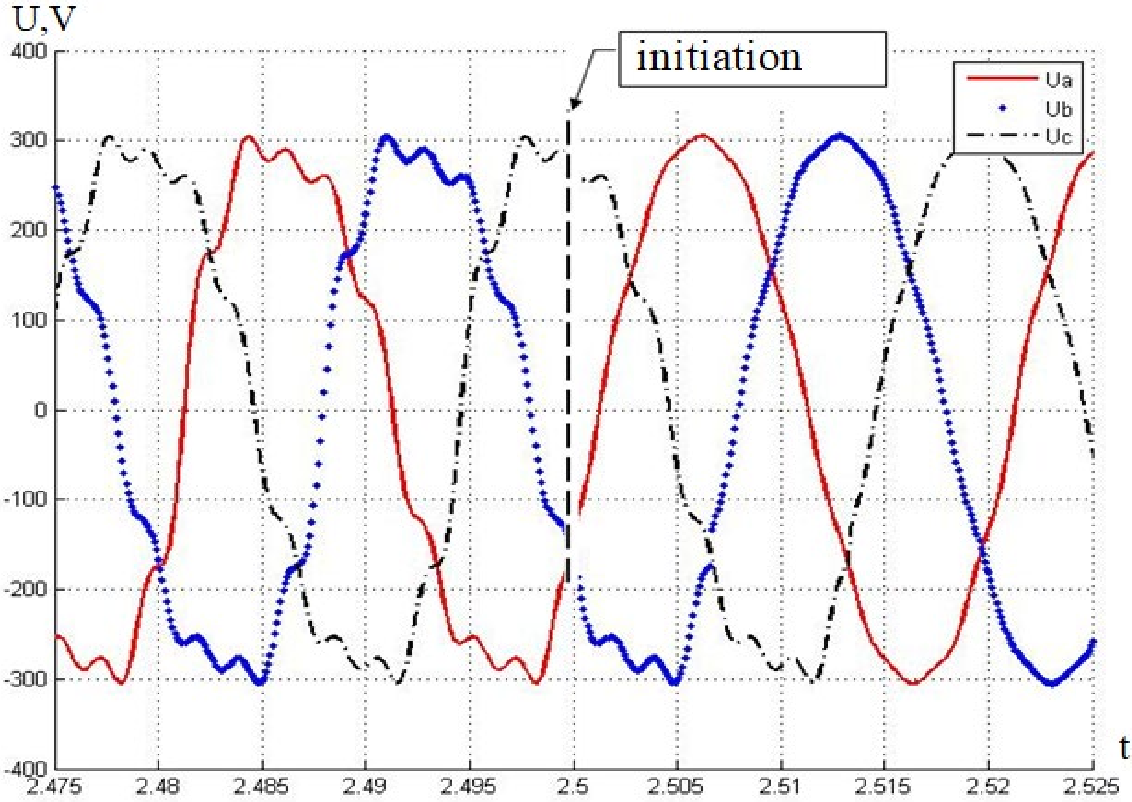


Fig. 12 – Graphs of voltage mains before and after the initiation of an active filter

Filter-compensating devices (FCD) suppress harmonics selectively, and correct asymmetry of supply voltage to a certain degree as it is shown in Fig. 13.

It is impossible to suppress the whole range of spurious harmonics with the help of FCD since each of them needs individual resonance short circuit. Usually, FCDs are adjusted to the harmonics generating the greatest negative impact.

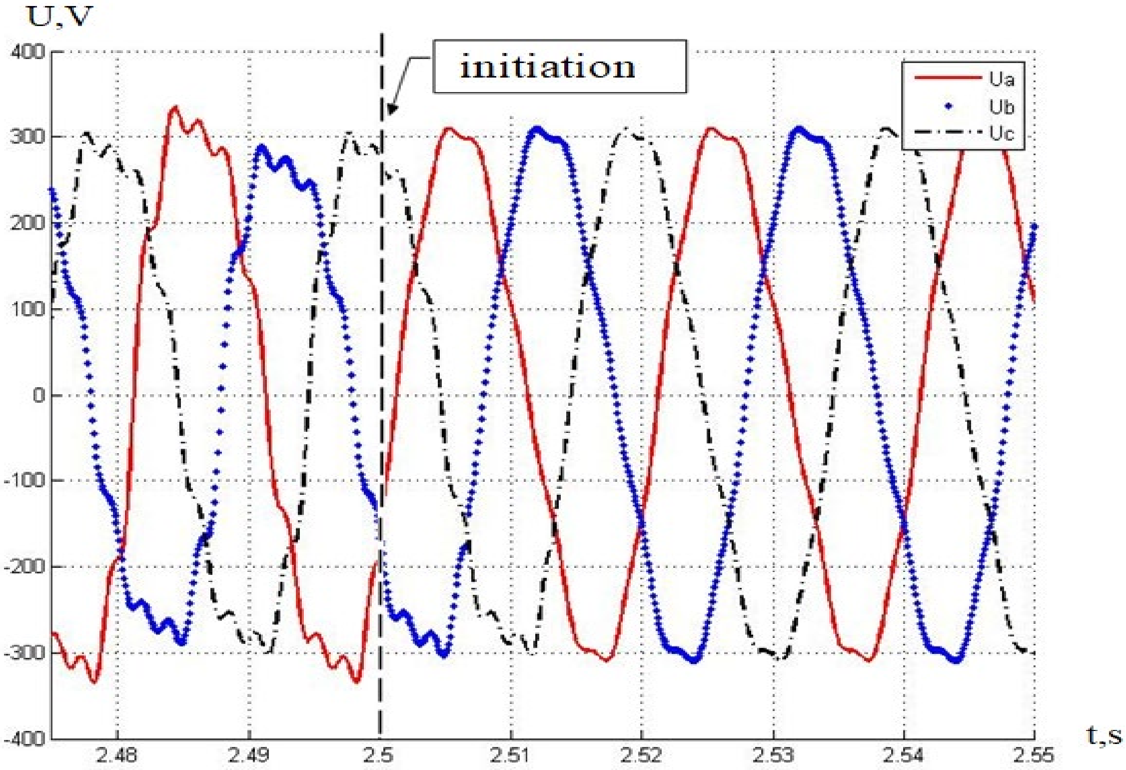


Fig.13 – Graphs of voltage mains before and after the initiation of an active filter-compensating device

Series filters

Increase in the total circuit inductance (i.e. series reactance connection to AM supply voltage) is expedient for higher-order harmonic filtration. However, the process should take into consideration the fact that inductive filter resistance takes place in parallel with a voltage drop value, impacting negatively loading capacity of the motor. At the same time, connection of series LC circuits may help generate resonance voltage and, consequently, minimal resistance for the specified frequency current. Fig. 9a demonstrates such a connection circuit.

Nevertheless, operation of the asynchronous motor integrated into the circuit is not always stable. Resonance mode entry causes the decreased resulting resistance of a filter thus decreasing their voltage drop. Voltage increase within the asynchronous motor terminals factors into the increased stator current and, consequently, into the increased torque factoring into changes in sliding motion. As a result, resulting complex resistance of each phase varies and resonance conditions turn out to be broken. Fig. 14 illustrates the generated unstable operation mode of an asynchronous motor involving series resonance LC filter adjusted to 100 Hz frequency.

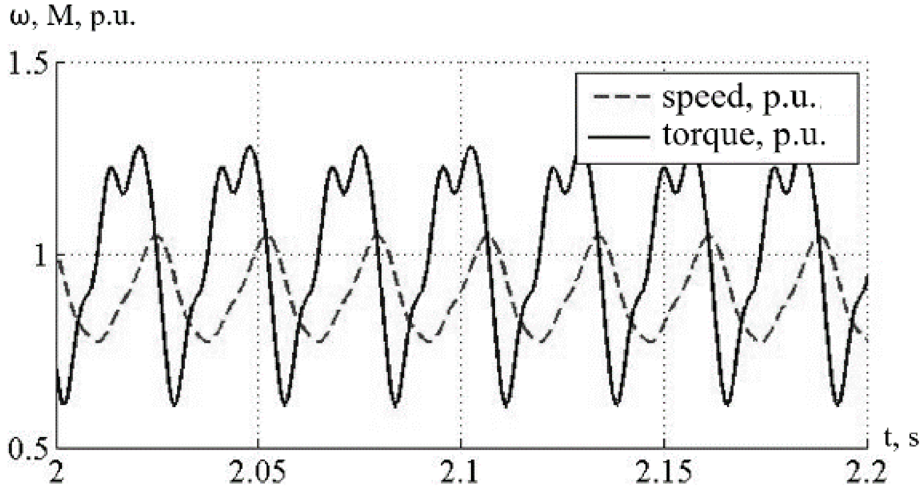


Fig. 14 – Changes in torque and speed of an asynchronous motor with the use of series LC filter

Besides, the mode is dangerous due to potential excess voltage within the AM stator. Hence, the use of series LC filters in terms of the circuit, represented in Fig. 9a, is impractical technically due to the resonance mode instability.

Parallel filters

As it has been demonstrated, 2nd harmonic of supply voltage, which filtration is the priority task, generates the most negative impact on the power indices of AM. Parallel LC filters are the most adequate solution for the problem (Fig. 9b), if they are adjusted to current resonance on 100 Hz frequency. In this context, filter resistance for 2nd harmonic approaches infinity thus opening circuit for it. That is why such filters are often called “traps”.

In practice, selection of filter parameters should involve simultaneously several factors. Technologic implementation of the required inductance and capacity values; and value and nature of resistance introduced by the filters on the basic frequency are the key factors. The parameters also depend upon selection of a harmonic which should be suppressed by the filters. To provide current resonance, the inductance and capacity should be selected relying upon ratio:

$$\omega_r^2 LC = 1,$$

where $\omega_r = 2\pi f_r$ is the resonance angular frequency.

Any inductance-capacity combination, satisfying the equation, will provide the required resonance. However, it is necessary to involve the resulting complex filter resistance first, since efficiency of filter traps will vary depending upon different L-C combinations. Cost of components (i.e. inductance and capacity), providing resonance effects, is also important.

Fig. 15 demonstrates changes in a complex resistance of the resonance trap filter adjusted to 100 Hz frequency, if capacity varies within 1 µF-10 mF (technically implementable capacity values). The graphs are represented logarithmically. In terms of 2nd harmonic (100 Hz), resistance of ideal filter traps is equal to infinity; thus, the Figure does not show it.

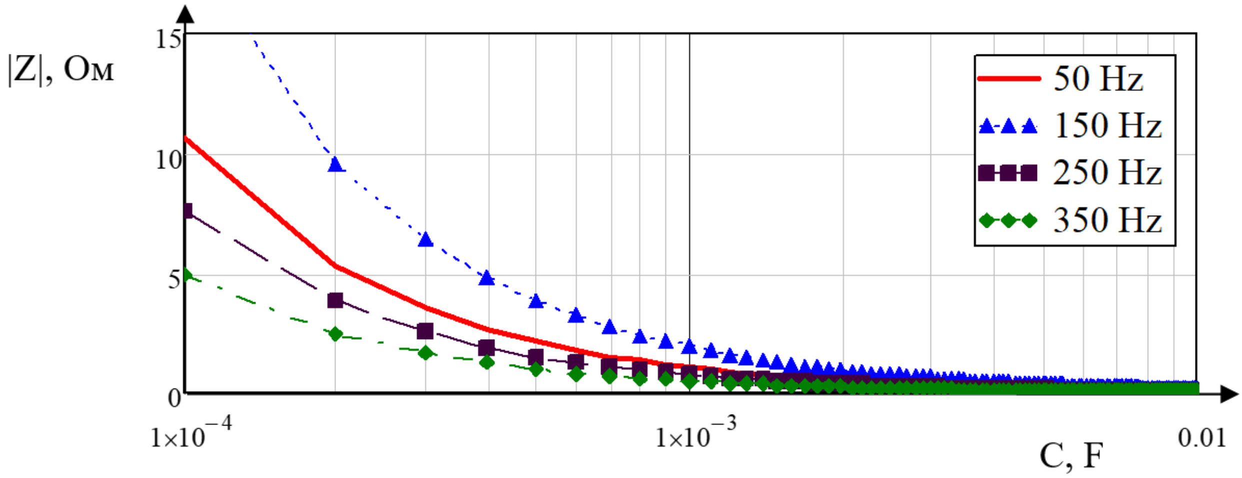


Fig. 15 – Dependences of resulting resistances of the resonant filter trap upon the capacity value for different higher harmonics

Analysis of graphs in Fig. 15 explains that capacity increase results in rapid decrease in the trap filter for the basic frequency. It is understood that use of the filters which input resistance is dozens of Ohm on the basic frequency is inadmissible due to significant voltage decrease.

Thus, almost 100 µF (10^{-4} F) value should be a lower capacity boundary restricting input resistant value at the level of Ohm units. Upper capacity boundary is identified with the help of the filter efficiency in terms of integral power criterion and economic criterion.

To provide current resonance inside 2nd harmonic, 25-0.5 mH inductance should be selected in terms of capacity changes within a certain small range to identify the value. In this context, resulting filter resistance will be 10-0.1 Ohm.

Modeling [38] has helped verify efficiency of the filter traps which parameters were selected as mentioned above. Fig. 16 demonstrates voltage graphs without the filter and with it; values are L=25 mH and C=100 μF if 2nd harmonic prevails in the supply voltage.

As it is seen, a curve shape of the phase voltage "evens out" in this context at the expense of 2nd harmonic suppression. Fig. 17 shows AM stator current with the filter and without it.

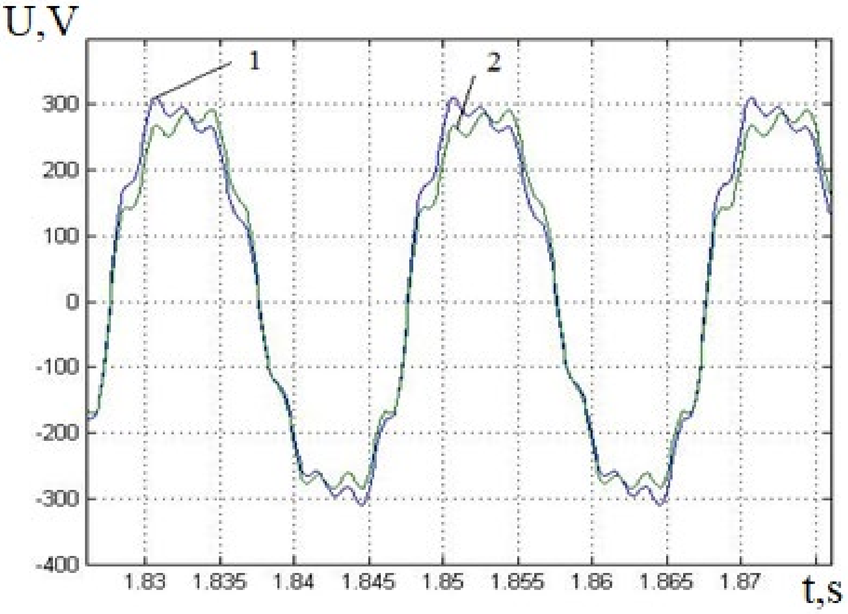


Fig. 16 – AM phase supply 7.5 kW power without a parallel trap filter (1) and with it (2)

Thus, the filter traps may be applied as the independent means to improve power quality during the operation of asynchronous motors.

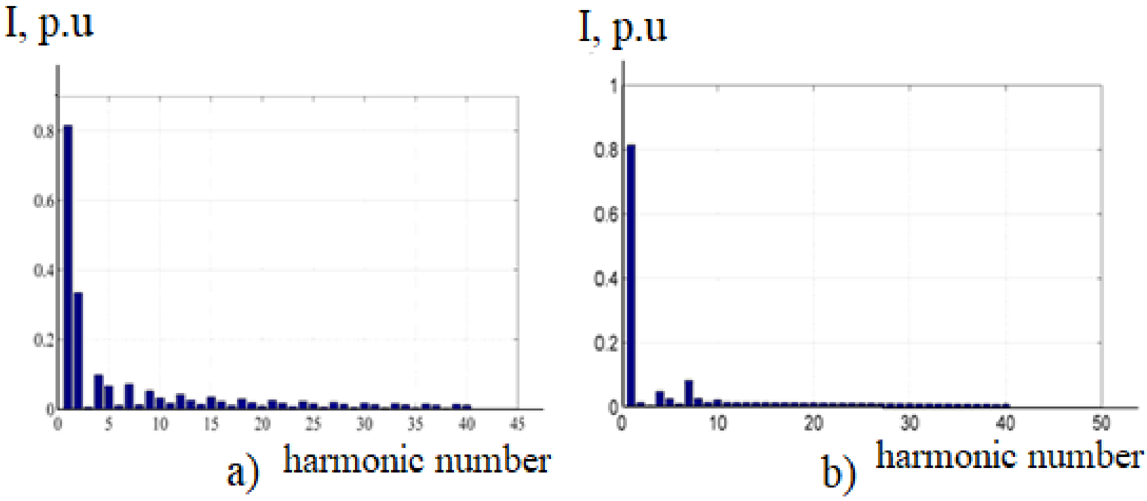


Fig. 17 – Range of stator current in the process of AM supply without a filter (a) and with a trap filter (b) adjusted to 100 Hz resonance

Combined filters

It goes without saying that filter efficiency may be improved by means of combination of circuits matching up various approaches to suppress supply voltage harmonics. The circuit, represented in Fig. 18, is one of them being applied currently to filter output voltage of frequency converters.

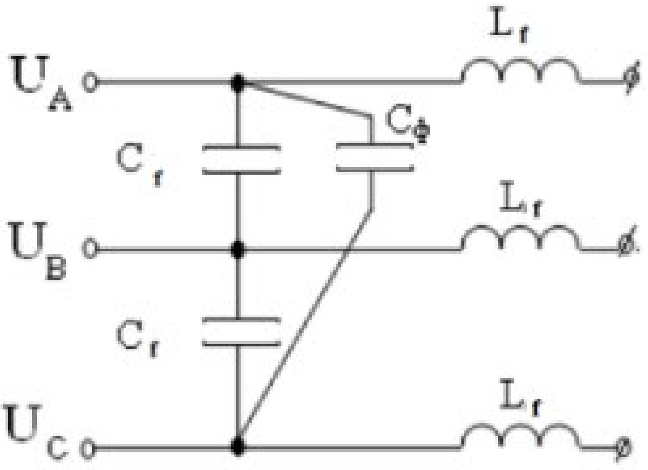


Figure 18 – LC filter applied in output of frequency converters

Capacities, being a part of such filters, are low resistant for impulse fronts of output stages. As a result, supervoltage levels decrease within a system with a long cable; intensity of electromagnetic interference, generated by a converter, drops etc. At the same time, the series connected on-load inductances are the restricting resistance for high-frequency current. We believe that nonavailability of resonance is the circuit disadvantage.

Consider possible circuits of the combined resonance filters, and evaluate their efficiency. Below you can find only their components, corresponding to one phase. The procedure will simplify the circuit implementation. A circuit, shown in Fig. 19, may be applied as the simplest resonance filter.

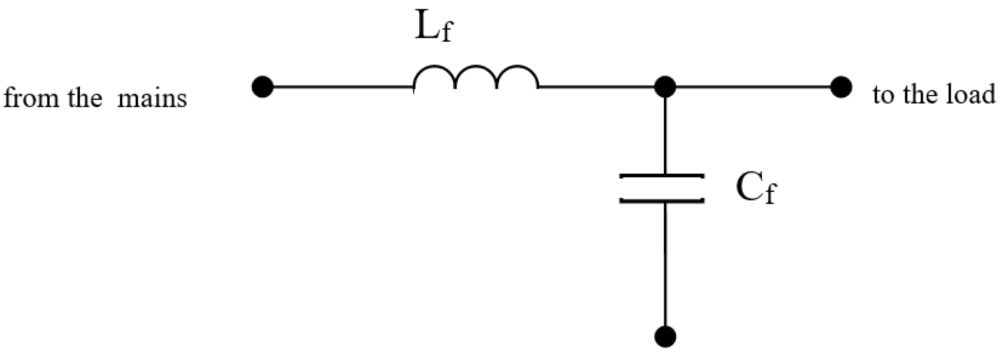


Fig. 19 – L-shaped resonance first-order LC filter

To compare with the traditional circuit of filter compensating devices, in this case inductance is connected in parallel with load. In such a way, higher harmonics are limited.

Taking into consideration the fact that here we can find resonance short circuit for one of the higher harmonics from the mains, the filter helps suppress that of them, corresponding to resonance frequency, and to restrict other significantly.

Paper [Wu, W., He, Y. and Blaabjerg, F. “An LLCL power filter for single-phase grid-tied inverter” (2012) IEEE Transactions on Power Electronics 27(2), pp.782-789] represent second-order series-parallel filter which circuit is shown in Fig. 20. Two resonance circuits are implemented in it.

The researchers tried to identify such combination of the filter parameters in terms of which the circuit is of maximum resistance on the frequency of spurious harmonics, and of minimum one on the basic frequency.

The activities are performed simultaneously with the consideration of all parameters – L_f inductance, and C_{f1} and C_{f2} capacities. Active resistance plays a role of a trimming element. Unfortunately, implementation of the filter is complicated due to conflicting requirements for the total voltage drop on it, and parameters of the components.

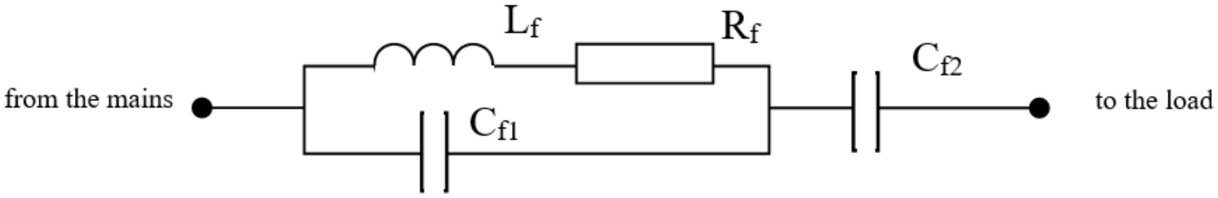


Figure 20 – Second-order series-parallel filter

1.4.3. Studies concerning parameter selection and efficiency of the proposed means to improve AM energy performance

It is more expedient to use circuits shown in Fig. 21. The filter, implemented in such a manner, is a combination of a rejecting device connected in series with load to provide current resonance on the frequency of one of higher harmonics, and a secondary member (capacity of inductance) to provide short circuit for another harmonic.

The two possible filter structures differ in the type of a member, connected to load in parallel. Selection of one or another structure depends upon selection of resonance frequencies for the blocking filter component f_1 providing current resonance to "trap" one of the harmonics, and f_2 component for a "phase-zero point" circuit providing voltage resonance and, hence, short circuit for another harmonic.

All the filter parameters (i.e. resonance frequencies; branch resistances on different frequencies; and complex resistance on the basic frequency) are interconnected. They are determined using its inductance-capacity combination. Suppose the filter part series-connected with a load as a "filter trap"; when a "mains-zero point" current flow circuit (i.e. current flow through the whole filter) is meant, then resistance of the combined filter is discussed.

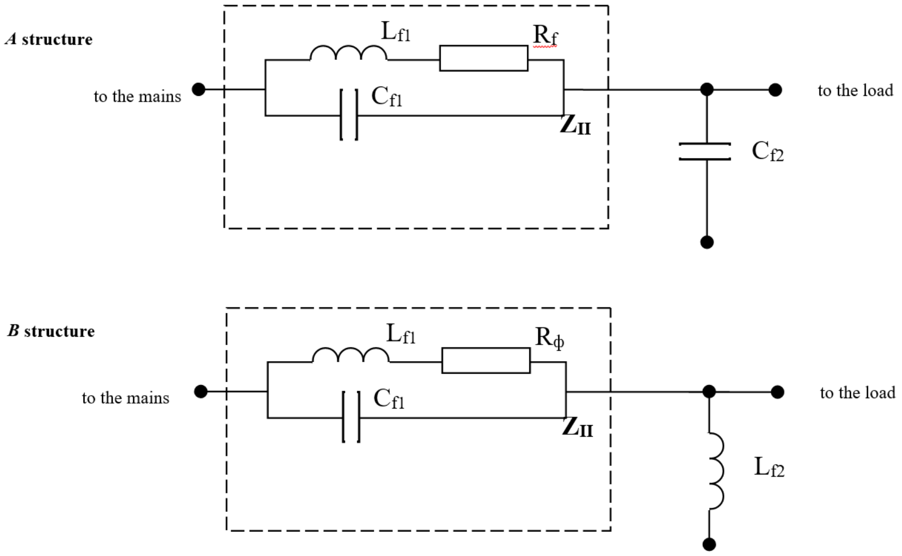


Fig. 21 – Proposed alternations to implement the combined second-order L-shaped LC filter

Hence, formulate optimization problem relying upon simultaneous fulfillment of the conditions:

- current resonance on the undesirable spurious harmonic within a circuit, series on load (trap filter);
- voltage resonance of the combined filter on the frequency of one of spurious harmonics; selection and substantiation of the voltage resonance frequency;
- trap filter resistance should be minimal one on 50 Hz frequency;
- inductive nature of the trap filter resistance should be provided;
- voltage frequency of the combined filter on the required frequency of one of the spurious harmonics;
- to compensate reactive power within the mains, nature of the combined filter should be capacitive one; and
- technical operability of the filter parameters.

Total filter resistance in terms of *A* circuit can be calculated as a resistance of series-connected "trap" and C_{f2} capacitor. In this context, dependence of complex resistance upon frequency is:

$$Z_{\Sigma}(\omega)=\frac{R_f\omega^2L_{f1}^2}{R_f^2+\left(\omega L_{f1}-\frac{1}{\omega C_{f1}^2}\right)^2}+j\left[\frac{\omega L_{f1}R_F^2+\frac{L_{f1}}{\omega C_{f1}^2}}{R_F^2+\left(\omega L_{\phi}-\frac{1}{\omega C_{f1}^2}\right)^2}-\frac{1}{\omega C_{f2}}\right],$$

where ω is the angular frequency of supply voltage.

In terms of B circuit, the dependence is:

$$Z_{\Sigma}(\omega)=\frac{R_F\omega^2L_{f1}^2}{R_F^2+\left(\omega L_{f1}-\frac{1}{\omega C_{f1}^2}\right)^2}+j\frac{\omega L_{f1}R_F^2+\frac{L_{f1}}{\omega C_{f1}^2}+\omega L_{f2}}{R_F^2+\left(\omega L_{f1}-\frac{1}{\omega C_{f1}^2}\right)^2}.$$

The total resistance of the combined filter and is a function of several variables. It is of interest to analyze its frequency characteristics, dependence upon frequency to which current resonance of the trap filter is adjusted, and L_f, C_{f1}, C_{f2} parameters of the filter. It is impossible to represent graphically functions of three variables; hence, analyze the dependence in terms of sections.

Figure 21 illustrates the dependences of resistances introduced by the trap filter into the circuit in series under varying frequency conditions. The chart provides a detailed representation of how the trap filter behaves across different resonance frequencies, with each line in the graph corresponding to a specific resonance frequency setting. This visual representation enables a comprehensive understanding of the filter's operational characteristics and its impact on the circuit.

The analysis of these dependences reveals an important relationship: as the frequency to which the current resonance is adjusted increases, the resistance introduced by the trap filter into the consumer supply circuit at the standard frequency of 50 Hz decreases. This observation underscores the inverse relationship between the resonance frequency adjustment and the resistance effect at the fundamental supply frequency.

Such insights are critical for designing and optimizing trap filters in practical applications. By carefully selecting the resonance frequency, it is possible to minimize the resistance introduced into the supply circuit at 50 Hz, thereby ensuring efficient and stable operation of the electrical system while maintaining the desired level of harmonic suppression or filtering at higher frequencies. This balance is essential for achieving both power quality and system efficiency in various industrial and commercial settings.

Hence, the trap filter adjustment to current resonance on 100 Hz frequency is inexpedient; it is more preferable to use adjustment to higher harmonics (i.e. 5th, 7th, 11th etc.) since in this context filter resistance on the basic frequencies is Ohm units. 2nd harmonic should be suppressed with the help of short circuit.

Voltage drop on the trap filter is determined by means of resulting resistance as well as by means of consumer current. Thus, the higher consumer voltage is, the resonance frequency greater should be, which the trap filter is adjusted to.

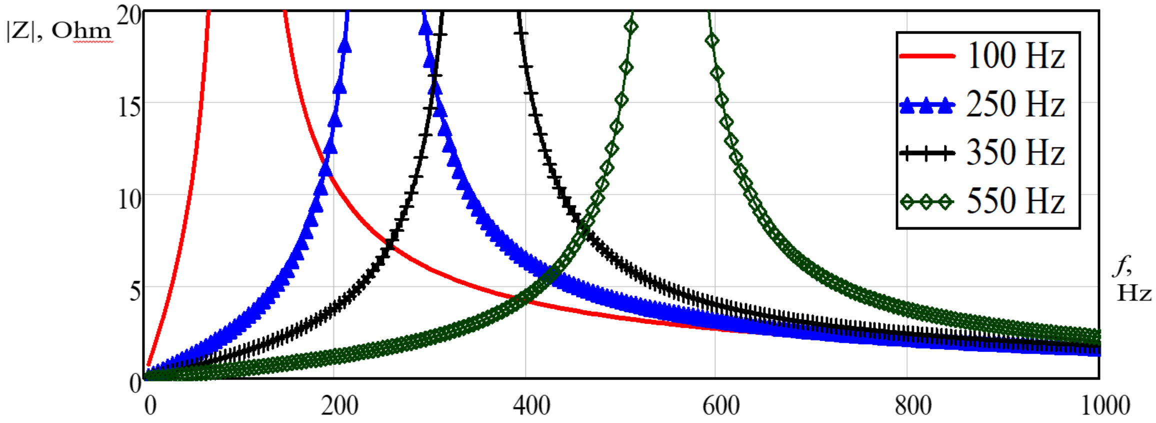


Fig. 21 – Dependence of the trap filter resistance at a frequency of 50 Hz on the frequency to which the current resonance is tuned

Determine the best combination of resonance frequencies of the combined filter. Specify a cycle in terms of which consider all possible combinations of f_1-f_2 frequencies. Calculate resistances of the filter members for each combination; simulate the steady conditions to evaluate electric drive efficiency taking into consideration filter availability in terms of a circuit in Fig. 20.

It should b noted that if $f_1 > f_2$, it is required to select *A* structure; otherwise, *B* structure is selected. That is connected with a condition of the specific nature of resulting resistance of the trap filter.

Fig. 22 shows efficiency dependence upon the resonance frequencies f_1 and f_2, being 3D surface (a) and its projection within the frequency plane (b).

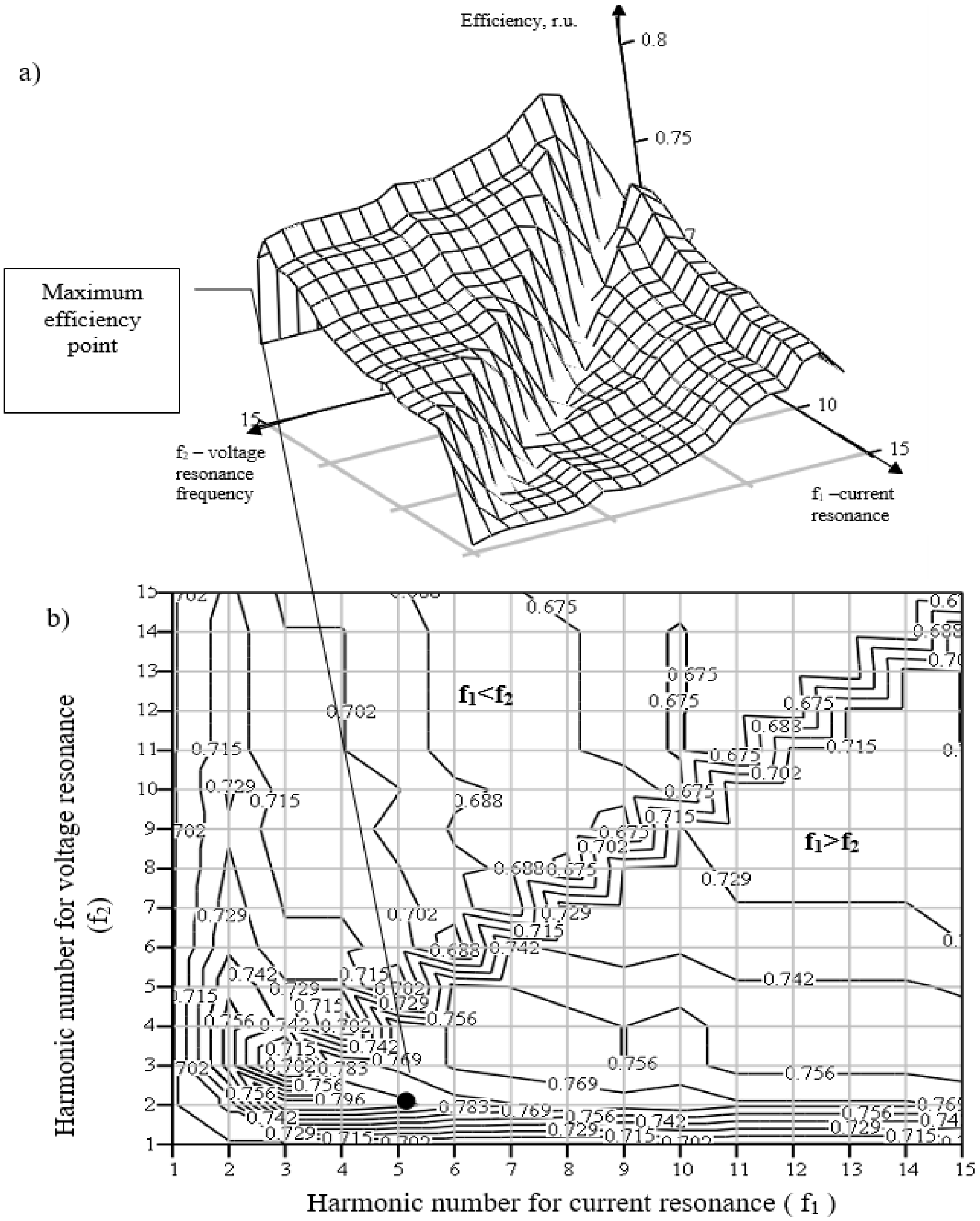


Fig. 22 – Dependence of the efficiency of an asynchronous motor with the combined filter upon resonance harmonics (a); its projection (b)

Analysis of the represented surface demonstrates that the resultant efficiency of an electric motor is greater when current resonance is higher to compare with the voltage resonance frequency $f_1>f_2$.

It depends on the fact that if trap filter is adjusted to certain frequency f_1, this filter share is the inductive resistance for all harmonics, which frequencies are less than f_1. Consequently, extra decrease in loss, stipulated by supply voltage distortion, takes place.

Hence, the highest efficiency of the system is obtained if voltage resonance is adjusted to the 2nd harmonic frequency (f_2=100 Hz). It is required to select the frequency, to which current resonance is adjusted, relying upon specific nature of quality indices under the conditions of the definite workshop.

It has been identified that in the context of cases, considered in chapter one, 500 Hz frequency is the most expedient one.

Thus, iterative approach may help determine such a ratio of parameters of the combined L-shaped filter, in terms of which high resistance on the frequency of one of spurious higher harmonics is introduced into supply circuit of AM; along with it, interphase short circuit is developed for one of the harmonics (say, on 100 Hz frequency).

The abovementioned should take into consideration actual coat of the filter components depending upon the desired adjustment. Their prices have to be used.

Fig. 23 demonstrates current of earlier asynchronous motor with 7.5 kW capacity, operating under the conditions of noisy power when the combined filter is connected to it.

The parameters have been calculated according to the represented technique. Analysis of the graphs supports the idea that significant decrease in harmonic component level has been achieved.

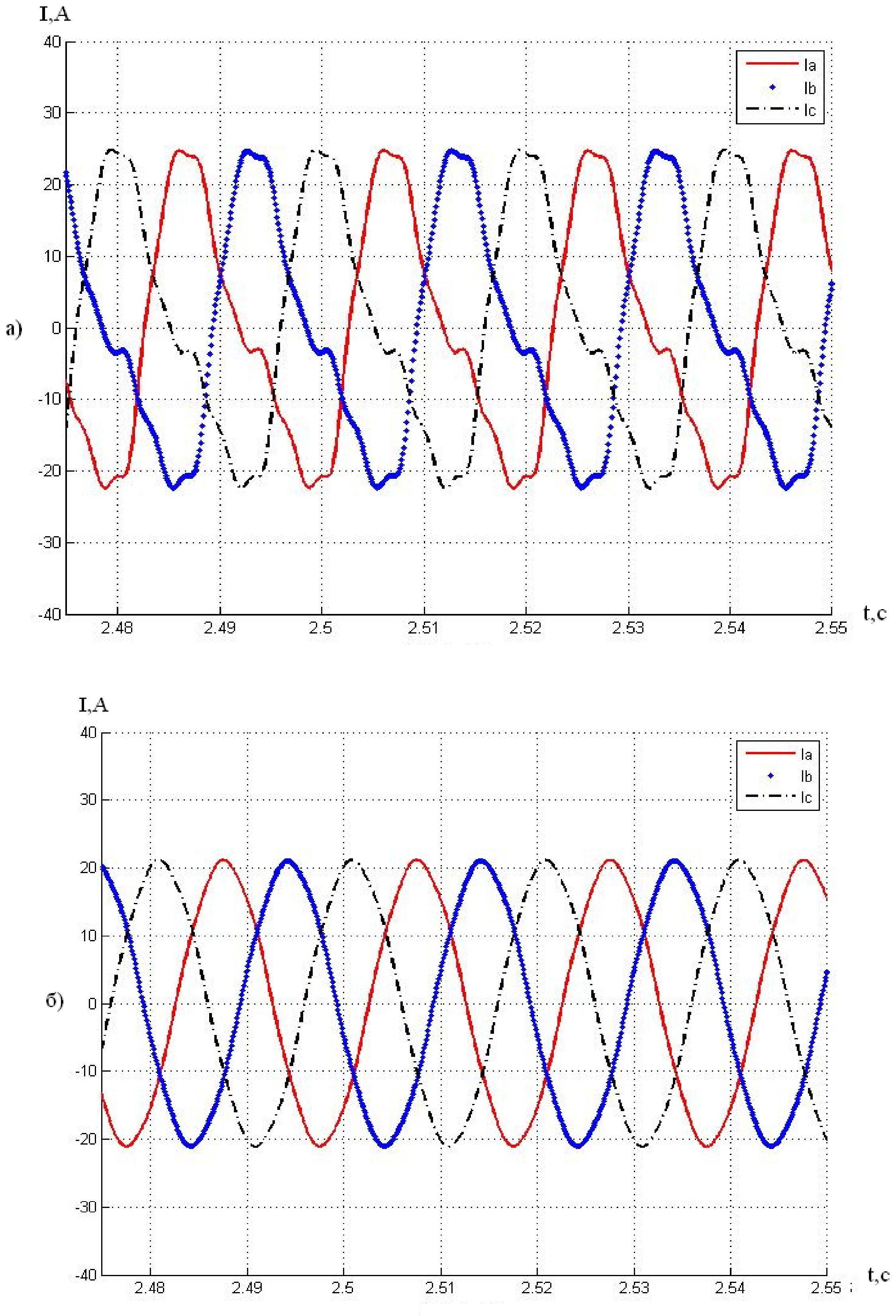


Fig. 23 – Current of an asynchronous motor (7.5 kW), operating under the conditions of noisy electricity: a) without filter; b) after the combined filter connection

Efficiency of the proposed technique has also been verified by computations of all-purpose electric motors with 7.5 to 250 kW capacity, operating under the conditions of noisy electricity. Histograms in Figures 24 and 25 represent the basic power indices, involving nonavailability/availability of input combined filter in terms of circuit shown in Fig. 9 (a).

Analysis of the modeling results shows the filter efficiency (i.e. relative changes in power parameters are inversely related to the specified capacity of the electric motors). That is connected with less sensitivity of high-capacity motors to the supply voltage distortions.

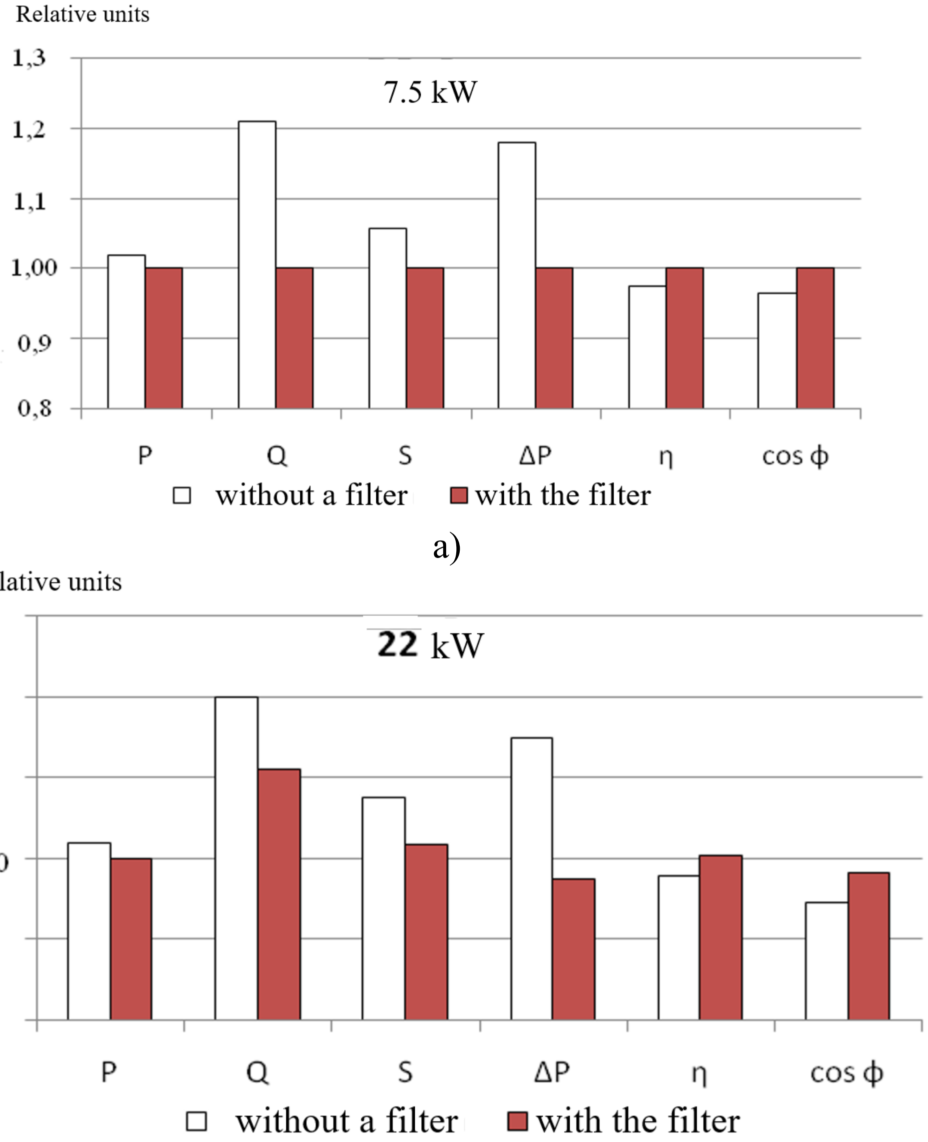
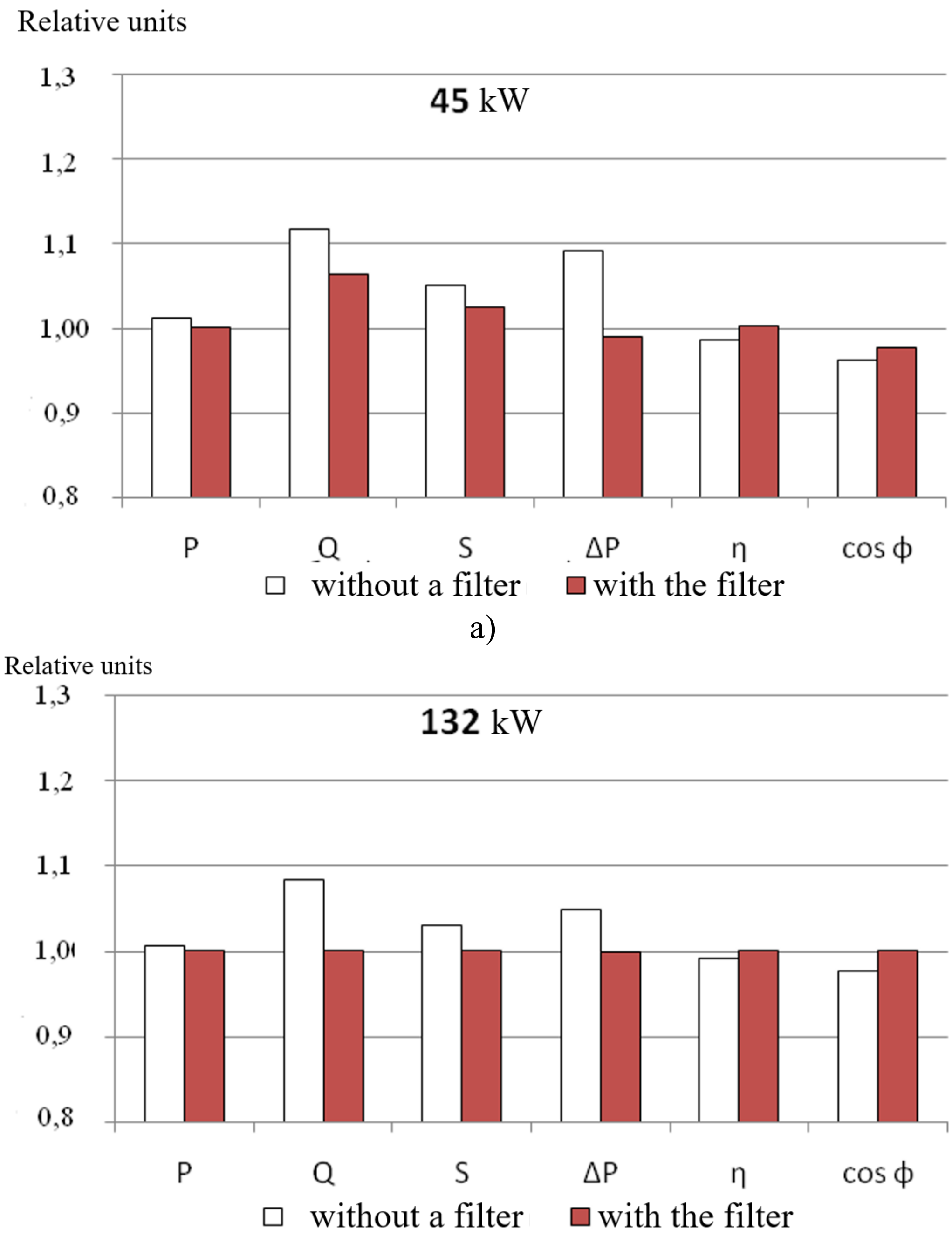


Figure 24 – The basic power indices of motors with 7.5 kW capacity (a), and 22 kW capacity (b) in terms of availability/nonavailability of input combined filter



a)

b)

Figure 25 – The basic power indices of motors with 45 kW capacity (a), and 132 kW capacity (b) in terms of availability/nonavailability of input combined filter

It should be noted that although the proposed filter options have been studied in relation to the operation of an induction motor with a power of 7.5 kW, there are no fundamental restrictions for their use, for example, for asynchronous motors with a power of 45 kW.

In section II of this chapter, it was noted that passive filters, in contrast to active ones, have a low cost compared to the cost of an induction motor. However, the final decision on the use of a particular filter or refusal from it is a difficult task, depending on many technical and economic factors and should be made based on the results of computational studies on a simulation energy-economic model of an induction motor.

1. To improve efficiency of asynchronous motors, operating within the mains with noisy electricity, it is expedient to apply the combined filter being a series-connected trap (stopper) in each phase, and star-connected capacities.

2. The highest efficiency of electric motor equipped with such a filter, being a series-connected trap (stopper) in each phase, and star-connected capacities, is achieved when the trap is adjusted to current resonance on 100 Hz frequency and 500 Hz voltage resonance.

3. Passive combined filters are the most expedient ones for small- and average-capacity electric motors (up to 45 kW).

4. The developed method, described in the chapter, makes it possible to adjust parameters of AM power efficiency improvement for the specific operation conditions.

Conclusions on chapter 1.

The studies, carried out at industrial enterprises, helped conclude: power quality of many Ukrainian enterprises does not correspond to GOST. Distortions, stipulated by operation of semiconductor converters, saturation of transformer cores etc., are available within workshop power systems. If current waveform distortion factor meets the requirements of GOST, significant excess in coefficients of harmonic components of supply voltage is observed. Thus, the latter is more preferable to be used while analyzing energy efficiency of AMs operating under substandard supply. It has been determined experimentally that input power differs from that in the enterprise workshops. Thus, one and the same suppliers, locating in different workshops, have unlike power efficiency depending upon PQ deviations thus involving individual approach to solve the problem of their protection.

Results of the carried out studies, concerning power quality indices within supply lines of non-traction railway consumers, has helped determine that the problem of electricity quality provision in the context of the cases is more topical in view of the changes taking place in the load nature. Special attention should be paid to the solution of that problem for departmental industrial enterprises since they are characterized by a number of equipment which performance depends significantly upon power quality.

Results of the research mean that reactive power compensation at the enterprises has its own specific character at each voltage level which should be taken into consideration while elaborating measures intended to improve power quality. Indices of the latter, defined by national regulations, cannot meet enforceable standards, and have spread in statistical characteristics. As for the current waveform distortion factor, specified by International Standards, it also excesses permissible values. As a result, the problem of power quality improvement within supply lines of non-traction networks is a more complex one; its solution should involve efforts aimed at power efficiency increase as well as at power supply reliability support and decreased losses within power lines [20].

Based on the foregoing, the further area of research of the authors is the task of clarifying the assessment of the economic damage caused by low-quality electricity in the power supply systems of industrial enterprises. This is due to the following reasons:

1. Practice shows that the majority of enterprises are observed exceeding the permissible levels of at least one of the standardized indicators of the quality of electricity. At the same time, while the integral indicators of symmetry and sinusoidality are normal, the coefficients of individual harmonic components significantly exceed the maximum permissible values.

2. At the same levels of power quality indicators, the spectral composition of the voltage can vary significantly, since it is determined by the type of power consumers that distort the voltage and their mode of operation.

3. According to traditional approaches to assessing economic damage, the latter is taken to be zero in the case when the deviations of the power quality indicators do not exceed the normally permissible values [21].

4. There is no methodology for a comprehensive assessment of economic damage,

which correctly takes into account all its components (an increase in the level of heating losses, a decrease in the life of insulation, etc.), as well as the non-stationarity of indicators of the quality of electricity in time [21].

The above circumstances lead to the fact that the enterprise either does not take measures to reduce the negative impact of low-quality electricity, or erroneous decisions are made (installation of ineffective devices, devices of overpriced or insufficient power, etc.). This causes additional damage to the enterprise, reducing the technical and economic indicators of production. Thus, first of all, a toolkit is needed to quantify the negative impact of low-quality electricity on the systems of electricity consumers.

First of all, it is required to develop a model of the electric network, which makes it possible to predict changes in the indicators of the quality of electricity in the latter. The data obtained using the model will serve as input data for assessing additional costs for electricity when operating electricity consumers in conditions of low-quality electricity.

It should be noted that the problem of the negative impact of low-quality electricity is complex, affecting the reliability of electrical equipment, the development of measures to ensure its uninterrupted operation throughout the entire standard service life. Therefore, when considering such issues, it is necessary to establish the dependence of the level of heat losses on the indicators of the quality of electricity.

All the above aspects of the operation of electrical consumers in these conditions should be combined in one approach, developing an energy-economic model that allows researchers and industrial personnel to make informed decisions regarding measures to improve the energy efficiency of electrical equipment.

CHAPTER 2
MODELING OF THE “ELECTRIC MAIN – ELECTRIC CONSUMER” SYSTEM

2.1. Statement of a problem concerning workshop power grid modeling

Noisy electric energy within workshop power grids of industrial enterprises results in accelerated physical ageing of electrical facilities as well as in the increased risk of emergency situations. Early evaluation of power quality indices and provision of adequate modes of electric equipment operation under specific conditions is essential research and practice problem.

The problem solution involves a number of experiments under the conditions of different power quality indices, different modes of electric equipment operation, and different means to protect the latter from noisy power. However, such experiments carried out in the context of a real object would result in: significant time consumption because of the necessity to wait for such situations when energy within power grids corresponds to the required quality indices without mentioning losses of electric equipment life; financial expenditures due to the necessity to purchase various high-priced devices to protect the electric facilities and to rehabilitate electric energy within the grids; and accident threat due to the decreased reliability indices of electric facilities operating under the considered conditions.

Computational studies, based upon the development of simulation system as well as upon statistical tests by computers, helps accelerate and simplify considerably the process of the experiments [22]. The method differs from standard experimental ones in the fact that simulation model, implemented by a computer, is analyzed rather than the object itself. In this context, interaction with the former is performed just as it was done with a prototype system and simulation results are processed and tested in such a way as if they were data of full-scale experiments [23].

As for the development of generation of random changes in linear voltage within power grid of a workshop, it is independent problem to be considered separately in this chapter. It assumes the definition: structures of generator of the random changes;

statistical regularities of the latter; and, as a consequence, parameters of the generator being synthesized.

2.2. Developing a structure of the generator of random voltage changes within electric grids of an enterprise

Direct simulation of linear voltage within an electrical grid characterized by noisy electricity presents a significant challenge due to the inherent complexities of harmonic components. In such grids, all harmonic components maintain fixed frequencies of their oscillations, which are determined by the physical characteristics of the system and the nature of the electrical loads. However, random variations in their amplitudes and initial phases are superimposed on these harmonic components, introducing a stochastic element to the overall voltage waveform. These random variations make it difficult to model the voltage directly in its entirety, as the interplay between fixed frequencies and random factors adds layers of complexity to the simulation process.

Given this context, it becomes apparent that a more effective and efficient approach to simulation lies in generating the amplitudes and initial phases of the harmonic components directly, rather than attempting to simulate the entire random voltage sequence. By focusing on these specific parameters, the model can account for the essential stochastic characteristics of the grid while simplifying the overall computational requirements. This approach enables the development of more accurate and manageable simulation models that can provide valuable insights into the behavior of the system under different conditions.

To implement this method, it is first necessary to obtain the statistical regularities governing the changes in the amplitudes and initial phases of the harmonic components. These statistical properties must be derived through detailed analysis of real-world data, capturing the patterns and probabilities associated with the random variations observed in the grid. Once these statistical regularities are established, they can be used to generate synthetic amplitudes and phases for the harmonic components in the simulation, ensuring that the model reflects the true nature of the system's stochastic behavior.

By adopting this targeted approach, the simulation process becomes not only more practical but also more robust, as it isolates and focuses on the key variables that influence the noisy characteristics of the grid. This strategy allows for a more precise representation of the system, facilitating better analysis and understanding of its performance. Additionally, it provides a solid foundation for developing control and mitigation strategies aimed at improving power quality and reliability within the grid, particularly in environments where noisy electricity is a common challenge. Ultimately, this approach highlights the importance of leveraging statistical analysis and focused modeling techniques to overcome the complexities associated with simulating linear voltage in noisy electrical grids [24].

Fig. 26 represents one of the potential variations of the generator of random changes in linear voltages taking into consideration the mentioned above [25].

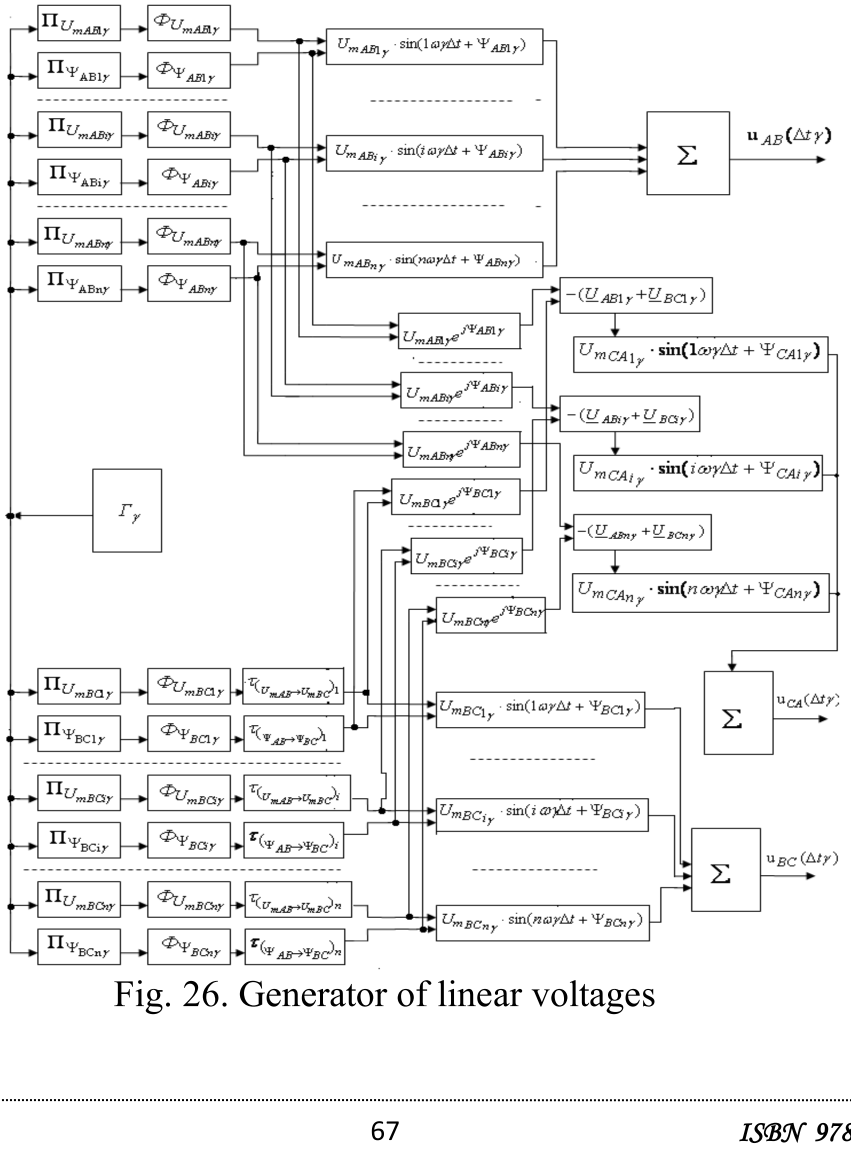


Fig. 26. Generator of linear voltages

In this context, Γ_γ is generator of “white” noise (i.e. values of uniformly distributed uncorrelated random value corresponding to time moments Δt_γ within 0;1 interval); $\Pi_{U_{mABi\gamma}}$, and $\Pi_{U_{mBCi\gamma}}$ are converters of amplitude distribution laws $i=\overline{1,n}$ – harmonics of linear voltages U_{mAB} and U_{mBC} respectively; $\Pi_{\Psi_{ABi\gamma}}$, and $\Pi_{\Psi_{BCi\gamma}}$ are converters of the initial phase distribution laws $i=\overline{1,n}$ – harmonics of the listed voltages U_{AB} , and U_{BC}; $\varPhi_{U_{mABi\gamma}}$, and $\varPhi_{U_{mBCi\gamma}}$ are filters generating the correlated amplitudes of harmonics of linear voltages U_{AB} , and U_{BC} respectively; $\varPhi_{\Psi_{ABi\gamma}}$, and $\varPhi_{\Psi_{BCi\gamma}}$ are filters generating the correlated initial phases of harmonics of the same voltages; $\tau_{(U_{mAB} \to U_{mBC})i}$ is amplitude shift of i^{th} harmonic of linear voltage U_{BC} relative to linear voltage U_{AB} along the τ axis being determined on their cross-correlation function; and $\tau_{(\Psi_{AB} \to \Psi_{BC})i}$ is a shift of the initial phase of i^{th} harmonic of linear voltage U_{BC} relative to the initial phase of i^{th} harmonic of linear voltage U_{AB} along the τ axis being determined on their cross-correlation function.

According to random changes in amplitudes (U_{mABi}, U_{mBCi}, U_{mCAi}), and initial phases ($\psi_{ABi}, \psi_{BCi}, \psi_{CAi}$) of harmonic components of linear voltages, simulated in such a way, their instantaneous values are determined. Then the latter are added algebraically in summators forming random sequences $u_{AB}(\Delta t\gamma)$, $u_{BC}(\Delta t\gamma)$, and $u_{CA}(\Delta t\gamma)$.

As it is seen from Fig. 26, initial random process, being a random uncorrelated value, distributed on uniform laws within [0;1] interval, is simulated by corresponding generator. There are different techniques to obtain it; however, to all practical purposes, program method to generate pseudorandom sequences (PRS) is the most convenient in this context. In their software, the current computers have built-in function to generate PRSs helping them solve the majority of problems of signal simulation.

$\Pi_{U_{mABi\gamma}}$, $\Pi_{U_{mBCi\gamma}}$, and $\Pi_{\Psi_{ABi\gamma}}$, $\Pi_{\Psi_{BCi\gamma}}$ units transform initial random signal to those uncorrelated ones predetermined distribution laws. Selection of the most efficient signal depends upon the type of the laws. Nonlinear transformation methods (i.e. inverse function), piecewise-linear approximation of distribution law, and a method of elimination (by Neumann) are mostly used to perform the operation [26].

Generating filters $\Phi_{U_{mABi\gamma}}$, $\Phi_{U_{mBCi\gamma}}$, $\Phi_{\Psi_{ABi\gamma}}$, and $\Phi_{\Psi_{BCi\gamma}}$ transform uncorrelated random sequences with the predetermined distribution laws into the correlated ones according to autocorrelation functions of the considered values. Nonrecursive filtration of input sequence is one of the most popular transformation techniques [26,27]:

$$y_n = \sum_{k=0}^{N} S_k x_{n-k}, \tag{1}$$

where $\mathrm{M}[y_n] = 0$, and

$$\mathrm{M}[y_n y_k] = \begin{cases} \mathrm{K}_{n-k,} |n-k| \le \mathrm{N}; \\ 0, |n-k| > \mathrm{N}, \end{cases}$$

where y_n is output correlated sequence, x_n is input uncorrelated sequence, S_k are coefficients, K_{n-k} is a value of correlation function within $(n-k)\Delta$ point, and M is expectation symbol.

Random change in linear voltage U_{BC} results from its cross-correlation function with U_{AB} voltage. The simplest technique to solve the problem is in PRS generation with the prescribed type of a correlation function, and its corresponding time interval delay. The fact can explain availability of $\tau_{(U_{mAB} \to U_{mBC})i}$ and $\tau_{(\Psi_{AB} \to \Psi_{BC})i}$ units within the structural circuit [26]. Instantaneous value of linear voltage $u_{CA}(t)$ is determined according to the known ratio:

$$\underline{U}_{CA} = -(\underline{U}_{AB} + \underline{U}_{BC}). \tag{2}$$

It is clear that (2) dependence use will result in the formation of systematic error since values of linear voltage $\underline{U}_{CA}$ will not correspond to a distribution law being typical for it. It is possible to eliminate the error while implementing randomly selected sequence (i.e. randomization) of linear voltage generation.

2.3. Determining statistical regularities of linear voltages within a workshop power grid

As stated above, the use of statistical modeling technique to simulate linear voltages within a workshop power grid with the help of a computer, involves availability of information concerning statistical regularities of values being modeled.

Obtaining of the latter is connected with the analysis of random processes, i.e. time functions which can be obtained on the basis of passive industrial experiments.

Currently, the required data are recorded by means of digital controlling devices generating random sequence with Δt discreteness from a continuous signal.

Such a transformation may result in so-called frequency masking and, as a consequence, in the distortion of the signal statistical characteristics.

Hence, to avoid the masking errors, initial signal should be passed through low-frequency filter while linear voltage recording in the context of a certain workshop.

Parameters of the filter are selected basing upon following assumptions. If the recordable analogue linear voltages should be digitalized for their further analysis (for instance, over a range of $f_{min}= 0 - f_{max} = 2000$ Hz), then filter frequency is to be determined in accordance with [28] expression:

$$f_{nf} = \frac{f_{\max}}{0.8} = \frac{2000}{0.8} = 2500\ Hz. \tag{3}$$

Hence, the required discreteness interval Δt is:

$$\Delta t = \frac{1}{2 f_{nf}} = \frac{1}{2 \times 2500} = 2 \times 10^{-4}\ s. \tag{4}$$

While quantizing the analogous signal on a level, it is required to provide its ratio to mean-square noise intensity being no less than 80 dB (i.e.10^4 on amplitude). That can be achieved, if following condition is fulfilled:

$$\frac{2^n}{0.289} = 10^4, \tag{5}$$

where n is the number of bits per one counting.

While taking the base-10 logarithm of both sides of the equation, we obtain $0.301n = 3.46$, i.e. $n = 11.5$. Thus, 12 is the number of bits required to quantize analogue signal per one counting. Among all the available industrial detectors, such a device as *SCPED* (i.e. a system to control parameters of electric drives) by RPE *Center for Electromechanical Diagnostics* Ltd transforms analogue signal with the prescribed signal/noise ratio.

During industrial experiment, carried out in the context of rolling plant 1 of *Dneprospetsstal* OJSC (Zaporozhie), implementations of random sequences of linear voltages with 22...24 hour duration were obtained. Fig. 27 demonstrates their fragments. Initial stage of such random sequences should determine their classification.

The procedure makes it possible to identify the process kind (i.e. steady-flow or transient one); its type (i.e. additive, multiplicative, or additive-multiplicative one); as well as a type of a deterministic component (i.e. linear, exponential, repetitive, or repetitive extinction process).

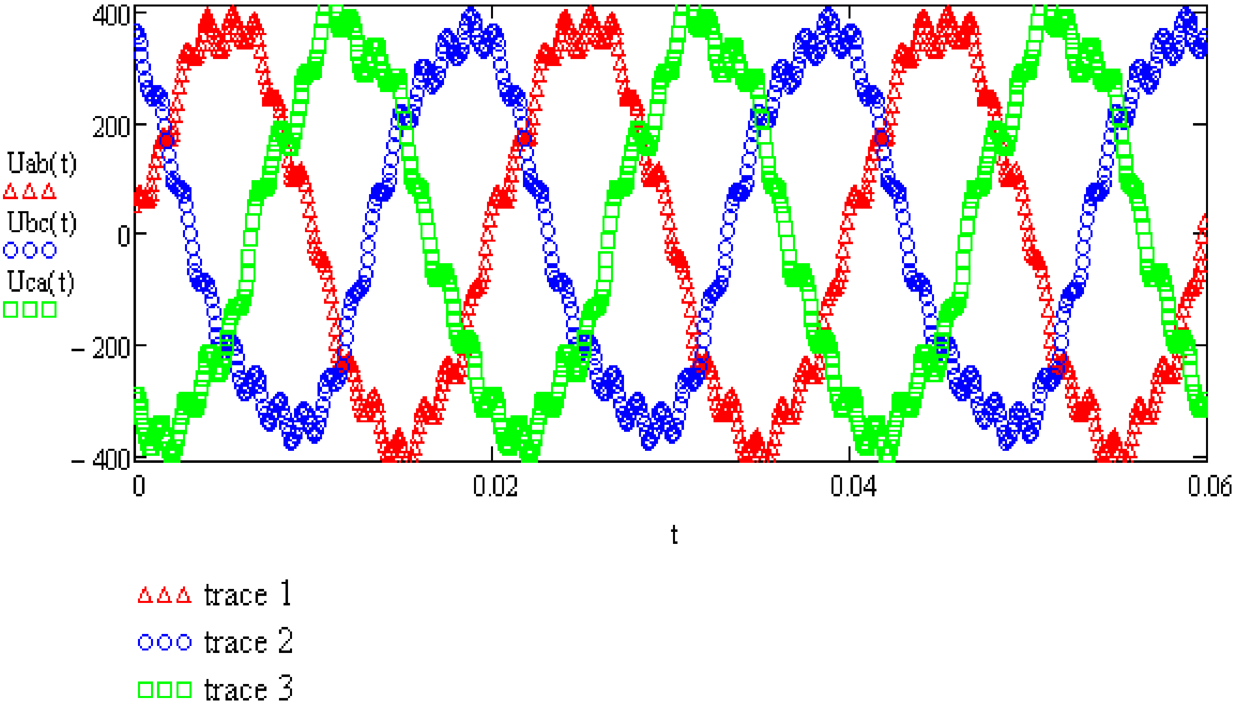


Fig. 27 A fragment of linear voltages u_{AB}, u_{BC}, and u_{CA} within power grid of rolling plant 1 of *Dneprospetsstal* OJSC (Zaporozhie)

Initial stage of such random sequences should determine their classification. The procedure makes it possible to identify the process kind (i.e. steady-flow or transient one); its type (i.e. additive, multiplicative, or additive-multiplicative one); as well as a type of a deterministic component (i.e. linear, exponential, repetitive, or repetitive extinction process).

Correct classification determines broadly reasonableness of further statistical processing; as a rule, it is identified according to a scheme represented in Fig. 28. In this context: ME is mathematical expectation; SFRP and TRP are steady-flow and transient random processes respectively; and CF is correlation function.

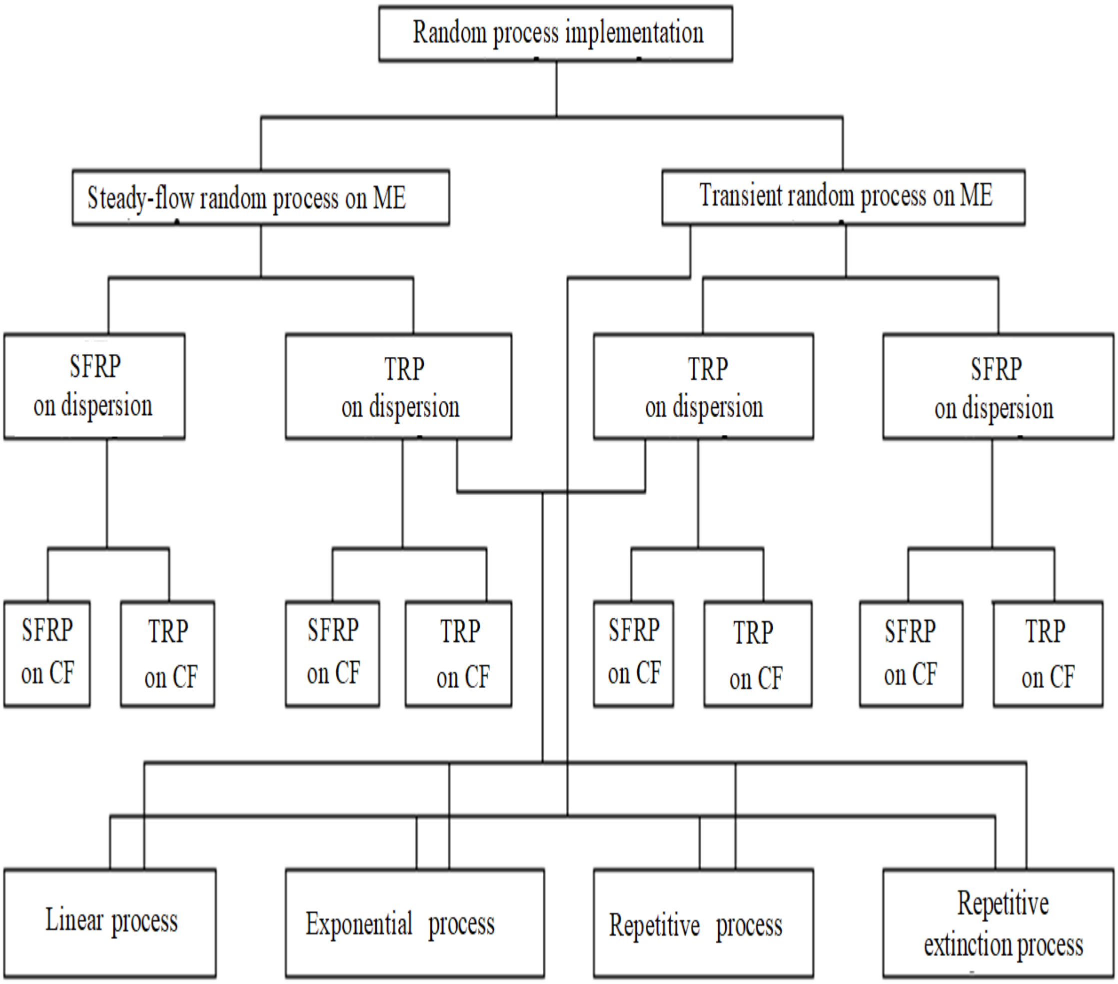


Fig. 28. Classification of random processes

It is common knowledge that linear voltages are polyharmonic sequence being a full amount of repetitive signals which frequencies are divisible by ω=314 rad/s. Taking into consideration the fact that the harmonic signal components, which frequencies are higher than harmonic six, effect electric consumer operation nonessentially [24]; hence, it is proposed not to involve them for further analysis.

It is quite understood (Fig. 27) that the linear voltages, generated in the process of the passive industrial implementation experiment, are transient ones. Thus, beforehand each implementation was visually divided into steady-flow sections (i.e. certain temporal fragments with invariant signal format). Each of the fragments was enumerated in the order of time increasing.

The enumerated random sequences were tested on the steady state of the average according to inversion criterion [28]. Taking into consideration the fact that the latter is parametric, its application does not involve any preliminary determination of distribution laws for random values and their parameters. To accept zero hypothesis that there are no average drift, it is quite sufficient to use following inequality:

$$[\xi / \sigma_{\xi}^{2}] < \Xi(\frac{1+v_0}{2}), \qquad (6)$$

where ξ is test statistic; σ_{ξ}^{2} is statistic dispersion ξ; Ξ is critical value of a zero hypothesis criterion; v_0 is probability of the assumed zero hypothesis, if it is valid (confidence probability).

ξ and σ_{ξ}^{2} values are calculated on the formulas:

$$\xi = 1 - \frac{4 \cdot \Omega_И}{\Omega_C \cdot (\Omega_C - 1)}, \qquad (7)$$

$$\sigma_{\xi}^{2} = \frac{2 \cdot (2 \cdot \Omega_C - 5)}{9 \cdot \Omega_C \cdot (\Omega_C - 1)}, \qquad (8)$$

where $\Omega_И$ is the total number of inversions; and Ω_C is the number of averages within the sequence under study.

The tests results have specified steady-state sections of random sequences resulting from the industrial experiment. Amplitudes of harmonic components of linear voltages within the steady-state stations as well as their phases were considered as invariant ones.

Generally, analytical expressions of distribution laws to describe the linear voltages, being studied, are selected basing upon the problem root. Specifically, simultaneous operating electrical facilities effect parameters of harmonic components of linear voltages. Moreover, effect of each of them is random one. If there are more than six simultaneous operating electrical facilities, it is quite proper thing to suggest a hypothesis concerning normality of distribution of amplitudes and phases of harmonic components in the context of each steady-state section of random implementations basing upon central limit theorem of probability theory. The hypothesis has been tested according to Shapiro-Wilk normality test [29]. Parameters of distribution laws are summarized in Tables 5-7.

Table 5

Numerical characteristics of harmonics of linear voltage U_{AB}

Harmonic	Frequency, rad/s	Amplitude, V		Phase, degrees	
		Average	Dispersion	Average	Dispersion
1	314	529.82	19.11	-	-
2	628	4.23	1.42	63	112
3	942	17.60	9.35	206	68
4	1256	1.51	0.06	92	85
5	1570	18.54	8.29	130	214
6	1884	3.05	0.27	290	152

Table 6

Numerical characteristics of harmonics of linear voltage U_{BC}

Harmonic	Frequency, rad/s	Amplitude, V		Phase, degrees	
		Average	Dispersion	Average	Dispersion
1	314	532.09	17.36	-	-
2	628	3.98	1.56	78	102
1	2	3	4	5	6
3	942	19.13	8.19	235	49
4	1256	1.55	0.06	111	106
5	1570	16.77	6.44	114	210
6	1884	4.15	1.11	325	138

Table 7

Numerical characteristics of harmonics of linear voltage U_{CA}

Harmonic	Frequency, rad/s	Amplitude, V		Phase, degrees	
		Average	Dispersion	Average	Dispersion
1	314	530.41	17.28	-	-
2	628	3.71	1.25	94	96
3	942	18.27	7.14	182	78
4	1256	1.50	0.06	83	56
5	1570	16.01	7.66	165	183
6	1884	3.82	0.53	310	240

It should be also meant that changes in amplitudes of harmonic components of linear voltages as well as in their phases take place at random time intervals. Analysis of numerical characteristics of the time intervals as well as further tests of several hypotheses concerning distribution laws (normal, exponential, and uniform one) according to Pearson criterion have demonstrated that their description should accept a hypothesis on exponential distribution law with $\Delta T_{cp} = 18$ min average value and $\lambda = 1/\Delta T_{cp} = 1/18$ min^{-1} intensity:

$$f(\Delta T) = \frac{1}{18} e^{-\frac{1}{18}\cdot\Delta T}. \qquad (9)$$

To identify correlation ratio between amplitudes (phases) of harmonics of linear voltages of the same frequency, both autocorrelation functions and cross-correlation ones were calculated. In this context, steady-state section number was taken as actual parameters. That hmotmade it possible to assess statistic dependence of amplitudes (phases) of harmonic components in the process of electric workshop equipment switching on/switching off taking place at random time moments.

The process of approximating calculated curves should primarily be grounded in general theoretical principles that address the initiation and behavior of random processes. These principles provide a foundational framework for interpreting and modeling the curves in a meaningful way. However, in situations where such theoretical factors are unavailable or remain unclear, it becomes necessary to shift the focus to observable characteristics. In particular, attention should be directed toward the general nature and properties of the correlation function associated with the random process. By examining the common features of this function, it is possible to establish meaningful comparisons between the calculated curves and a set of representative or reference curves, which can serve as a benchmark for approximation.

In practice, the approximation often relies on the use of certain critical or "support" points. These points are carefully selected to ensure that there is a direct match between experimentally obtained values and the corresponding values derived from the chosen approximating function. This alignment serves as a verification mechanism, helping to ensure the validity and accuracy of the approximation model. By anchoring the approximating function at these key points, the method achieves consistency between the empirical data and the theoretical constructs, enabling more reliable interpretation and application of the results. Furthermore, this approach not only compensates for the absence of detailed theoretical guidance but also reinforces the robustness of the approximation process by grounding it in both experimental evidence and general statistical trends.

Points, within which ordinates of experimental curve are equal to zero, are applied as support ones [27].

To approximate autocorrelation function of harmonic components, a representative curve, being described with the help of following analytical expression, has been selected:

$$R(i) = \sigma^2 e^{-j \cdot i} \cos(\theta \cdot i) \tag{10}$$

where j and θ are the curve coefficients, and σ is a mean-square deviation of a random function.

Similar expression, where graph shift along abscise axis is *m* pitches, may be used to approximate cross-correlation function:

$$R(i) = \sigma^2 e^{-j \cdot i} \cos(\theta \cdot i - m) \tag{11}$$

j, θ, and *m* coefficients of the considered functions for amplitudes and phases of linear voltages of the mentioned workshop are in the corresponding Tables 8-15.

Table 8

Coefficients of analytical curves of autocorrelation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	U_{AB}		U_{BC}		U_{CA}	
	J	θ	J	θ	J	θ
1	0.85	4.1	0.61	2.9	0.5	0.47
2	1.4	-	0.52	-	0.52	-
3	0.73	-	0.87	1.3	1.0	-
4	0.51	3.12	0.61	2.1	0.5	0.47
5	1.73	-	1.81	-	1.79	-
6	0.49	1.57	1.11	0.50	0.5	0.47

Table 9

Coefficients of analytical curves of autocorrelation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	U_{AB}		U_{BC}		U_{CA}	
	J	θ	J	J	θ	J
1	-	-	-	-	-	-
2	0.87	5.2	0.72	3.80	0.79	4.30
3	0.52	-	0.60	-	0.57	1.20
4	0.61	-	0.56	0.50	0.69	-
5	1.20	1.10	0.97	1.80	0.83	1.5
6	0.67	0.8	0.52	0.95	0.49	0.88

Table 10

Coefficients of analytical curves of cross-correlation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	$U_{AB/BC}$			$U_{AB/CA}$		
	J	θ	m	J	θ	m
1	0.51	3.12	3	0.61	2.9	3
2	1.73	-	2	0.52	-	3
3	0.49	1.57	2	0.87	1.3	1
4	0.52	-	1	0.5	0.47	2
5	1.0	-	2	0.52	-	2
6	0.5	0.47	1	0.87	1.3	2

Table 11

Coefficients of analytical curves of cross-correlation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	$U_{BC/AB}$			$U_{BC/CA}$		
	J	θ	m	J	θ	m
1	0.87	1.3	3	0.52	-	2
2	0.61	2.1	3	1.0	-	2
3	1.81	-	2	0.85	4.1	3
4	0.87	1.3	1	1.4	-	1
5	0.61	2.1	2	0.87	1.3	1
6	0.5	0.47	3	0.61	2.1	2

Table 12

Coefficients of analytical curves of cross-correlation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	$U_{CA/AB}$			$U_{CA/BC}$		
	J	θ	m	J	θ	m
1	0.52	-	2	1.4	-	2
2	0.61	2.1	2	0.73	-	3
3	1.81	-	3	1.79	-	3
4	1.0	-	1	1.73	-	2
5	0.87	1.3	3	0.61	2.1	2
6	0.51	3.12	3	0.49	1.57	3

Table 13

Coefficients of analytical curves of cross-correlation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	$U_{AB/BC}$			$U_{AB/CA}$		
	J	θ	m	J	θ	m
1	0.56	0.50	1	0.50	0.69	2
2	0.97	1.80	3	0.52	-	2
3	0.87	5.2	3	0.61	-	2
4	0.83	1.5	2	0.60	-	1
5	0.49	0.88	1	0.56	0.50	1
6	1.20	1.10	1	0.67	0.8	1

Table 14

Coefficients of analytical curves of cross-correlation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	$U_{BC/AB}$			$U_{BC/CA}$		
	J	θ	m	J	θ	m
1	0.69	-	2	0.60	-	2
2	0.83	1.5	2	0.79	4.30	2
3	0.49	0.88	3	0.57	1.20	1
4	0.56	0.50	1	0.87	5.2	1
5	0,97	1.80	2	0.52	-	2
6	0.52	0.95	2	0.52	0.95	3

Table 15

Coefficients of analytical curves of cross-correlation functions of amplitudes of harmonics of linear voltages

Harmonic	Linear voltages					
	$U_{CA/AB}$			$U_{CA/BC}$		
	J	θ	m	J	θ	m
1	1.20	1.10	2	0.87	5.2	3
2	0.67	0.8	3	0.52	-	3
3	0.60	-	1	0.97	1.80	2
4	0.56	0.50	2	0.52	0.95	1
5	0.79	4.30	2	0.61	-	3
6	0,57	1.20	3	0.56	0.50	2

2.4. Digital implementation of linear voltage generators within power grid of industrial enterprises.

While implementing voltage generators within power grid, it is required to have signals with standard distribution laws to simulate amplitudes and phases of their harmonic components as well as exponential law for time intervals between electric equipment switching on/switching off. Currently, almost each application program package (for instance, MatLAB), intended to solve such problems, has built-in functions helping model random values including those with standard law. As for the exponential law, it is more expedient to use a method of inverse functions.

Idea of the method is as follows [30]. Mathematical ratio is known; it connects random numbers y_i with the prescribed distribution law $f(y)$, and x_i number distributed uniformly within [0; 1] interval:

$$x = \int_{\infty}^{y} f(y)dy \quad . \tag{12}$$

If there is integral in a right side, then:

$$x = F(y) \quad . \tag{13}$$

Further, inverse function $F^{-1}(x)$ is being determined to identify dependence according to which the numbers are generated:

$$y = F^{-1}(x) \quad . \tag{14}$$

Numbers, distributed uniformly within [0;1] interval, are connected with exponential law with the help of following mathematical expression:

$$x = \int_{0}^{y} \frac{1}{18} e^{-\frac{1}{18}\cdot \Delta T} dy \quad . \tag{15}$$

Determine integral in a right side:

$$x = \int_{0}^{y} \frac{1}{18} e^{-\frac{1}{18}\cdot \Delta T} dy = -e^{-\frac{1}{18}\Delta T} \Big|_{0}^{y} = -e^{-\frac{1}{18}\Delta T} + 1 \tag{16}$$

as well as inverse function:

$$\Delta T = -18 \cdot \ln(1 - x) \quad . \tag{17}$$

Uncorrelated random values are transformed into a sequence with the prescribed autocorrelation function and cross-correlation one using moving average method; it is based upon the use of the dependence [31-33]:

$$X(l) = \sum\nolimits_{j=-\infty}^{\infty} S_j I(i-j) \quad , \tag{18}$$

where $X(l)$ is a running *l* value of a centered random variable; S_j are real numbers or complex numbers; and I is a unit random sequence.

In this context, autocorrelation function *R(i)* can be determined as follows:

$$R(i) = \sum\nolimits_{j=-\infty}^{\infty} S_{j+i} \cdot S_j \quad . \tag{19}$$

If $R(i)$ is attenuating, (18 and 19) ratios are:

$$X(l) = \sum_{j=0}^{\eta_3} S_j \cdot I(l-j), \tag{20}$$

$$R(i) = \begin{cases} \sum_{j=0}^{\eta_3-|i|} S_{j+|i|} \cdot S_j, when\ |i| \le \eta_3 \\ 0, when\ |i| > \eta_3 \end{cases}, \tag{21}$$

where η_3 is attenuating interval of cross-correlation function of a random process.

In practice, η_3 value is selected in such a way to fulfill the inequality:

$$R(\eta_3) \ge 0.05R(0). \tag{22}$$

Determination of S_j coefficients is to solve (21) when i is varying from 0 to η_3, i.e. to solve a set of the equations:

$$\begin{cases} R(0) = S_0^2 + S_1^2 + \cdots + S_{\eta_3}^2 \\ R(1) = S_1 S_0 + S_2 S_1 + \cdots + S_{\eta_3} S_{\eta_3 - 1} \\ \cdots \\ R(\eta_3 - 1) = S_{\eta_3 - 1} S_0 + S_{\eta_3} S_1 \\ R(\eta_3) = S_{\eta_3} S_0 \end{cases} \tag{23}$$

The last equation has been implemented in an application program package MathCAD.

$R(i)$ values for workshop grid of *Dneprospetsstal* PJSC have been determined according to analytical expressions of corresponding autocorrelation functions; in this context, Tables 16-26 explain values of the related coefficients to simulate amplitudes of harmonic components, and their phases.

Table 16

Coefficients to simulate amplitudes of linear voltages of harmonic one

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	0.95	3.537	0.634	0.93	-0.197	0.362	0.195	0.387	-0.051
S_1	1.91	-1.909	1.177	-0.53	-0.713	0.077	0.311	0.637	-0.006
S_2	1.83	0.969	1.939	2.84	2.571	2.458	-0.01	-0.002	0.049
S_3	-2.99	-0.458	2.447	2.72	1.015	0.98	-0.312	-0.637	0.166
S_4	1.52	0.43	1.804	1.03	-	-	0.194	0.386	0.361
S_5	-	-	-1.577	-	-	-	0.195	0.387	-0.051

Table 17

Coefficients to simulate amplitudes of linear voltages of harmonic two.

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	0.07	0.389	0.694	-0.051	-0.197	0.362	0.07	-0.022	0.93
S_1	0.02	-0.189	-0.166	-0.006	-0.713	0.077	0.03	-0.092	-0.53
S_2	1.16	0.446	0.151	0.049	2.571	2.458	0.06	0.074	2.84
S_3	028	0.816	0.218	0.166	1.015	0.98	-0.15	0.079	2.72
S_4	-	0.647	0.546	0.361	-	-	0.15	0.116	1.03
S_5	-	0.298	1.339	0.606	-	-	-0.08	0.18	-

Table 18

Coefficients to simulate phases of linear voltages of harmonic two

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	-0.79	2.21	1.88	-0.79	2.21	1.88	7.72	-2.69	6.47
S_1	-0.89	-5.51	-5.61	-0.89	-5.51	-5.61	4.21	6.56	3.25
S_2	2.27	7.90	6.37	2.27	7.90	6.37	2.92	6.22	1.63
S_3	10.26	2.10	4.52	10.26	2.10	4.52	1.24	3.74	0.83
S_4	-	-	-	-	-	-	0.96	1.75	0.54
S_5	-	-		-	-		-	-0.5	-

Table 19

Coefficients to simulate amplitudes of linear voltages of harmonic three.

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	0.93	-0.197	0.362	0.362	0.195	0.07	-0.022	0.07	-0.197
S_1	-0.53	-0.713	0.077	0.077	0.311	0.03	-0.092	0.03	-0.713
S_2	2.84	2.571	2.458	2.458	-0.01	0.06	0.074	0.06	2.571
S_3	2.72	1.015	0.98	0.98	-0.312	-0.15	0.079	-0.15	1.015
S_4	1.03	-	-	-	0.194	0.15	0.116	0.15	-
S_5	-	-	-	-	0.195	-0.08	0.18	-0.08	-

Table 20

Coefficients to simulate phases of linear voltages of harmonic three

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	6.63	3.57	1.45	2.01	3.61	3.61	14.29	7.72	-2.69
S_1	3.92	5.63	-1.76	5.14	7.25	7.25	-1.46	4.21	6.56
S_2	2.34	0.86	-4.39	7.07	9.09	9.09	-1.90	2.92	6.22
S_3	1.40	1.84	5.27	3.45	4.03	4.03	-	1.24	3.74
S_4	0.83	0.17	4.12	-6.76	-8.69	-8.69	-	0.96	1.75
S_5	0.77	0.67	2.98	-	-	-	-	-	-0.5

Table 21

Coefficients to simulate amplitudes of linear voltages of harmonic four

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	0.195	0.07	-0.022	0.07	-0.022	0.694	-0.051	0.387	-0.051
S_1	0.311	0.03	-0.092	0.03	-0.092	-0.166	-0.006	0.637	-0.006
S_2	-0.01	0.06	0.074	0.06	0.074	0.151	0.049	-0.002	0.049
S_3	-0.312	-0.15	0.079	-0.15	0.079	0.218	0.166	-0.637	0.166
S_4	0.194	0.15	0.116	0.15	0.116	0.546	0.361	0.386	0.361
S_5	0.195	-0.08	0.18	-0.08	0.18	1.339	0.606	0.387	-0.051

Table 22

Coefficients to simulate phases of linear voltages of harmonic four

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	7.72	-2.69	6.47	13.27	3.57	14.29	7.72	14.29	6.30
S_1	4.21	6.56	3.25	0.53	5.63	-1.46	4.21	-1.46	10.41
S_2	2.92	6.22	1.63	-2.60	0.86	-1.90	2.92	-1.90	-1.03
S_3	1.24	3.74	0.83	-	1.84	-	1.24	-	0.35
S_4	0.96	1.75	0.54	-	0.17	-	0.96	-	-1.66
S_5	-	-	-	-	0.67	-	-	-	-

Table 23

Coefficients to simulate amplitudes of linear voltages of harmonic five

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	2.83	2.50	2.728	2.456	2.673	13.234	0.195	0.387	-0.051
S_1	0.52	0.42	0.469	-0.051	-0.197	0.362	0.311	0.637	-0.006
S_2	-	-	-	-0.006	-0.713	0.077	-0.01	-0.002	0.049
S_3	2	3	4	5	6	7	8	9	10
S_4	-	-	-	0.049	2.571	2.458	-0.312	-0.637	0.166
S_5	-	-	-	0.166	1.015	0.98	0.194	0.386	0.361

Table 24

Coefficients to simulate phases of linear voltages of harmonic five

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	-0.79	14.29	13.27	1.88	-0.79	2.21	1.88	3.61	6.47
S_1	2.14	-1.46	0.53	-5.61	-0.89	-5.51	-5.61	7.25	3.25
S_2	14.45	-1.90	-2.60	6.37	2.27	7.90	6.37	9.09	1.63
S_3	-	-	-	4.52	10.26	2.10	4.52	4.03	0.83
S_4	-	-	-	-	-	-	-	-8.69	0.54
S_5	-	-	-		-	2.21	1.88	-	-

Table 25

Coefficients to simulate amplitudes of linear voltages of harmonic six

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	0.195	0.387	-0.051	0.195	0.07	-0.022	0.93	0.95	3.537
S_1	0.311	0.637	-0.006	0.311	0.03	-0.092	-0.53	1.91	-1.909
S_2	-0.01	-0.002	0.049	-0.01	0.06	0.074	2.84	1.83	0.969
S_3	-0.312	-0.637	0.166	-0.312	-0.15	0.079	2.72	-2.99	-0.458
S_4	0.194	0.386	0.361	0.194	0.15	0.116	1.03	1.52	0.243
S_5	0.001	0.001	0.606	0.195	-0.08	0.18	-	-	-

Table 26

Coefficients to simulate phases of linear voltages of harmonic six

	U_{AB}	U_{BC}	U_{CA}	$U_{AB/BC}$	$U_{AB/CA}$	$U_{BC/AB}$	$U_{BC/CA}$	$U_{CA/AB}$	$U_{CA/BC}$
S_o	6.30	2.01	3.61	2.21	1.88	2.21	-0.022	0.07	-2.69
S_1	10.41	5.14	7.25	-5.51	-5.61	-5.51	-0.092	0.03	6.56
S_2	-1.03	7.07	9.09	7.0	6.37	7.90	0.074	0.06	6.22
S_3	0.35	3.45	4.03	2.10	4.52	2.10	0.079	-0.15	3.74
S_4	-1.66	-6.76	-8.69	-	-	-	0.116	0.15	1.75
S_5	-	-	-	-		2.21	0.18	-0.08	-0.5

Fig. 29 demonstrates enlarged algorithm to simulate sequences of linear voltages with the prescribed statistical regularities.

Unit 1 loads modeling time T, and array $\vec{S}$ used to transform uncorrelated random sequences, distributed according to a standard law with zero mathematical expectation as well as with the preset dispersion, into the correlated ones. Unit 2 prepares k variable for further accumulation of intervals of steady-state sections; unit 3 generates uncorrelated random sequences. Unit 4 calculates duration of the current steady-state modeling interval of random values. Unit 5 calculates total duration value of the steady-state sections.

As it has been stated below, decrease in systematic modeling error of linear voltages is possible owing to randomly selected sequence (i.e. randomization) while generating amplitudes and harmonic phases. Unit 6 performs the procedure. Then, parameter values of linear voltage harmonic are calculated (Units 7 and 8). The obtained values help determine instaneous harmonic values (Unit 10) as well as linear voltages properly (Unit 11). Unit 12 storages them.

Consequently, duration of the current total modeling period is checked (Unit 13). If it is less than the prescribed *T* then the considered procedure, corresponding to the algorithm, recurs. Otherwise, simulation of random sequences of linear voltages terminates.

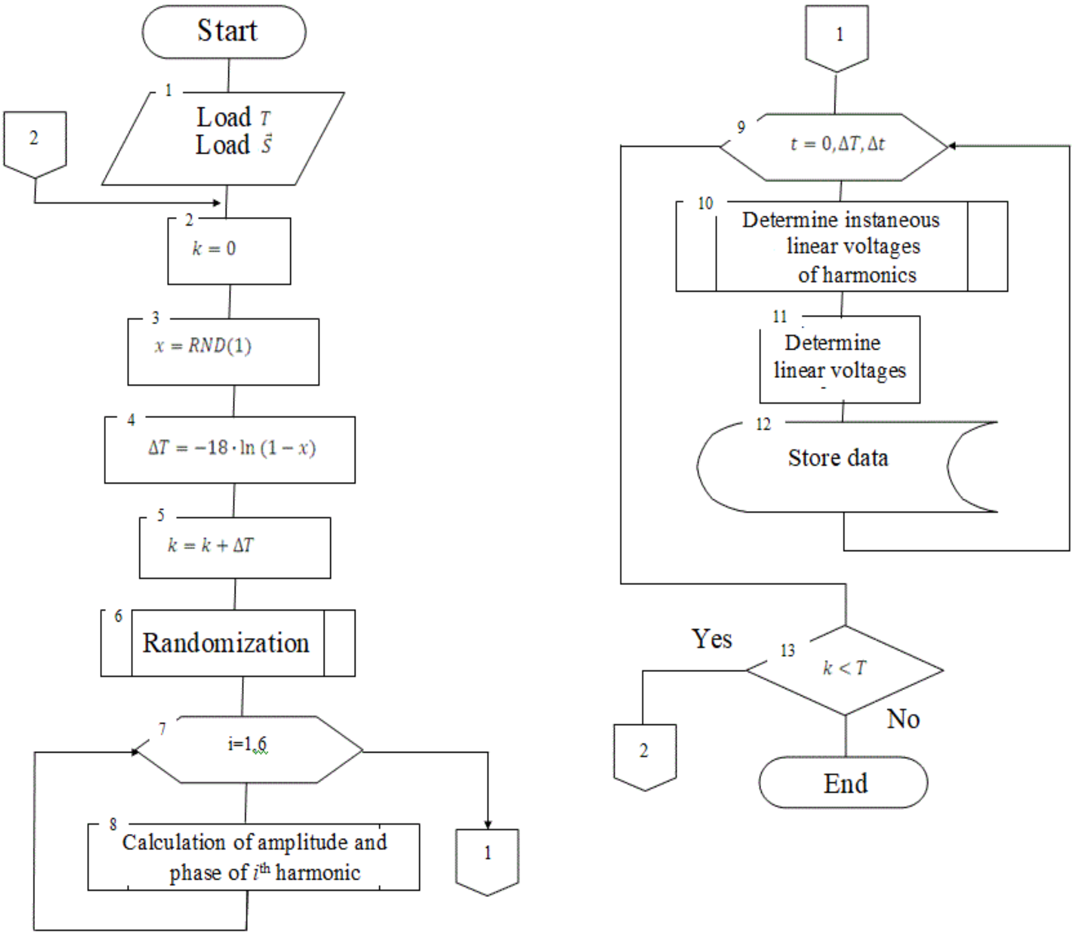


Fig. 29. Algorithm to simulate linear voltages

Fig. 30 explains randomization algorithm, implemented by Unit 6.

Its idea is as follows. As it has been mentioned above, determination of amplitudes, and harmonic phases of linear voltages within steady-state sections may involve one of the calculation techniques: either relying upon the prescribed autocorrelation functions (i.e. moving-average method) or upon cross-correlation functions (i.e. moving-average retarded method), or upon the known electrotechnical ratios between instaneous values of linear voltages (formulas 2; 10; and 11).

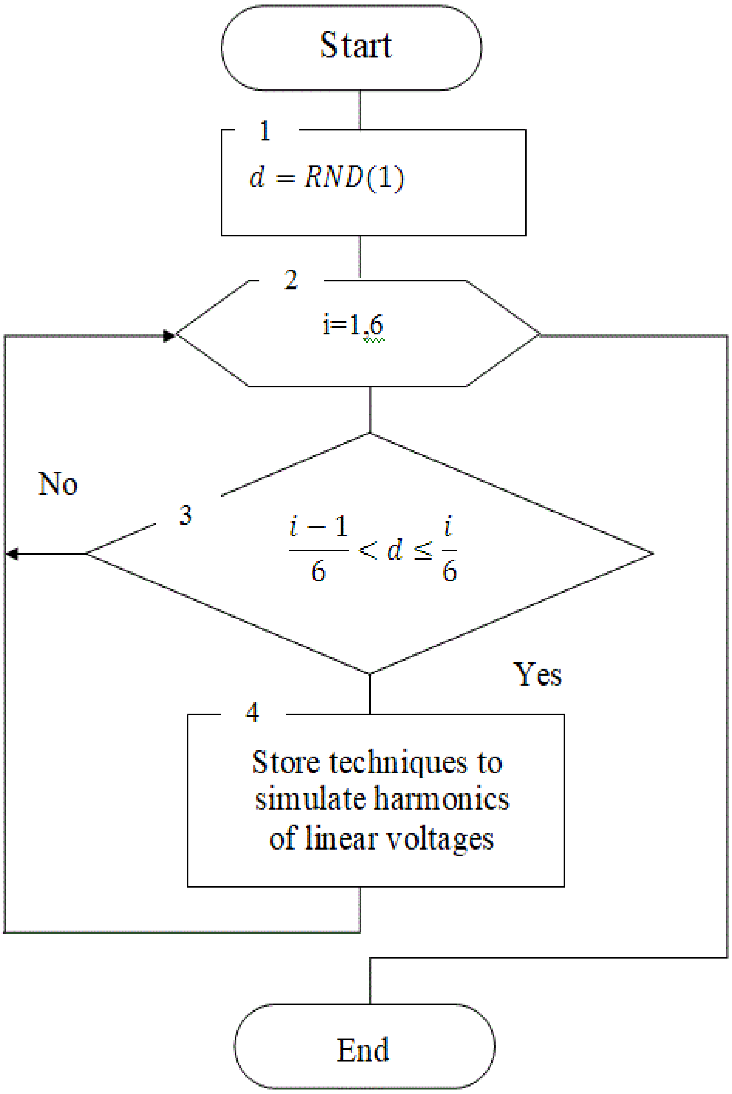


Fig. 30 Randomization algorithm

Table 27 shows all possible combinations of sequences to calculate linear voltages.

Table 27

Determination of a technique to simulate harmonics of linear voltages.

	Random value d	Calculation on autocorrelation function	Calculation of cross-correlation function	Calculation on formula (2)
1	$0 \le d \le 1/6$	U_{AB}	U_{BC}	U_{CA}
2	$1/6 < d \le 2/6$	U_{AB}	U_{CA}	U_{BC}
3	$2/6 < d \le 3/6$	U_{BC}	U_{AB}	U_{CA}
4	$3/6 < d \le 4/6$	U_{BC}	U_{CA}	U_{AB}
5	$4/6 < d \le 5/6$	U_{CA}	U_{AB}	U_{BC}
6	$5/6 < d \le 1$	U_{CA}	U_{BC}	U_{AB}

Separate regular numeric intervals for each of them within $[0;1]$. Then, while producing sequence of potential values of random variable d (Unit 1) distributed uniformly within $[0;1]$ interval, it is possible to select one of the sequences randomly (Units 2 and 3). It follows from probability theory and from mathematical statistics that selection frequencies will be identical, if tests are numerous.

Conclusions on chapter 2

To investigate the efficiency of electrical equipment operating within power grids subject to noisy electricity, it is practical to utilize computational experiments based on linear voltage generators designed using statistical testing methods. These generators enable the detailed modeling and analysis of complex electrical behaviors under non-ideal conditions, providing a robust framework for understanding performance and optimizing system reliability.

The modeling process is particularly suited to the statistical approach due to the specific characteristics of harmonic components in linear voltages within noisy power grids. In these environments, the oscillation frequencies of harmonic components remain constant, while variations are limited to changes in amplitudes and initial phases. By generating random sequences that reflect these variations, statistical methods allow for a more accurate representation of the random behavior of electrical parameters, facilitating effective analysis and prediction of system responses.

One of the challenges in such grids is the inherent nonstationarity of linear voltages caused by the presence of random and relatively infrequent switching on and off of electrical equipment. This nonstationarity necessitates the identification and segmentation of stationary sections within the voltage waveforms to enable meaningful analysis. The separation of these sections ensures that the computational models accurately reflect the dynamic behavior of the grid while maintaining statistical validity.

To further enhance the accuracy of the models, the randomization of computational sequences associated with the harmonic components of linear voltages is employed. This technique reduces systematic modeling errors, ensuring that the simulations provide a more realistic depiction of the grid's performance under noisy conditions. By addressing these complexities, the modeling approach ensures the reliability and robustness of the simulation results.

The developed probabilistic model of a workshop power grid under noisy electricity conditions offers significant practical value. It enables the formulation of precise engineering solutions aimed at ensuring the optimal functioning of asynchronous motors and other critical equipment. Through computational studies based on this model, engineers can make informed decisions to maintain the desired operating conditions, ultimately improving the efficiency, reliability, and safety of power grid systems in industrial environments.

CHAPTER 3
IMPROVING THE RELIABILITY OF SIMULATING THE OPERATION OF AN INDUCTION MOTOR IN SOLVING THE TECHNICAL AND ECONOMIC PROBLEM

3.1. Problem statement

It is a well-known fact that there is certain negative effect of poor-quality power supply upon operational characteristics of electric consumers (for example as induction motors) (IM) [34-38]. Moreover, availability of noisy electric energy within workshop grids of industrial enterprises results in the accelerated physical ageing; in the decreased power efficiency of equipment in use; and in the increased risk of industrial emergency situations.

It is a well-established principle that addressing complex problems in the field of electrical power systems requires solutions to be developed at the intersection of technical and economic considerations, often leveraging advanced methods of mathematical modeling. This approach ensures that both operational efficiency and cost-effectiveness are prioritized. To address the challenges associated with operating electrical equipment under conditions of noisy power supply, the authors have developed a specialized technique for making optimal decisions. This technique integrates technical analysis and economic evaluation to determine the most suitable course of action for maintaining and restoring supply voltage to meet predefined quality standards.

The proposed technique begins with a comprehensive economic assessment of various possible alternatives aimed at improving the quality of the power supply. This evaluation is guided by a systematic analysis of power quality indices and their impact on the performance of electromechanical transducers within the power grid of an enterprise. To achieve this, the method incorporates detailed calculations based on current power quality parameters, combined with sophisticated modeling approaches. These include both electrical and thermal models of the consumer's electrical equipment, which together provide an in-depth understanding of the equipment's behavior and its interaction with the power supply.

If the calculated performance indices of the electrical consumer—derived through these models—significantly deviate from the predefined quality benchmarks, the technique facilitates the exploration of multiple engineering solutions. These solutions are designed to address the identified discrepancies and restore the power supply to the desired quality levels. Each proposed alternative is subjected to a thorough cost analysis, which encompasses not only the direct expenses of implementation but also potential long-term economic impacts, such as operational savings or performance improvements.

The final stage of the technique involves a comparative evaluation of the alternatives, where both their technical feasibility and economic implications are taken into account. The alternative that offers the best balance between cost efficiency and technical effectiveness is selected as the optimal solution. This decision ultimately governs the future operation of the electrical equipment under consideration, ensuring that it meets the operational requirements while minimizing unnecessary expenditures. This structured approach provides a robust framework for addressing power quality issues in industrial settings, aligning technical optimization with sound economic reasoning [39].

Method relies upon the use of power and economic model of certain electric equipment; taken as a whole, it helps optimize selection of technical means aimed at electric energy quality recovery according to cost criterion involving restrictions to power indices of the electrical consumer. However, calculation of different variants is based upon the knowledge of statistic regularities of linear voltage change under specific operation conditions of the equipment. That supposes carrying out of a number of expensive and long-term experiments using real object. To reduce both cost of the experiments as well as their period, it has been proposed to substitute industrial experiments for computational ones. For that purpose, power and economic model is supplemented by a unit to form linear voltages and to control them. Probability model of linear voltages to be applied in workshops of industrial enterprises is represented in [24].

3.2. Power and economic model of electric equipment

Fig. 31 demonstrates one of the variations of power and economic model making it possible to perform computational studies of IM operation. In this context, making a correct decision is possible, if only linear voltages are simulated in accordance with their statistic regularities. Basing upon specific features of linear voltage simulation [24, 39] it is required to control average values, dispersion, autocorrelation, and cross-correlation functions of harmonics of linear voltages. Moreover, the listed values and functions should be evaluated simultaneously and continuously during the modeling process. Such an evaluation can be performed relying upon adaptive approach.

Average value of continuous stationary random process at t time moment is determined using the formula:

$$\bar{x}(t)=\frac{1}{t}\int_{0}^{t}x(t)dt \qquad (24)$$

where $x(t)$ is continuous stationary random process.

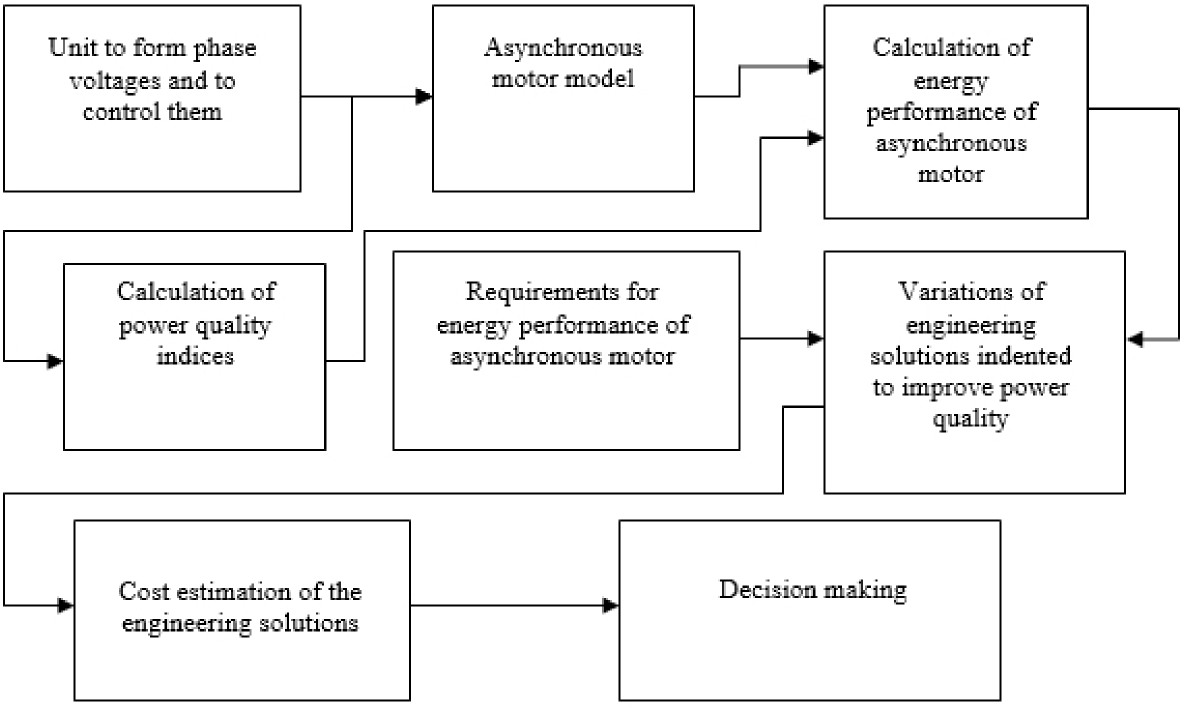


Fig. 31 Schematic diagram of power and economic model of electric equipment

Differentiate left side and right side of expression (24) with respect to t:

$$\frac{d\overline{x}(t)}{dt} = -\frac{1}{t^2}\int_0^t x(t)dt + \frac{1}{t}x(t)$$

or:

$$\frac{d\overline{x}(t)}{dt} = -\frac{1}{t}\overline{x}(t) + \frac{1}{t}x(t)\frac{1}{t}(x(t) - \overline{x}(t)). \tag{15}$$

If the random process is represented by a discrete (impulse) function, then expression (25) is:

$$\overline{x}[iT] - \overline{x}[(i-1)T] = \frac{1}{i}(x[iT] - \overline{x}[(i-1)T]) \tag{26}$$

where T is time discretization of $x(t)$ function; $i = \overline{1,n}$ is discretization interval number; and n is a total of discretization intervals.

It is more convenient to demonstrate expression (26) as follows:

$$\overline{x}[iT] = \overline{x}[(i-1)T] + \frac{1}{i}(x[iT] - \overline{x}[(i-1)T]) \tag{27}$$

Dispersion of continuous stationary random process at t time moment is determined by means of the formula:

$$D_x(t) = \frac{1}{t}\int_0^t (x(t) - \overline{x}(t))^2 dt \tag{28}$$

and values of autocorrelation function and cross-correlation function for different time shifts τ are determined by means of the formulas:

$$R_{x,x}(t,\tau) = \frac{1}{t}\int_0^t ((x(t) - \overline{x}(t))(x(t-\tau) - \overline{x}(t)))dt \tag{29}$$

$$R_{x,y}(t,\tau) = \frac{1}{t}\int_0^t ((x(t) - \overline{x}(t))(y(t-\tau) - \overline{y}(t)))dt \tag{30}$$

where $y(t)$ is continuous stationary random process, and $\overline{y}(t)$ average $y(t)$ value at t time moment.

After performing transformation of (28), (29), and (30) expressions, being analogous to the above mentioned ones, we obtain the following for continuous random functions:

$$\frac{dD_x(t)}{dt} = \frac{1}{t}((x(t) - \overline{x}(t))^2 - D_x(t)) \tag{31}$$

$$\frac{dR_{x,x}(t,\tau)}{dt}=\frac{1}{t}((x(t)-\overline{x}(t))(x(t-\tau)-\overline{x}(t))-R_{x,x}(t,\tau)) \tag{32}$$

$$\frac{dR_{x,y}(t,\tau)}{dt}=\frac{1}{t}((x(t)-\overline{x}(t))(y(t-\tau)-\overline{y}(t))-R_{x,y}(t,\tau)) \tag{33}$$

In a digital form, (31), (32), and (33) expressions are:

$$D_x[iT]=D_x[(i-1)T]+\frac{1}{i}((x[(i-1)T]-\overline{x}[(i-1)T])^2-D_x[(i-1)T]) \tag{34}$$

$$R_{x,x}[iT,\tau]=R_{x,x}[(i-1)T,\tau]+\frac{1}{i}((x[(i-1)T]-\overline{x}[(i-1)T])\times \times((x[(i-1)T]-\overline{x}[(i-1)T]))-R_{x,x}[(i-1)T,\tau]) \tag{35}$$

$$R_{x,y}[iT,\tau]=R_{x,y}[(i-1)T,\tau]+\frac{1}{i}((x[(i-1)T]-\overline{x}[(i-1)T])\times \times((y[(i-1)T]-\overline{y}[(i-1)T]))-R_{x,y}[(i-1)T,\tau]) \tag{36}$$

Fig. 14 represents structural scheme of a control system implementing (25), (31), (32), and (33) algorithms to evaluate statistic characteristics of continuous implementations of random functions of first harmonics of amplitudes (phases) of linear voltages AB and BC $U_{mAB1}(t)$ and $U_{mBC1}(t)$ ($\psi_{AB1}(t)$ and $\psi_{BC1}(t)$).

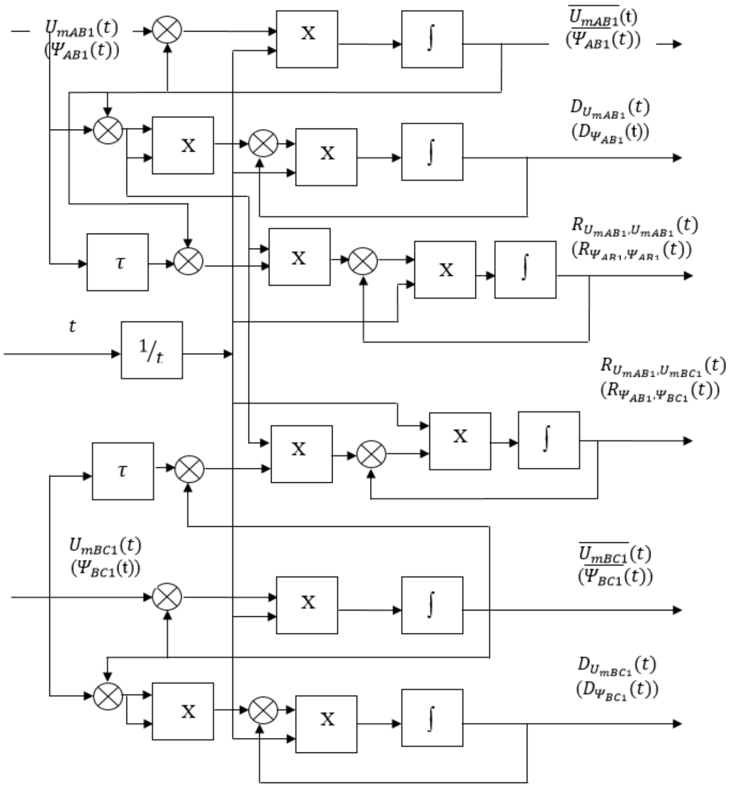


Fig.32 Diagram of analogous control system

Fig. 33 represents structural scheme of a control system implementing (27), (34), (35), and (36) algorithms to evaluate statistic characteristics of discrete implementations of the same random functions according to [24].

The control system scheme, shown in Fig. 31, can be used in the process of analogous modeling of linear phase voltages; the scheme, shown in Fig. 32, is applicable in the context of digital modeling. Letter D specifies discrete integrator, i.e. digrator. Values of the averages and dispersions of the generated random functions, obtained during the modeling, have been checked for significance of their variation from those hypothetic average values and dispersions obtained in [24].

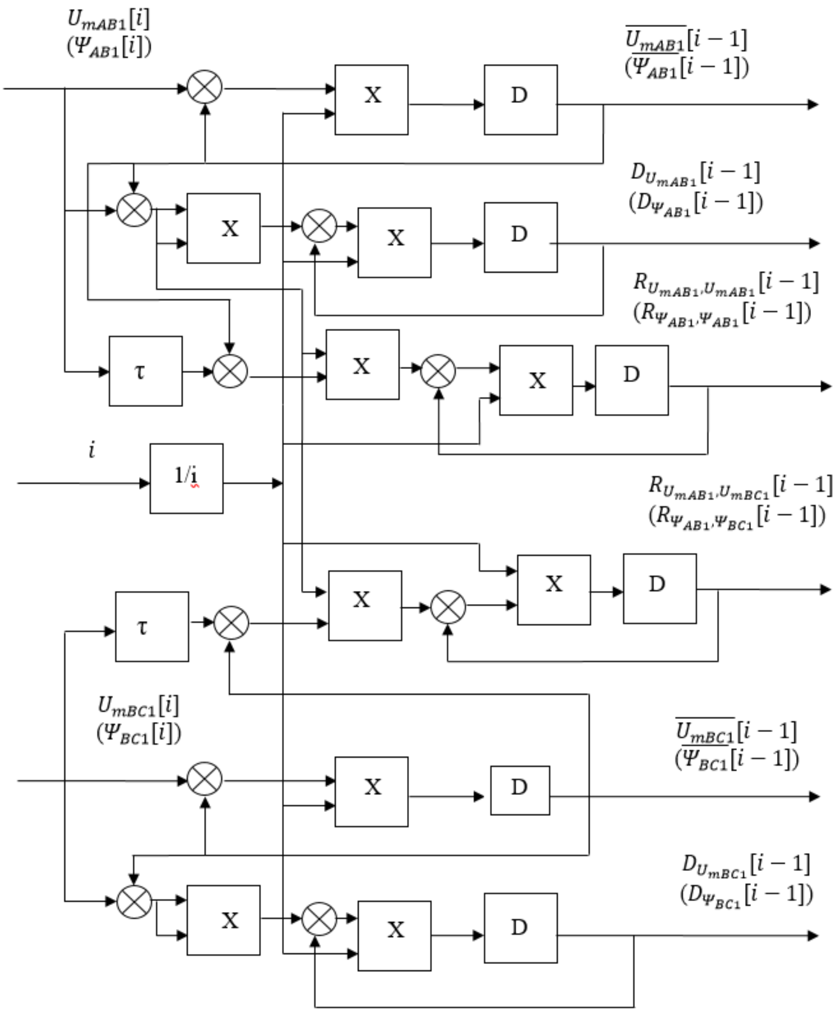


Fig.33 Diagram of discrete control system

Zero hypothesis checking in terms of α H_0: $\bar{x}=x_0$ significance level concerning equality between an overall average $\bar{x}$ of normal population with the known dispersion *D₀* and hypothetic value x_0 in terms of a competing hypothesis $H_1: \bar{x} \neq x_0$ has been performed basing upon the criterion value [40,41]:

$$U_{observ} = \frac{(\bar{x}-x_0)\sqrt{n}}{D_0}$$

and critical point u_{cr} of two-sided critical region determined according to Laplace function table relying upon the equation:

$$\phi(u_{cr}) = \frac{(1-\alpha)}{2}.$$

In this context, n is the number of observations.

If $|U_{observ}| < u_{cr}$, then there is no necessity to reject zero hypothesis.

Determine $\phi(u_{cr}) = 0,475$ for $\alpha = 0,05$ where $u_{cr} = 1,96$.

Table 28 demonstrates checking results of the average random sequences of harmonics of linear voltages generated according to [40,41] and evaluated with the help of a control system (Fig. 33) if $n = 30$.

Table 28

Checking results of average harmonics of linear voltages

Linear voltage U_{AB}						
Harmonic	**Amplitude, V**			**Phase, degrees**		
	Average x_0	Average $\bar{x}$	$\lvert U_{observ}\rvert$	Average x_0	Average $\bar{x}$	$\lvert U_{observ}\rvert$
1	529.82	531.26	|1.8|	-	-	-
2	4.23	4.38	|0.7|	63	59.95	|-1.58|
3	17.60	16.85	|-1.35|	206	208.01	|1.34|
4	1.51	1.58	|1.63|	92	94.88	|1.71|
5	18.54	17.75	|-1.51|	130	134.99	|1.87|
6	3.05	2.95	|-1.02|	290	286.24	|-1.67|
Linear voltage U_{BC}						
Harmonic	**Amplitude, V**			**Phase, degrees**		
	Average x_0	Average $\bar{x}$	$\lvert U_{observ}\rvert$	Average x_0	Average $\bar{x}$	$\lvert U_{observ}\rvert$
1	532.09	533.38	|1.70|	-	-	-
2	3.98	4.41	|1.88|	78	74.63	|-1.83|
3	19.13	18.38	|-1.44|	235	236.7	|1.33|
4	1.55	1.64	|1.92|	111	114.27	|1.74|
5	16.77	17.35	|1.25|	114	109.11	|-1.85|
6	4.15	4.33	|0.94|	325	327.08	|0.97|
Linear voltage U_{CA}						
Harmonic	**Amplitude, V**			**Phase, degrees**		
	Average a_0	Average $\bar{y}$	$\lvert U_{observ}\rvert$	Average a_0	Average $\bar{y}$	$\lvert U_{observ}\rvert$
1	530.41	531.85	|1.90|	-	-	-
2	3.71	4.07	|1.78|	94	91.23	|-1.55|
3	18.27	19.09	|1.69|	182	182.31	|0.19|
4	1.50	1.57	|1.63|	83	85.42	|1.77|
5	16.01	16.56	|1.08|	165	169.22	|1.71|
6	3.82	3.57	|-1.88|	310	315.34	|1.89|

Zero hypothesis checking in terms of α $H_0 : D_x = D_0$ significance level concerning equality between unknown overall dispersion D_x with the known dispersion D_0 and hypothetic value D_0 in terms of a competing hypothesis $H_1 : D_x \neq D_0$, has been performed basing upon the criterion value [40-41].

$$\chi^2_{observ} = \frac{(n-1)D_x}{D_0}$$

Zero hypothesis is accepted if $\chi^2_{l\,cr.(1-\alpha/2;k)} < \chi^2_{observ} < \chi_{r.cr.(\alpha/2;k)}$ inequality is met. In this context, $k = n-1$ is the number of degrees of freedom; $\chi^2_{l.cr.(1-\alpha/2;k)}$ and $\chi^2_{r.cr.(\alpha/2;k)}$ are left and right critical points determined according to Laplace function table. In the context of $n = 30$ and $\alpha = 0{,}05$, $\chi^2_{l.cr.(1-\alpha/2;k)} = 16$ and $\chi^2_{r.cr.(\alpha/2;k)} = 42.6$

Table 29 demonstrates checking results of dispersions of random consequences of harmonics of linear voltages generated with the help of digital generators.

Table 29

Control results of dispersions of harmonics of linear voltages

Linear voltage U_{AB}						
Harmonic	**Amplitude,V**			**Phase, degrees**		
	Dispersion D_0	Dispersion D_x	χ^2_{observ}	Dispersion D_0	Dispersion D_x	χ^2_{observ}
1	19.11	21.19	32.16	-	-	-
2	1.42	1.24	25.34	112	70.06	18.14
3	9.35	6.41	19.87	68	62.16	26.51
4	0.06	0.04	21.19	85	68.06	23.22
5	8.29	11.35	39.72	214	276.06	37.41
6	0.27	0.31	33.07	152	180.51	34.44
Linear voltage U_{BC}						
Harmonic	**Amplitude,V**			**Phase, degrees**		
	Dispersion D_0	Dispersion D_x	χ^2_{observ}	Dispersion D_0	Dispersion D_x	χ^2_{observ}
1	17.36	11.87	19.83	-	-	-
2	1.56	1.02	18.92	102	96.20	27.35
3	8.19	8.83	31.27	49	40.82	24.16
4	0.06	0.05	22.88	106	137.99	37.75
5	6.44	5.59	25.17	210	191.97	26.51
6	1.11	0.82	21.45	138	144.00	30.47

ContinuationTable 29

Linear voltage U_{CA}						
Harmonic	Amplitude,V			Phase, degrees		
	Dispersion D_0	Dispersion D_x	χ^2_{observ}	Dispersion D_0	Dispersion D_x	χ^2_{observ}
1	17.28	1.59	21.13	-	-	-
2	1.25	1.75	40.52	96	87.66	26.48
3	7.14	9.38	38.10	78	97.23	36.15
4	0.06	0.04	17.06	56	66.86	34.62
5	7.66	6.59	24.93	183	250.90	39.76
6	0.53	0.36	19.67	240	338.90	40.95

Experimental validation is the most reliable method to confirm adequacy of any mathematical model. The rolling shop No. 1 of Dneprospetsstal LLC was selected as the experimental one; the rolling shop contains powerful semiconductor converter which operation is accompanied by distortions in the workshop power grid (asymmetry and nonsinusoidality). During the experiment, oscillograms of currents used by IM of 7.5 kW power have been obtained. In the process of the experiment, there was an access to a zero point of the motor; thus, oscillograms of phase currents and voltages were taken. Measuring of active resistances of windings has shown their symmetry and correspondence to the certified values. IM shaft load was of random character changing within a wide range from 2.3 up to 12.8 kW. Fig. 34 and Fig. 35 demonstrate a window of CED Expert software in the process of oscillographic testing of signals during operation of tested electric motor under loading.

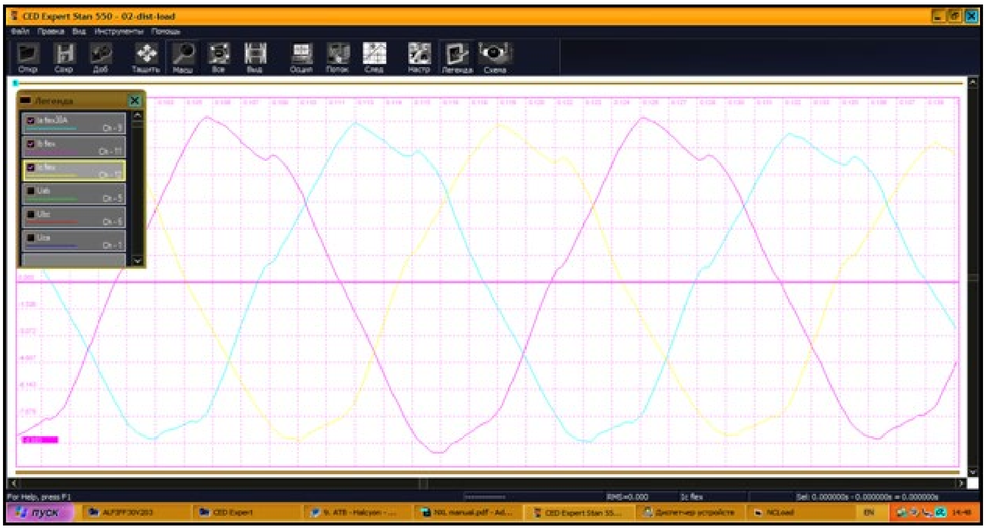


Fig. 34. Oscillograms of currents within the considered electric motor while operating under loading

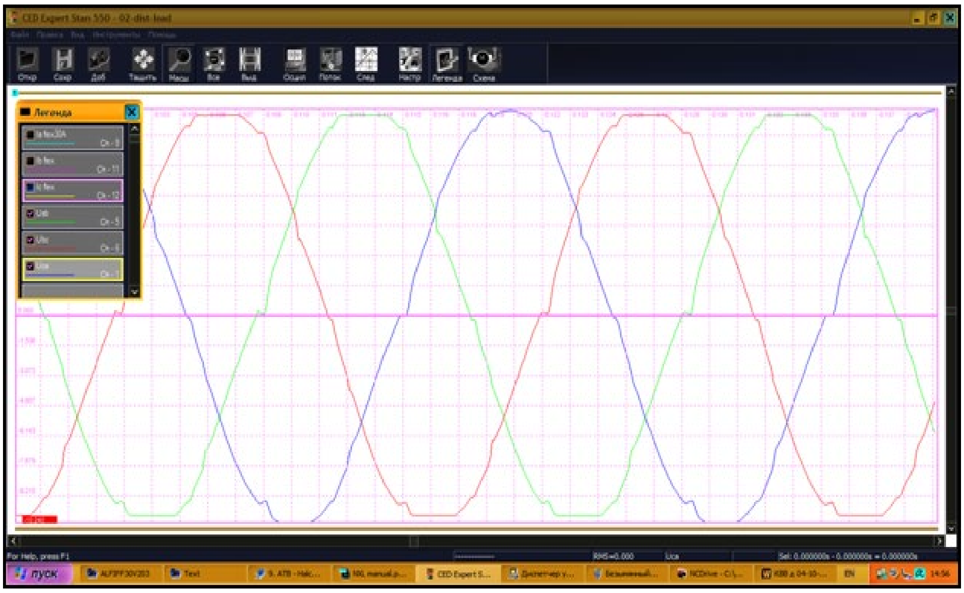


Fig. 35. Oscillograms of voltages within the considered electric motor while operating under loading

Conclusions on chapter 3.

Analysis of complex processes in terms of computer-based experiments involves errors resulting from the fact that a discrete function is represented as a set of its values in the context of different groups of arguments; if numbers, obtaining from the calculations, are rounded; and if decimal numbers as well as binary numbers are converted into floating-point numbers. Such errors may give rise to absolutely unexpected results.

Complementing of power-economic model of electrical consumer with the control system of static characteristics of linear voltages helps regulate correctness of the random sequences being generated during computational experiments to select cost-effective alternative for recovering quality of electric power being supplied to the electric consumer. The control systems have been synthesized with the use of adaptation concept based upon the mathematical expressions obtained in the process of the analysis. The chapter represents estimation results as for the control of averages and amplitude dispersions, and phases of six harmonics of linear voltages obtained during the computer-based modeling. Estimations of the averages and dispersions of the generated random sequences have been verified as for the value of their differences from the corresponding hypothetic averages and dispersions.

CHAPTER 4
DEVELOPMENT AND VERIFICATION OF DYNAMIC ELECTROMAGNETIC MODEL OF ASYNCHRONOUS MOTOR OPERATING IN TERMS OF POOR-QUALITY ELECTRIC POWER

4.1. Substantiation of the need to synthesize a mathematical analogue of an asynchronous motor.

It is widely recognized that the modeling of electromechanical systems provides a powerful tool for evaluating all processes occurring within these systems at the pre-project stage. Such modeling enables engineers and designers to gain critical insights into system behavior under various conditions, allowing for a comprehensive assessment before the actual implementation phase. The data obtained through this approach form the foundation for making adjustments to the parameters of power units and their associated control systems, ensuring optimal performance and reliability from the outset.

For asynchronous electric motors, this challenge has largely been addressed with the advent of specialized software tools, particularly modern CAD programs. These tools have revolutionized the design process by enabling the construction of detailed graphs of transient processes, the generation of precise dependencies of key parameters on input factors, and the simulation of a wide range of operating scenarios. The availability of such advanced software simplifies the process of modeling and optimizes the design workflow, significantly reducing development time while improving accuracy.

However, the complexity increases substantially when qualitative aspects of the input voltage, such as asymmetry and nonsinusoidality, must be taken into account. These factors introduce additional layers of variability and complexity into the modeling process, presenting challenges that are not as easily addressed by conventional software. The core issue lies in the inherent inadequacy of many existing models, which often rely on simplifying assumptions to reduce computational complexity. These assumptions can lead to a significant loss of fidelity, rendering the models less accurate and, in some cases, entirely unsuitable for capturing the real behavior of the system under such conditions.

When attempting to incorporate more comprehensive and complex models to address these issues, the situation often becomes even more challenging. The detailed description of processes under the influence of asymmetrical or nonsinusoidal input voltages can result in models that are not only computationally intensive but also exceedingly difficult to interpret. In such cases, the process of extracting meaningful dependencies between input factors and output parameters becomes so intricate that it may hinder the entire objective of the modeling exercise.

This dilemma underscores the need for a balanced approach in the development and application of electromechanical system models. On one hand, simplifications are necessary to make the models computationally feasible and user-friendly; on the other, these simplifications must not compromise the accuracy required for addressing complex input conditions. Advances in software tools and computational methodologies continue to evolve, offering the potential to bridge this gap. Future developments could focus on integrating adaptive algorithms, machine learning techniques, or hybrid models that combine the strengths of simplified and complex approaches. Such innovations would enable the accurate simulation of systems under challenging conditions, paving the way for more robust and reliable designs that account for the nuanced realities of input voltage variations.

Meanwhile, nowadays, assumption on symmetry and sinusoidality of supply voltage is completely substantiated only in rare cases. Workshops of industrial enterprises often use powerful consumers, distorting shape and disturbing voltage symmetry in workshop power grid, in one grid with asynchronous motor (AM).

Objective of the study is a synthesis and validation of a mathematical analogue of asynchronous motor characterizing changes in its power indices in terms of various values of all the indices of supply voltage quality as well as approbation of its software implementation.

4.2 Developing dynamic electromagnetic AM model operating in terms of poor-quality electric energy

Several approaches are known which help take into consideration parameters of supply voltage while modeling processes in electromechanical systems [12, 42]. In terms of nonsinusoidality of supply voltage in classic variant, its spectrum analysis is performed; then, the required equations are represented for each harmonic taking into account its amplitude and phase. Those equations are solved either analytically or numerically; the necessary value is found as a geometrical total of all the harmonic constituents.

In case of asymmetry of supply voltage, symmetrical component method is applied. Disadvantage of the approach is in considerable complication of the system of equations describing the object. Besides, in case of nonsinusoidal power, it is required to determine symmetric constituents for each considered harmonic. Then, if there will be, for instance, 10 of them in terms of asymmetric power, we will have to develop 30 equations for each basic equation describing the system. To simplify their representation, it is proposed to use differential equations set down relative to space-time complexes (STC) [38].

Space-time complex, so-called generalized vector, is calculated for each variable value Y as follows:

$$Y = \frac{2}{3}\left(Y_A + \alpha Y_B + \alpha^2 Y_C\right), \tag{37}$$

where Y_A, Y_B, Y_C are values of the considered variable in terms of phases. Projections of that complex within the axis of phases correspond to the indicated values.

Being set down relative to STC, Park-Gorev equations [38] which are the basis for a known AM models are of as follows:

$$\underline{U}_1 = \underline{I}_1 R_1 + \underline{I}_0 R_0 + \frac{d\underline{\Psi}_1}{dt}, \tag{38}$$

$$0 = \underline{I}_2 R_2 + \underline{I}_0 R_0 + \frac{d\underline{\Psi}_2}{dt} - j\omega_m \underline{\Psi}_2, \tag{39}$$

where $\underline{U}_1$ is STC of stator voltage, $\underline{I}_1$, $\underline{I}_2$, $\underline{I}_0$ are STC of currents of stator, rotor, and magnetizing current, $\underline{\Psi}_1$, $\underline{\Psi}_2$ are STC of stator and rotor flux linkages, ω_m is angular velocity of AM rotation, and R_1, R_2 are active stator and rotor resistances.

It should be taken into consideration that core saturation effects considerably both dynamic and power indicators of asynchronous motors. A phenomenon of saturation is stipulated by boundary orientation of magnetic dipoles within the material of the latter and, thus, termination of the magnetic flux increase along with the growth of magnetizing current as it is shown in Fig.36 [43].

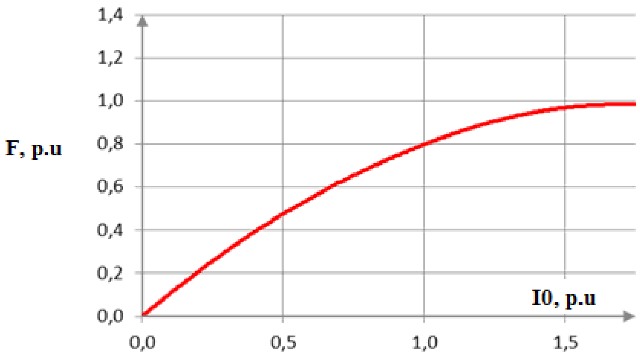


Fig. 36 Dependence of main magnetic flux upon magnetizing current

There are various methods to consider that effect [44-46]. Use of dependence of main mutual induction upon a value of magnetizing current L_{12}=f(I0) makes up the best combination of accuracy and simplicity of the calculation. For instance, [46] represents dependence of induction upon magnetizing current for asynchronous motors of general-purpose industrial version (Fig.37).

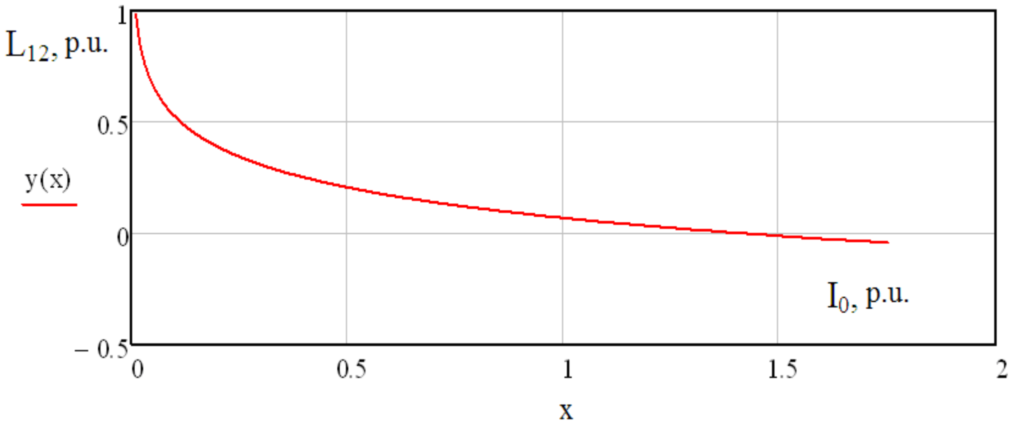


Fig. 37 Dependence of main induction upon magnetizing current

Such dependence may be described by polynomial functions of even degrees [46]. Induction value of a magnetizing branch without consideration of saturation effect is represented in reference literature [47] or it may be determined roughly according to the results of no load test [48]. Determination of coefficients of polynomial induction dependence upon the value of magnetizing current is an independent task. We took equation from [49] to perform modeling.

Thus, it is necessary to set down following things in the equation for flux linkage determination:

$$\underline{\Psi}_1 = \underline{I}_1 \cdot L_1 + L_{12}(I_0) \cdot \underline{I}_2, \tag{40}$$

$$\underline{\Psi}_2 = \underline{I}_2 \cdot L_2 + L_{12}(I_0) \cdot \underline{I}_1 \tag{41}$$

Fig. 20 demonstrates structural diagram of the modeling object; the diagram expresses equations (38) and (39) taking into account (40) and (41).

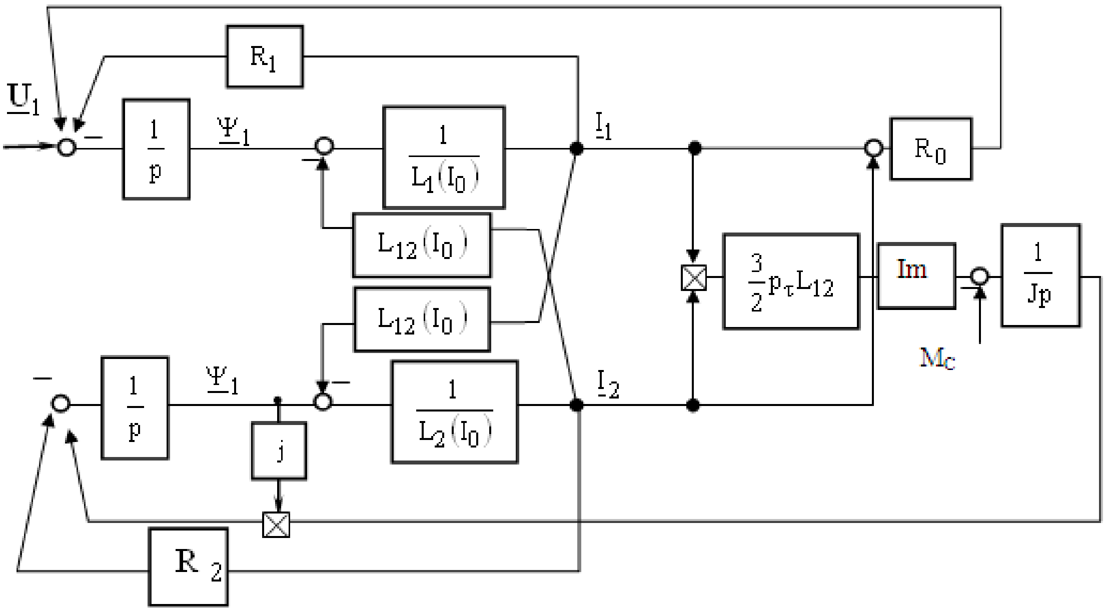


Fig.38 Structural diagram of asynchronous motor as a modeling object

Use of time-space complexes is characteristic for numerous models. Since they take into consideration instantaneous currents and voltages, there is no necessity in spectrum analysis and setting down equations for each harmonic. In addition, as such equations are contract representation of the three phases, they take into account possible asymmetry of supply voltage as well. The system under consideration is, actually, a universal model making it possible to analyze processes both in steady-state and transient modes (pulse, running-down, load change).

Analytical solution of system of equations (38) and (39) is complicated and connected with a series of considerable assumptions. In such cases, known numerical methods are used; their essence is in representation of infinitesimal increments of the required function by certain finite increments (Euler method) and representation of the equations in Cauchy form [50].

Velocity of asynchronous motor as well as space-time complexes of stator and rotor flux linkage are state variables of the modeled object in the considered case. To find them, initial system of equations is complemented by the known dependences

$$M = \frac{3}{2} p_\tau L_{12} \operatorname{Im}(\underline{I}_1^* \underline{I}_2), \qquad (42)$$

$$M - M_c = J \frac{d\omega_m}{dt}, \qquad (43)$$

where M_c is static moment; J is moment of inertia of a mechanical drive part; and p_τ is number of pole pairs.

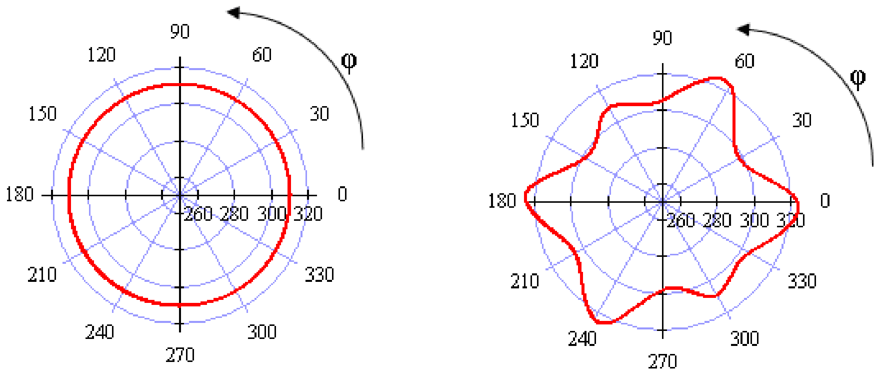
Software implementation of such AM model operating in terms of poor-quality power is tested by describing starting process, load rise, and steady-state mode of the motor of MTKH 112-6 type with the power of 5.3 kW characterized by following values: U_{1n}=310 V, n_n=875 rot/min, J=0.08 kg·m^2, R_1=1.61 Ohm, R_2=2.19 Ohm, R_0=6.2 Ohm, $L_{1\sigma}$=0.00362 H, $L_{2\sigma}$=0.00365 H, and L_{12}=0.294 H. In terms of power, in case one, ideal three-phase voltage corresponding to quality indices is used; in case two, asymmetric nonsinusoidal voltage is used corresponding to real one which indices are represented in Table 30. Fig. 39 demonstrates STC hodographs of the indicated voltages which show that asymmetric power stipulates elliptic hodograph shape while nonsinusoidality distorts its shape.

Further, there are obtained graphs of main motor coordinates. As it is seen, available harmonic constituents in AM power results in the development of moment pulsations.

Table 30

Indices of supply voltage quality

Voltage deviation in terms of phases, %	A	11.2
	B	18.8
	C	1.0
Coefficients of harmonic constituents, %	2	5.8
	3	0.83
	4	1.69
	5	0.03
	6	2.78
	7	0.03
	8	0.08
	9	0.23
	10	0.04

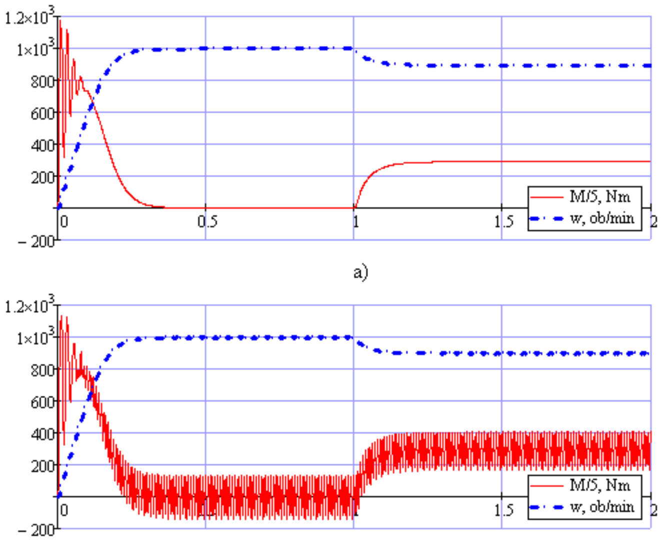


a)

b)

Fig.39 Hodographs of space-time voltage complexes corresponding to indices of quality (a) and asymmetric nonsinusoidal voltage (b).

Fig. 40 shows Moment and velocity of AM while starting and load rising in terms of ideal (a) and asymmetric nonsinusoidal (b) supply voltage.



a)

b)

Fig. 40. Moment and velocity of AM while starting and load rising in terms of ideal (a) and asymmetric nonsinusoidal (b) supply voltage

Fig. 41 shows instantaneous currents of stator and rotor.

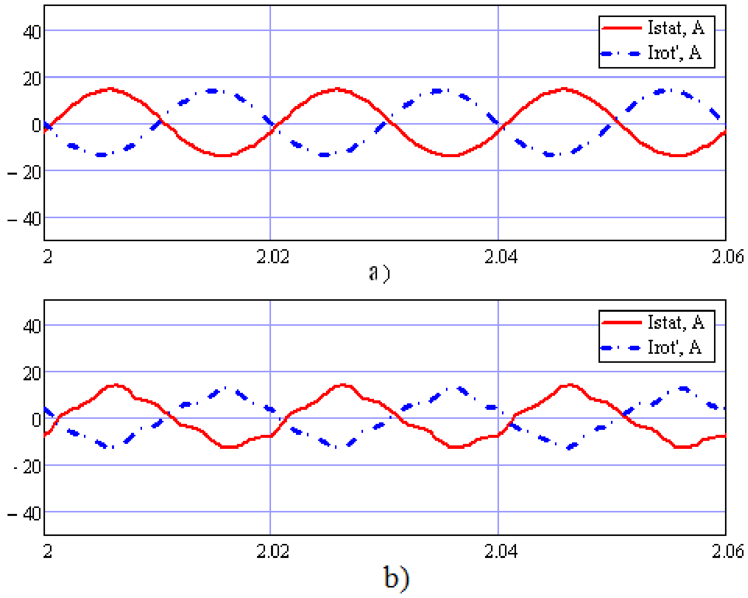
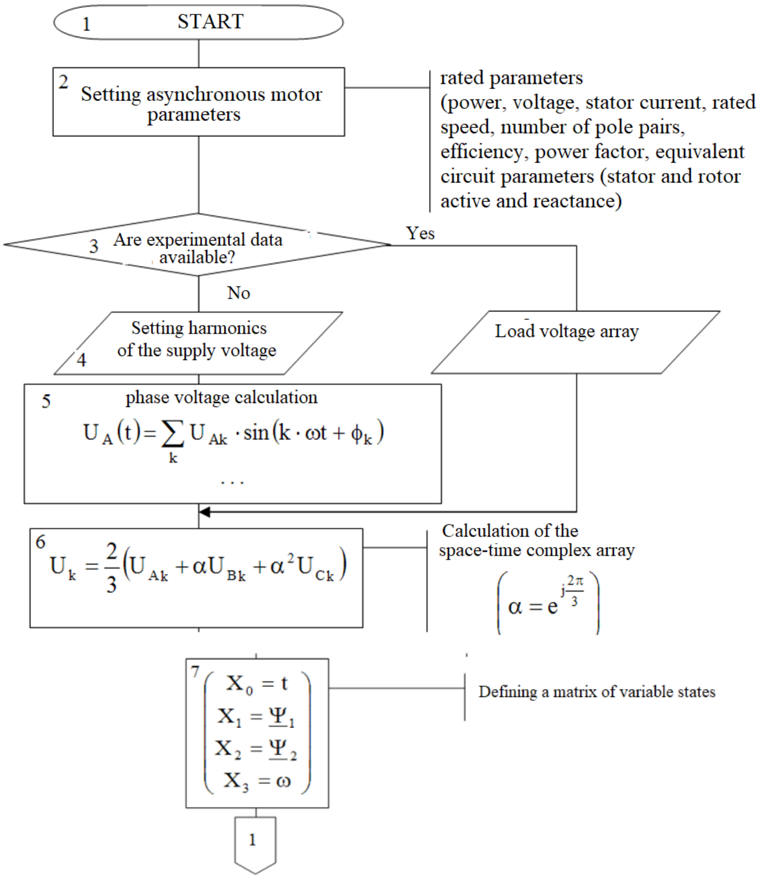
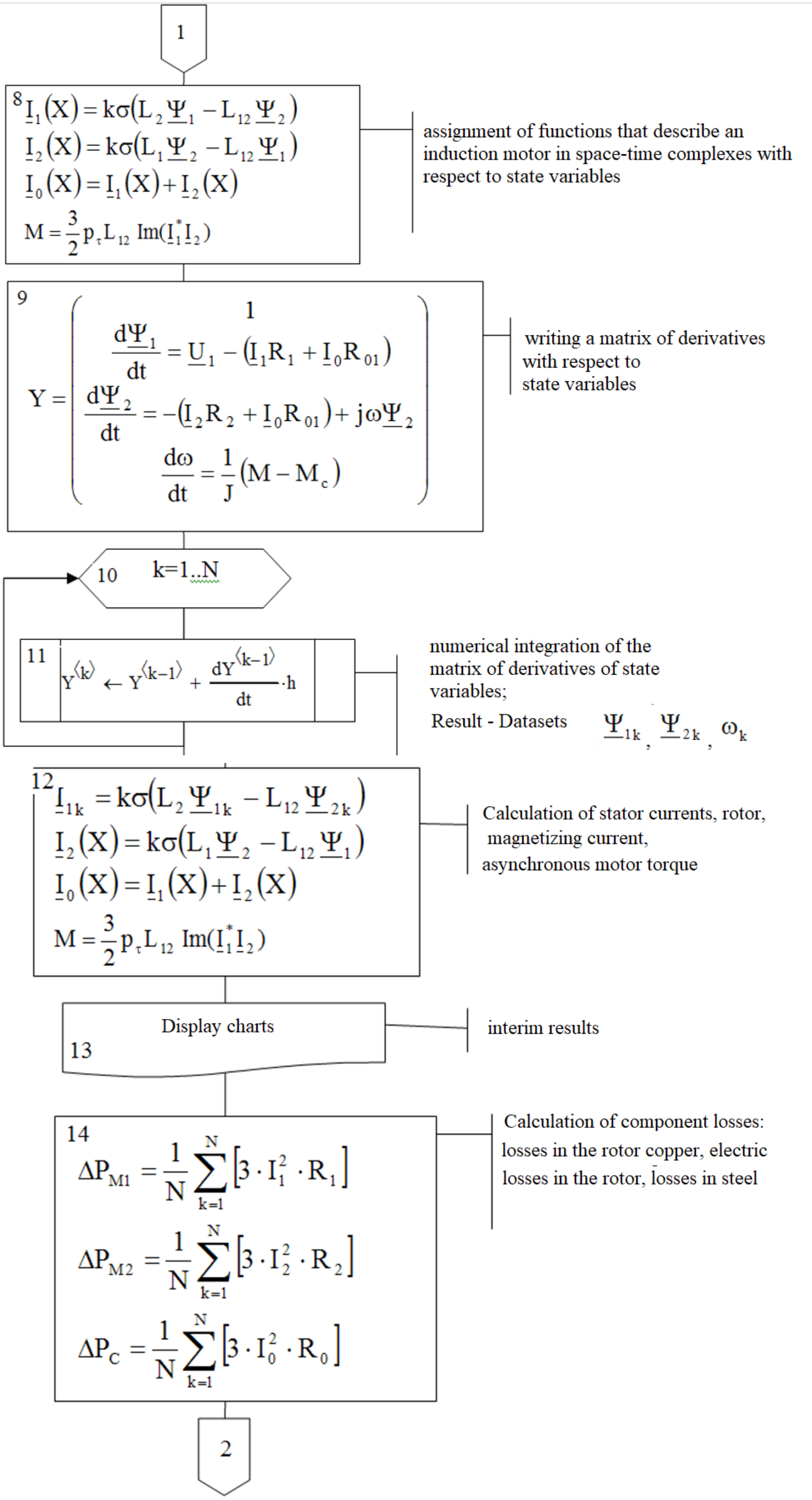


Fig. 41 Currents of stator and rotor in terms of ideal (a) and poor-quality (b) power supply in steady-state mode.

The block diagram of the developed model of the induction motor is presented in Fig. 42. It allows to estimate the considered energy parameters of the induction motor in any mode, at any form of supply voltage.





assignment of functions that describe an induction motor in space-time complexes with respect to state variables

writing a matrix of derivatives with respect to state variables

numerical integration of the matrix of derivatives of state variables;

Result - Datasets $\underline{\Psi}_{1k}$, $\underline{\Psi}_{2k}$, ω_k

Calculation of stator currents, rotor, magnetizing current, asynchronous motor torque

interim results

Calculation of component losses: losses in the rotor copper, electric losses in the rotor, losses in steel

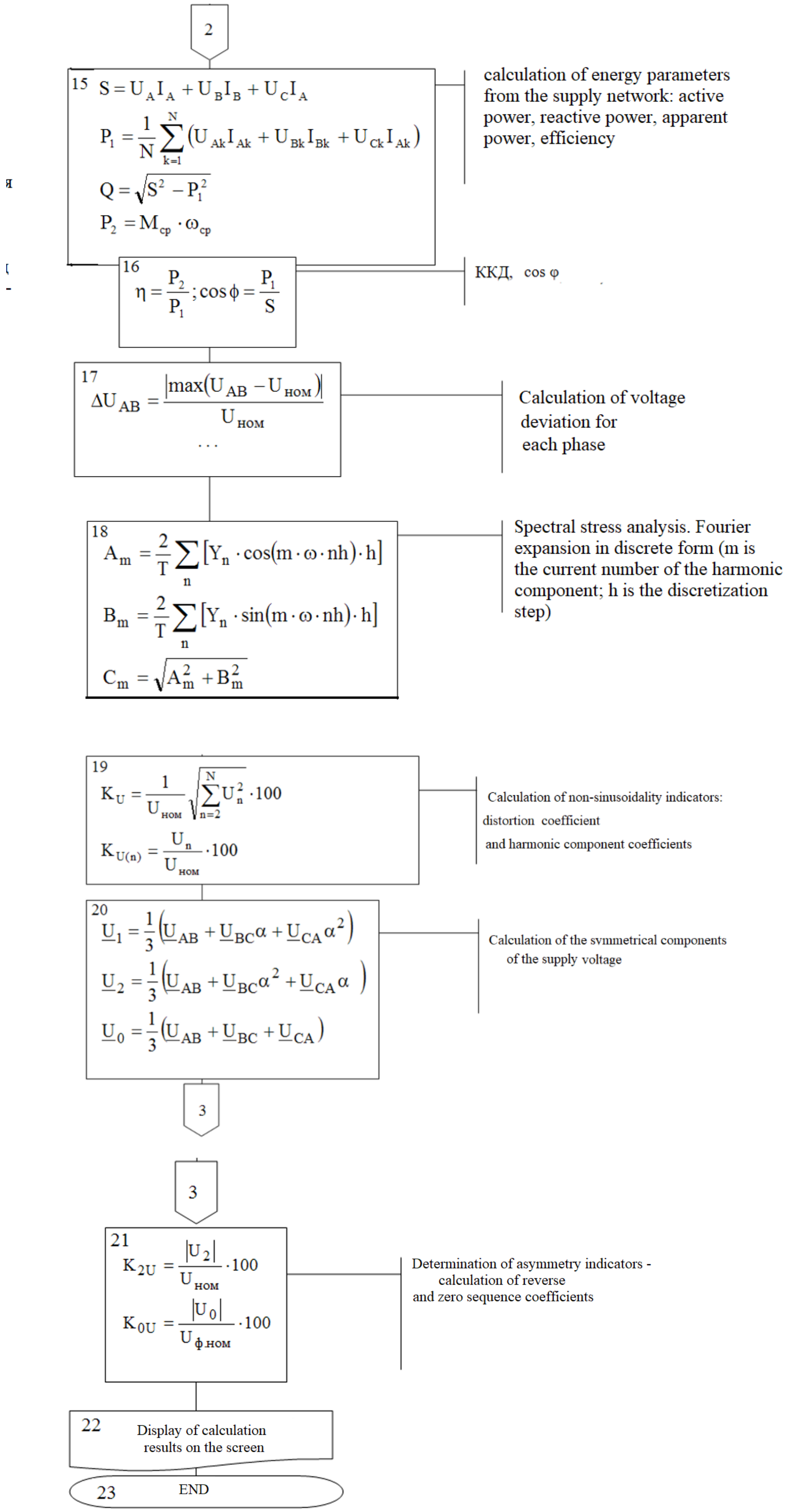


Fig. 42 - Block diagram of the developed combined simulation model of AM

Analysis of the obtained power indices of AM operation represented in Table 31 confirms the fact that poor quality of supply voltage stipulates growth of all the types of losses; consequently there is a decrease in efficiency coefficient and power coefficient of a motor. In this connection, the paper does not consider increase in "heating" losses due to poor quality of supply voltage being determined by motor state and load character. That is the subject of another study.

Table 31

Power indices of AM in terms of its poor-quality power supply

Parameters	Unit.	Sinusoidal power	Nonsinusoidal, asymmetric power
Electrical losses in a stator	W	491.3	498.3
Electrical losses in a rotor	W	652.2	661.5
Iron losses	W	89.2	90
Total losses	W	1235	1250
Coefficient of efficiency	%	81.4	81.2
Coefficient of power	p.u.	0.98	0.9

4.3. Validity check of a synthesized model of asynchronous motor

Experimental validation is the most reliable method to confirm adequacy of any mathematical model. It is required to compare experimental values of the required quantities with the ones obtained on the proposed model. Workshop of "Ukrspetsservis" Ltd was selected as the experimental one; the workshop contains powerful semiconductor converter which operation is accompanied by distortions in the workshop power grid (asymmetry and nonsinusoidality).

During the experiment, oscillograms of currents used by asynchronous motor with short-circuited rotor of 11 kW power (which nominal parameters are shown in Table 32) have been obtained. In the process of the experiment, there was an access to a zero point of the motor; thus, oscillograms of phase currents and voltages were taken. Measuring of active resistances of windings has shown their symmetry and correspondence to the certified values. AM shaft load was of random character changing within a wide range from 2.3 up to 12.8 kW that corresponds to (0.21…1.16)Pном. Respective GOST 7217-87 "Rotating electric machines. Asynchronous motors. Testing methods" were taken as the basic values of power parameters.

Table 32

Certified values of the considered motor

Parameters	Measuring unit	Value
Nominal power	kW	11
Stator current	A	22
Rotation frequency	rot/min	1450
Coefficient of efficiency	%	91
cosφ	p.u.	0.85

Electric motor is mounted to drive a crusher. Its load was varied by controlling the feed hopper loading. Fig. 43 demonstrates a diagram of equipment connection during the experiment. In this case, measuring complex SCEDP (System to control electric drive parameters) manufactured by TsED RPE Ltd. The latter includes current and voltage sensors made by LEM (Switzerland); the sensors operate on the basis of Hall effect, their dynamic error is 0.01%. Velocity was measured by a tachometer generator of ТМГ-30 type. AD conversion module by L-Card company (Russia) is also applied. Table 33 represents characteristics of measuring channels.

Table 33

Characteristics of measuring channels

Component	Characteristics
AD converter VDC	
TYPE	E-440
Number of channels	16 differential
Capacity	12 bit
Conversion time	1.7 mcs
Input signal range	±5.12V;±2.56V;±1.024V
Maximum conversion frequency	200 kHz
Zero shift	±0.5М3Р; max 1М3Р
Voltage sensor	
TYPE	LV-400
Input range	0 – 500 V
Output range	0 – 10 V
Maximum static error	0.015%
Maximum dynamic error	0.03%
Current sensor	
TYPE	LA-100C
Input range	0 – 250 A
Output range	0 – 10 V
Maximum static error	0.03%
Maximum dynamic error	0.08%
Tachometer generator	
Type	ТМГ-30
Transfer factor	1.12 V/rot/min

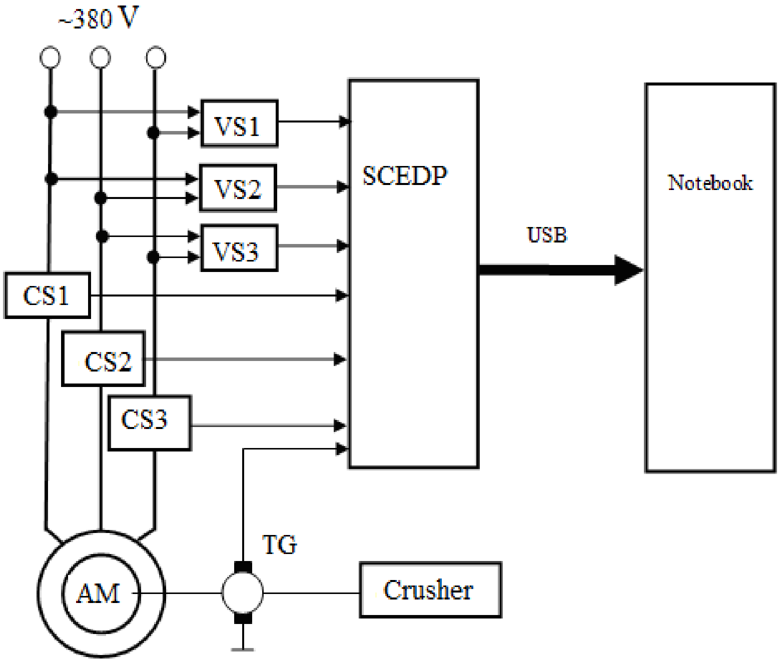


Fig. 43. Diagram of equipment connection to check validity of asynchronous motor model: VS – voltage sensor; CS – current sensor; TG – tachometer generator

An index determining difference between the totals of stator current projections within α-β axes has been used to compare accuracy of the model representation of the required currents within the three phases simultaneously [51]:

$$\varepsilon_i = I_{\alpha i} \cdot \hat{I}_\beta - I_{\beta i} \cdot \hat{I}_\alpha , \tag{44}$$

where $I_{\alpha i}, I_{\beta i}$ are STC projections of the stator current measured within the i^th^ step; $\hat{I}_\alpha, \hat{I}_\beta$ are the same values obtained in terms of the model.

Direct and reverse transition from instantaneous values of phase variables to their complex representation and projections used in the model is considered in detail in [52,53]. Relative mean square value of that difference within the period is applied as an adequacy criterion of the latter one:

$$\delta I = \frac{1}{I_d}\sqrt{\frac{\varepsilon_i^2}{N}} , \tag{45}$$

where N is number of measurements within the period; I_d is effective current.

In addition, accuracy of the velocity recovery was evaluated; to do that, value of mean square deviation of the recovered and changed signal was used:

$$\delta\omega = \frac{1}{\omega_{cp}}\sqrt{\frac{1}{N}\sum_i (\omega_i - \hat{\omega}_i)^2} \tag{46}$$

where ω_i is effective value of velocity within the i^th^ moment of time, $\hat{\omega}_i$ is recovered value of velocity, ω_{cp} is mean velocity value within the considered interval.

Arrays of phase voltages obtained experimentally were used as input effect of the model under consideration; phase currents acted as its output parameters. Comparison of the phase currents (Fig.44) demonstrates that the model is rather accurate to express real processes in AM. Relative error was not more than 2.4%.

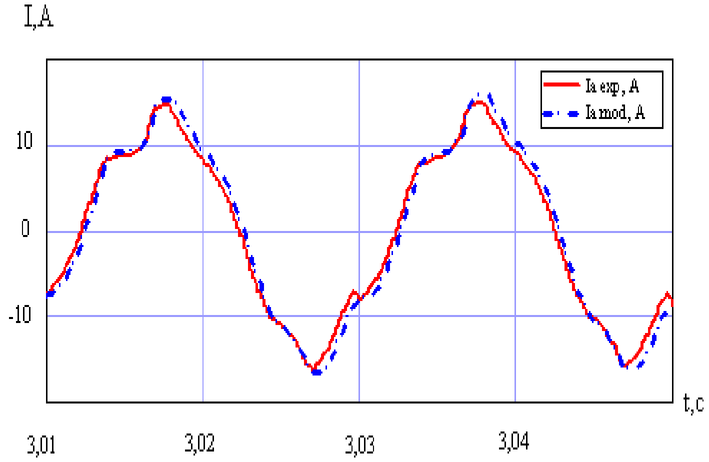


Fig. 44. Current of “A” phase registered experimentally (solid line) and obtained in terms of the model (dot-and-dash line).

Fig.45 shows experimental and model oscillograms of the motor velocity in terms of idle drive starting. As it is seen, poor quality of electrical power becomes apparent not only in current pulsations but also in velocity of the tested motor. Error of indirect measurement of the latter is not more than 4.5%.

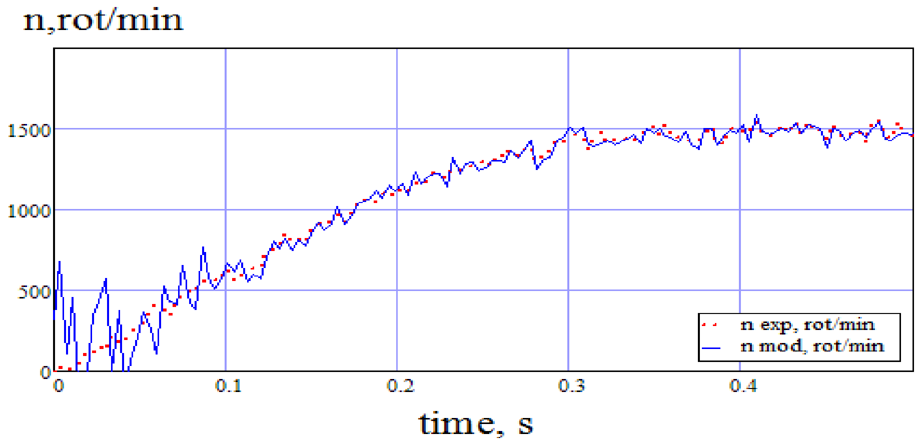


Fig. 45 Motor velocity in terms of idle starting obtained experimentally and by its modeling (solid line)

Basic problem of the carried out studies was to compare the abovementioned AM energy values. A degree of conformity of their prediction to the effective values was determined basing upon regression analysis according to [42,50]. Results of the latter are shown in Fig. 46. Here, a range of changes in total losses was 0.98…1.62 of their nominal value due to short-time AM overloads during the experiment.

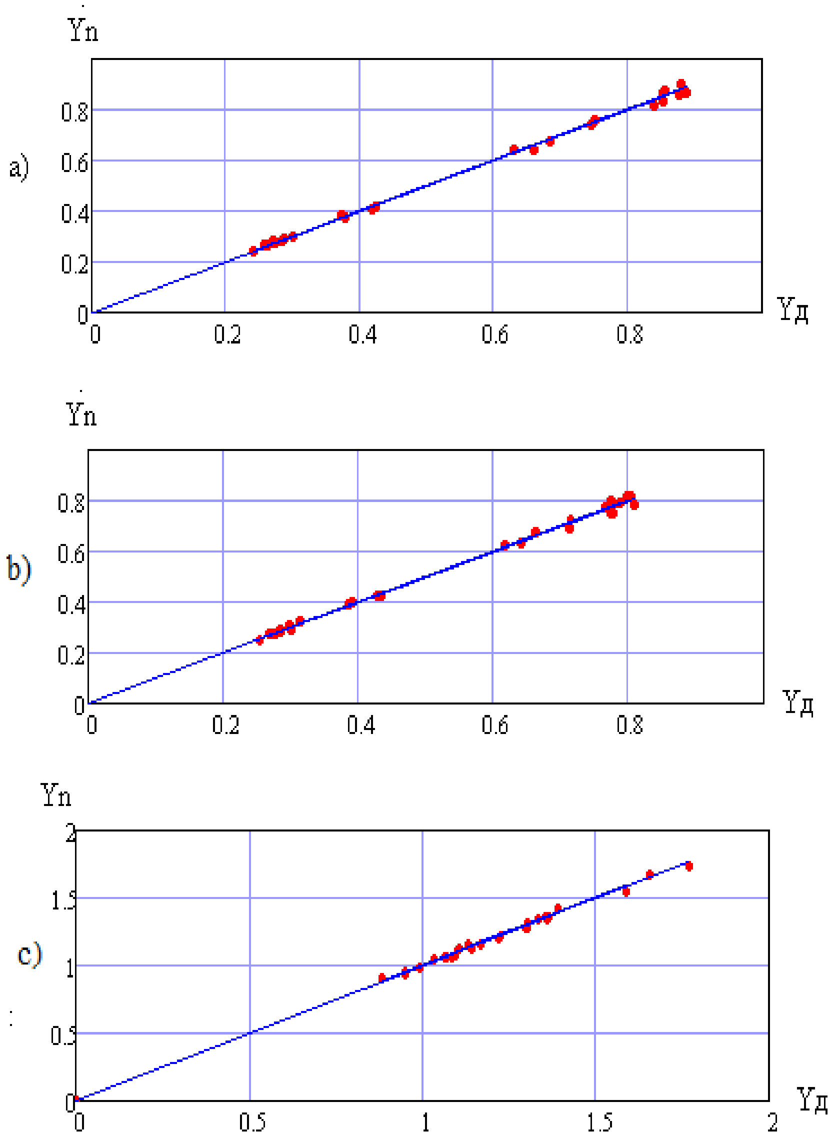


Fig. 46. Correspondence of the experimental data to the modeling results: a) motor efficiency; b) power factor; c) total losses

Adequacy of the model in terms of each criterion was evaluated by statistical methods involving regression dependence [54-58]:

$$Y_n^* = a_0 + a_1 Y_{\text{д}}, \qquad (47)$$

where $a_0 = \overline{Y_n} - r_{Y_{\text{д}} Y_n} \sigma_{Y_n} / \sigma_{Y_{\text{д}}} \overline{Y_{\text{д}}}$; $a_1 = r_{Y_{\text{д}} Y_n} \sigma_{Y_n} / \sigma_{Y_{\text{д}}}$.

Here $\overline{Y_n}$, $\overline{Y_{\text{д}}}$ are mean value of predicted and effective values; $r_{Y_{\text{д}} Y_n}$ is coefficient of correlation between those values; and $\sigma_{Y_n}, \sigma_{Y_{\text{д}}}$ are mean square deviations. The mentioned values were calculated according to formulas:

$$r_{Y_\partial Y_n} = \frac{\sum_1^L \left(Y_\partial - \overline{Y_\partial}\right)\left(Y_n - \overline{Y_n}\right)}{L\sigma_{Y_\partial}\sigma_{Y_n}}, \tag{48}$$

$$\sigma_{Y_\partial} = \sqrt{\sum_1^L \left(Y_\partial - \overline{Y_\partial}\right)^2 / \left(L-1\right)}, \tag{49}$$

$$\sigma_{Y_n} = \sqrt{\sum_1^L \left(Y_n - \overline{Y_n}\right)^2 / \left(L-1\right)}, \tag{50}$$

where $L = 27 -$ is volume of statistical sampling (number of the measurements).

Absolute mean square error of measurements was determined as follows:

$$\Delta Y_n = t_p \sigma^*_{Y_n}, \tag{51}$$

where t_p is Student's coefficient for the preset numbers of the degree of freedom $k = L - 1$ and reliability. In terms of the case being considered, the latter was taken as $p = 0.05$. Here $\sigma^*_{Y_n}$ is the residual mean square deviation calculated according to formula:

$$\sigma^*_{Y_n} = \sqrt{\sum_1^L \left(Y_n - Y_n^*\right)^2 / \left(L-1\right)}. \tag{52}$$

Mean square relative error of prediction was determined as follows:

$$\delta_{Y_n} = \left|\Delta Y_n\right| / Y_{n\max} 100\%, \tag{53}$$

where $Y_{n\max}$ is the highest predicted value among the obtained ones.

Table 34

Results of model verification

Criterion	Coefficient of efficiency	Coefficient of power	Total losses
Coefficients of regressive models			
a_0	-0.458	-0.493	0.656
a_1	0.97	1.13	0.98
Factors of model accuracy			
Mean square deviation of effective parameter	0.276	0.241	0.319
Mean square deviation of predicted parameter	0.273	0.241	0.317
Coefficient of correlation	0.99	0.99	0.99
Residual mean square deviation	0.0212	0.031	0.017
Absolute mean square error	0.024	0.027	0.036
Relative mean square error	2.72%	3.0%	3.99%

Table 34 shows results of calculations of all the modeled values. The obtained values of relative mean square error of the prediction prove the adequacy of the developed model.

Conclusions on chapter 4.

The developed model of asynchronous motor makes it possible to analyze static and dynamic processes in an electromechanical system in terms of nonsinusoidal and asymmetric rotor power supply.

While checking the validity of the model, the obtained values of relative mean square error of modeling make it possible to be used for the purpose of computational studies of AM energy efficiency.

Since the represented mathematical analogue of AM is the tool to analyze performance characteristics of the operation of electromechanical converter under conditions of varying power quality factor, it is obvious that it should be complemented with its probabilistic model of workshop power grid of industrial enterprises helping predict the mentioned PQI changes within a specific power grid.

CHAPTER 5
TESTING THE ADEQUACY OF A THERMAL DYNAMIC MODEL OF AN ASYNCHRONOUS MOTOR OPERATING IN THE MAINS WITH POOR POWER QUALITY

As is known [59], normative operating life of the all-purpose asynchronous motors is about ten years. However, that is true only for the cases when certain conditions are observed. The main condition here is the correspondence of the thermal mode of an electric machine to the insulation class. Deterioration of the power quality results in the increase of heating losses and insulation temperature respectively. Combined with the overloads, that results in the considerable reduction of the operating life of the electric motors. Practice shows that in terms of 40% of all-purpose AM with nominal voltage of 0.4 kV, the operating life is 1.25…2 years [60].

To study the effect of the operating modes of an electric motor on its thermal conditions, so-called thermal models are applied [61,62]. They are the equivalent circuits where electric losses act as the heat sources; temperatures of structural components are within the nodes; and corresponding heat conductivities and capacities are located between them. The considered models have different degree of detalization. A single-mass model, in which an electromechanical transducer is represented as a single homogeneous body with the overall temperature, is the simplest one. Although, the real temperature distribution is not uniform: temperature of the AM stator winding may exceed the case temperature by 15-20°C [63].

More detailed models have minor prediction errors; however, that requires having additional data on heat conductivities and capacities of separate structural components of a motor. As a rule, such models are used only at the design stage. Besides, while applying those models, the transient-free thermal conditions are analyzed without consideration of their dynamics.

We consider that during the operation, it is the most expedient solution to use a single-mass thermal model; moreover, it is necessary to analyze the temperature of the AM component, being critical in terms of heating, - stator end winding – as the initial parameter of the model. It is well-known that this component is under the poorest cooling conditions since its thermal efficiency is effected mainly by means of the air.

A single-mass dynamic thermal model of the asynchronous motor is described by the following differential equation:

$$\Delta P = A \cdot \tau + \frac{\Delta \tau}{\Delta t} \cdot C \qquad (54)$$

here ΔP is the power of heating losses generated in the electric motor; τ is the exceedance of the motor temperature over the surrounding temperature; $\Delta\tau$ is the increment of the motor temperature per time Δt; A is the coefficient of thermal efficiency, J/(sec·C) (equal to the radiation heat loss per 1 sec in terms of the difference in the indicated temperatures τ = 1 °C); C is the heat capacity of the motor, J/°C. The indicated heat capacity is equal to the amount of heat required for AM heating by 1°C in terms of the nonavailable radiation heat loss.

As is obvious, equation of thermal balance (54) has two unknown values – A and C, which may be defined with the help of experimental data by composing a system of equations relative to the unknowns. In this context, it is possible to improve the accuracy of determining a coefficient of thermal efficiency and heat capacity of a motor at the expense of the totals of parameters measured in several experiments:

$$\begin{cases} \frac{\sum \Delta P}{N} = A \cdot \sum \tau + \sum \frac{\Delta \tau}{\Delta t} \cdot C \\ \frac{\sum \Delta P \cdot \tau}{N} = A \cdot \sum \tau^2 + \sum \frac{\Delta \tau}{\Delta t} \cdot \tau \cdot C \end{cases} \qquad (55)$$

Corresponding experiments have been carried out in terms of experimental workshop of Ukrspetsservis Ltd. Asynchronous motor of 4АХ80А4У3 type has been analyzed (nominal parameters are as follows: U_n=220/380 V (Δ/Y), P_n=1.1 kW, n_n=1400 rot/min, I_n=4.8/2.8 A, η=75%, cos φ=0.81). The motor is loaded on a direct-current generator of П31У4 type (nominal parameters are as follows: U_n=230 V, P_n=1.0 kW, n_n=1450 rot/min, I_n=4.3 A, η=75%). During the experiments, AM was heated under the nominal load; the cooling took place in terms of the non-rotating rotor.

A hole was made in the motor cover to determine the temperature of winding faces with the help of laser pyrometer of Fluke 568 type. The hole was open only for a short period for measuring (5 sec); when the electric motor was operating, the hole was closed to prevent the heat exchange between the internal and external air. Currents and voltages were recorded with the help of a mobile measuring and diagnostic complex based on the current sensors of LA 25A type, voltage sensors LV100P (made by LEM, Switzerland), and AD converter E-440 (L-CARD, Russia). Table 35 shows the characteristics of the measuring channels.

Table 35

Characteristics Of The Measuring Channels Of A Mobile Measuring And Diagnostic Complex

Component	**Characteristics**
1	**2**
AD converter	
TYPE	E-440
Number of channels	16 differential ones
Digit capacity	12 bits
Conversion time	1.7 mcs
Input range	±5.12V;±2.56V;±1.024V;
Maximum conversion frequency	200 kHz
Zero shift	±0.5LOD; max 1LOD.
Voltage sensor	
TYPE	LV-400
Input range	0 – 500 V
Output range	0 – 10 V
Maximum static error	0.015%
Maximum dynamic error	0.03%
Current sensor	
TYPE	LA-100 C
Input range	0 – 250 A
Output range	0 – 10 V
Maximum static error	0.03%
Maximum dynamic error	0.08%

To eliminate the experiment error stipulated by the increased heating during the starting, the tested electric motor is accelerated with the help of a loading machine operating under the motoring conditions. Only when the facility reaches the idling speed, source voltage is supplied to the asynchronous motor, and a loading machine is placed in the dynamic braking mode (Fig. 47).

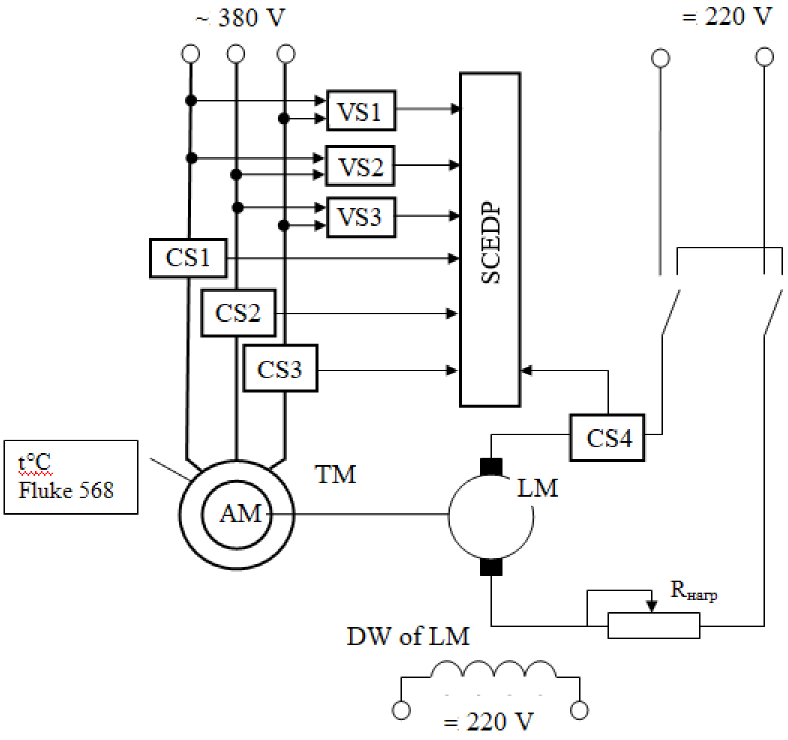


Fig. 47 Schematic of the experience to test adequacy of a thermal model of an asynchronous motor: TM, LM – test machine and loading machine; SCEDP– system to control electric drive parameters (measuring complex); VS – voltage sensor; CS – current sensor ; DW of LM – drive winding of loading machine.

Table 36 represents the results of the experiment of test motor heating in terms of ideal supply voltage.

Table 36

Results of experiment #1, ideal supply voltage

Time, sec	Effective temperature value, °C	Temperature value predicted in terms of the model, °C	Absolute error, °C
0	0.0	0	0
120	5.4	6	1
240	10.4	12	1
360	12.0	17	5
480	14.7	21	6
600	26.1	25	-1
720	28.7	28	0
840	34.7	31	-3
960	37.6	34	-3
1080	40.1	37	-3
1200	43.4	39	-5
1320	45.0	41	-4
1440	46,7	42	-4
1560	47.7	44	-4
1680	48.7	45	-3
1800	50.0	47	-3
1920	50.0	48	-2
Final value	75.7	73	-2

Fig. 48 shows the experimentally obtained curve of test motor heating in terms of ideal supply voltage.

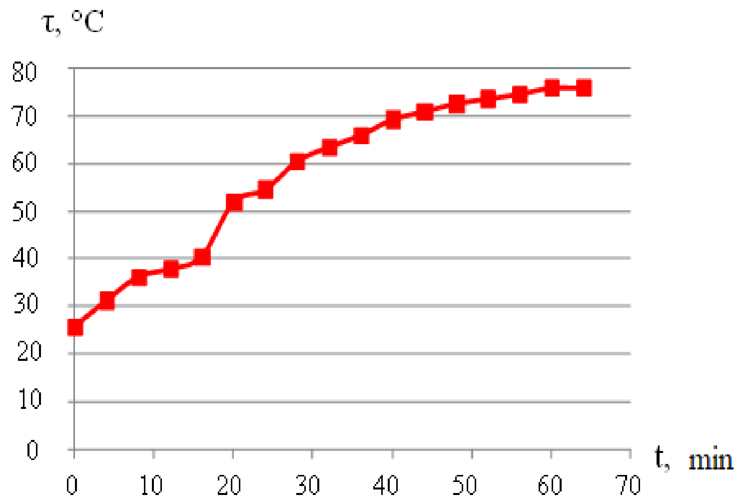


Fig. 48 Curve of motor heating while operating in terms of nominal load and ideal supply voltage

Within the period of 62 minutes, the motor temperature has reached the final value of 76.3°C. The experiment results have made it possible to compose a system of equations (55) and to calculate the parameters of a single-mass thermal model. The parameters are as follows: coefficient of the motor's thermal efficiency while rotating is A=11.2 J/(sec×°C), heat capacity of the electric motor is C – 12.1 kJ/°C.

Considering that the reference literature provides limited information on the thermal parameters of electric machines, this issue remains a significant challenge for engineers and researchers. Typically, available data are restricted to general thermal time constants for motors within specific classes and power ranges, leaving a considerable gap in detailed, machine-specific thermal characteristics. This lack of comprehensive information makes it difficult to accurately assess and model the thermal behavior of individual electric machines, particularly in non-standard applications or under unique operating conditions.

In light of this, the method under consideration for determining the thermal parameters of asynchronous motors (AMs) while identifying a specific model is of high relevance. This approach addresses the existing knowledge gap by offering a practical means to derive precise thermal characteristics tailored to individual motor models.

Such specificity is crucial for improving the accuracy of thermal models, which play a vital role in predicting performance, ensuring reliability, and preventing overheating or other thermal-related failures.

By focusing on the direct identification of thermal parameters through empirical or analytical techniques, the method enhances the ability to optimize motor design and operation. It provides engineers with valuable insights into the thermal dynamics of the motor, enabling more effective temperature management strategies and improved alignment with operational demands. As a result, the development and application of this method represent a significant step forward in advancing the understanding and modeling of electric machine thermal behavior, ultimately contributing to the overall efficiency and durability of electromechanical systems.

Further, the heating experiments were carried out in terms of different degrees of distortion of the electric motor supply voltage. The experimental results are represented in Tables 37 and 38.

Table 37

Results of experiment #2, distorted supply voltage

Time, sec	**Effective temperature value, °C**	**Temperature value predicted in terms of the model, °C**	**Absolute error, °C**
0	0.0	0	0.0
120	12.0	12	0.1
240	23.1	21	1.7
360	30.8	29	1.6
480	33.9	36	-1.7
600	38.7	41	-2.0
720	44.0	45	-0.8
840	44.3	48	-3.9
960	52.0	51	1.0
1080	54.1	53	0.9
1200	54.4	55	-0.6
1320	56.4	56	0.0
1440	56.2	58	-1.4
1560	58.1	59	-0.5
1680	62.0	59	2.6
1800	58.9	60	-1.1
1920	61.2	61	0.6
Final value	86.0	86	0.0

Table 38

Results of experiment #3, distorted supply voltage

Time, sec	Effective temperature value, °C	Temperature value predicted in terms of the model, °C	Absolute error, °C
0	0.0	0	0.0
120	13.8	13	0.6
240	21.9	24	-2.1
360	34.1	33	1.5
480	37.8	40	-1.9
600	46.9	45	1.5
720	47.9	50	-2.1
840	55.5	54	1.7
960	55.3	57	-1.6
1080	60.3	59	0.9
1200	61.1	61	-0.2
1320	64.3	63	1.4
1440	65.5	64	1.2
1560	62.8	65	-2.6
1680	62.8	66	-3.4
1800	69.7	67	2.8
1920	68.1	68	0.6
Final value	93.0	93	0.0

Further experiments #2-4 were carried out in terms of different degrees of distortion of electric motor power supply. The quality indices of the latter (coefficient of distortion of the sinusoidal voltage curve k_U, coefficient of voltage unsymmetry on the reverse sequence ε_2) are given in Table 39.

Table 39

Power quality indices in the experiments and final temperature values of the AM winding

Experience No.	Coefficient of distortion of the sinusoidal voltage curve k_U, %	Coefficient of voltage unsymmetry on the reverse sequence ε_2, %	Final absolute temperature, τ°C
1	0	0	76.3
2	0	4	85.1
3	8	0	92.5
4	13.0	0	117.8

Experience #4 corresponds to the motor operation with the temperature exceeding the admissible one for that insulation class F(105°C); AM may be in such a state only for a short period of time due to the possibility of thermal breakdown of its windings.

The considered experiments have been used to test the adequacy of the proposed AM dynamic thermal model.

Figures 49-54 show the comparison of the graphs of temperature exceedance of the motor over the surrounding temperature in those heating experiments with the calculated curves obtained with the help of electrochemical [64] and thermal model of an asynchronous motor. The Figures also contain oscillograms of voltages and currents of the corresponding experiments.

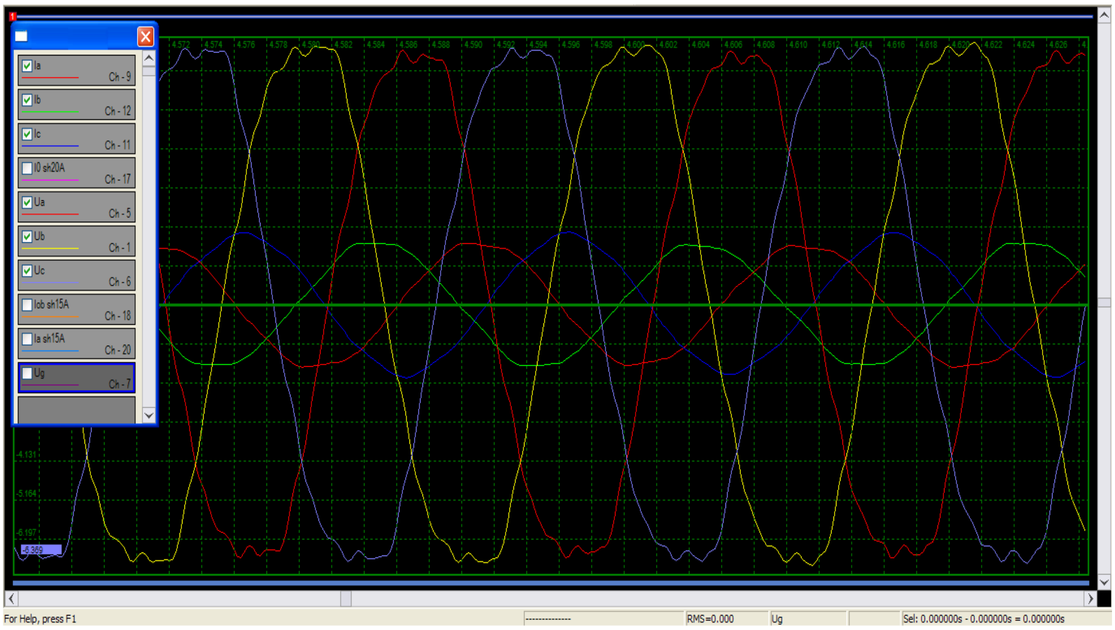


Fig. 49 Oscillograms of voltages and currents (k_U = 6%, ε_2 = 4%) in experiment #2

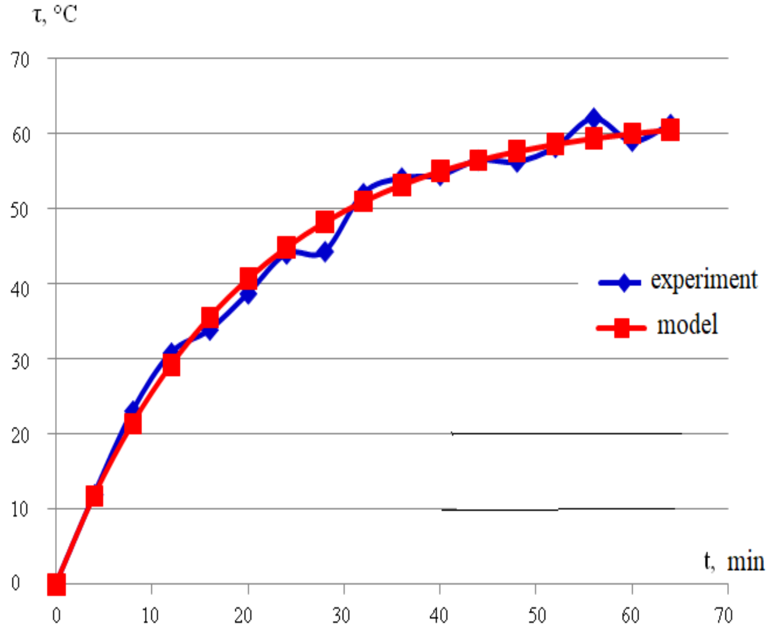


Fig. 50 Curves of motor heating in experiment # 2

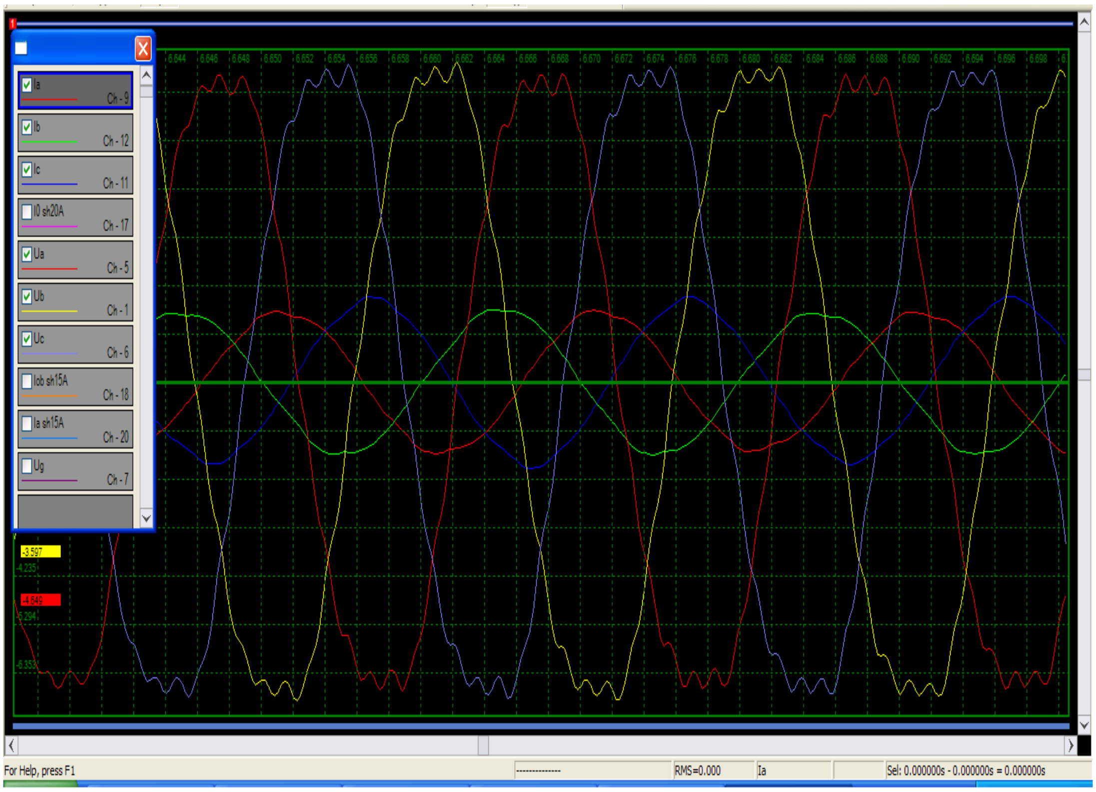


Fig. 51 Oscillograms of voltages and currents ($k_U = 8\%$, $\varepsilon_2 = 4\%$) in experiment #3.

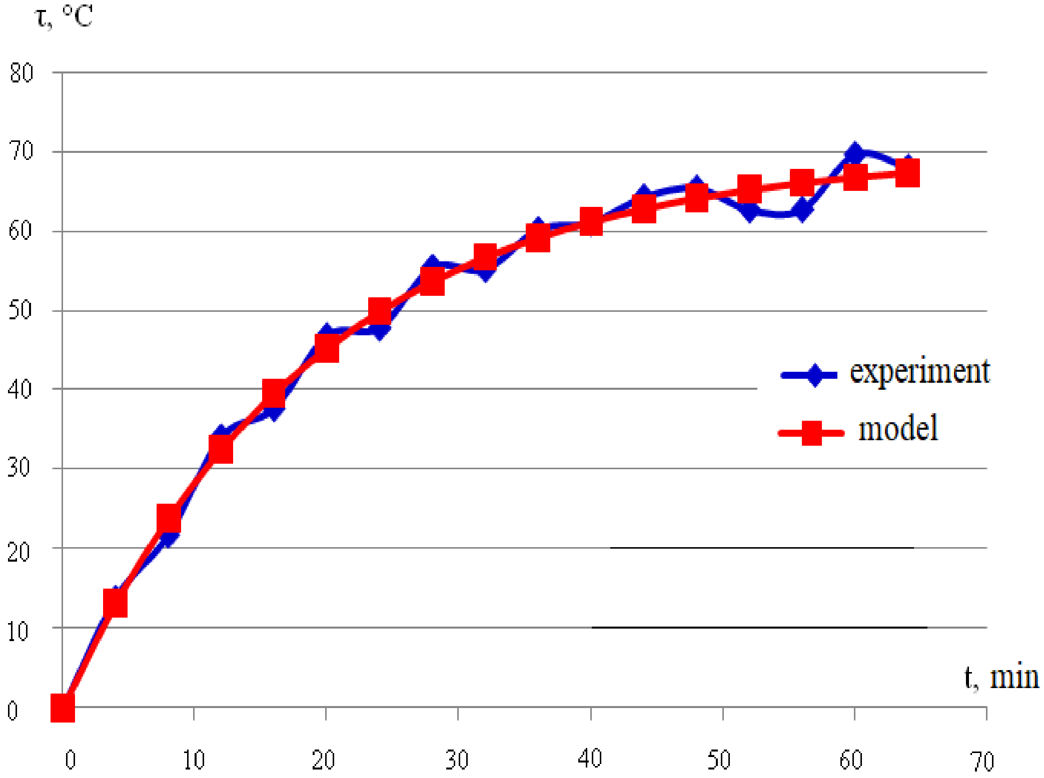


Fig. 52 Curves of motor heating in experiment # 3.

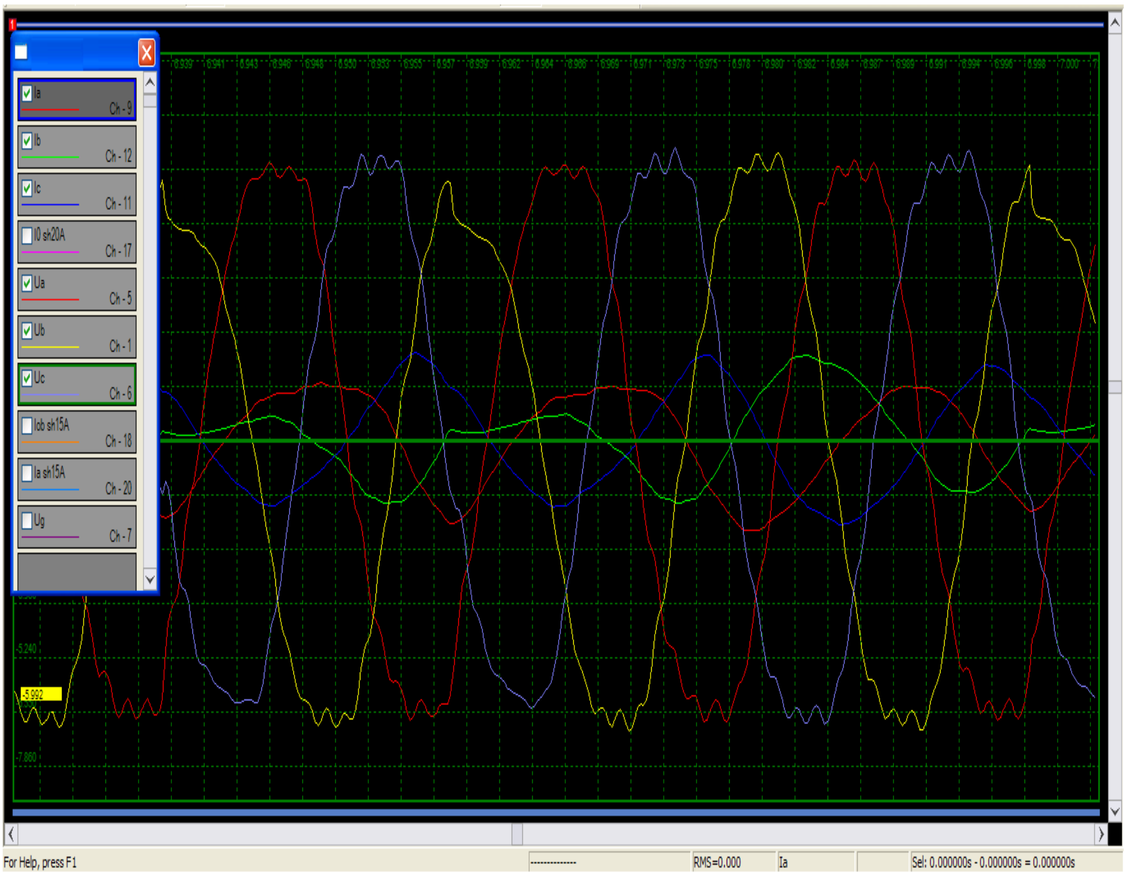


Fig. 53 Oscillograms of voltages and currents (k_U = 13%, ε_2 = 6 %) in experiment 4.

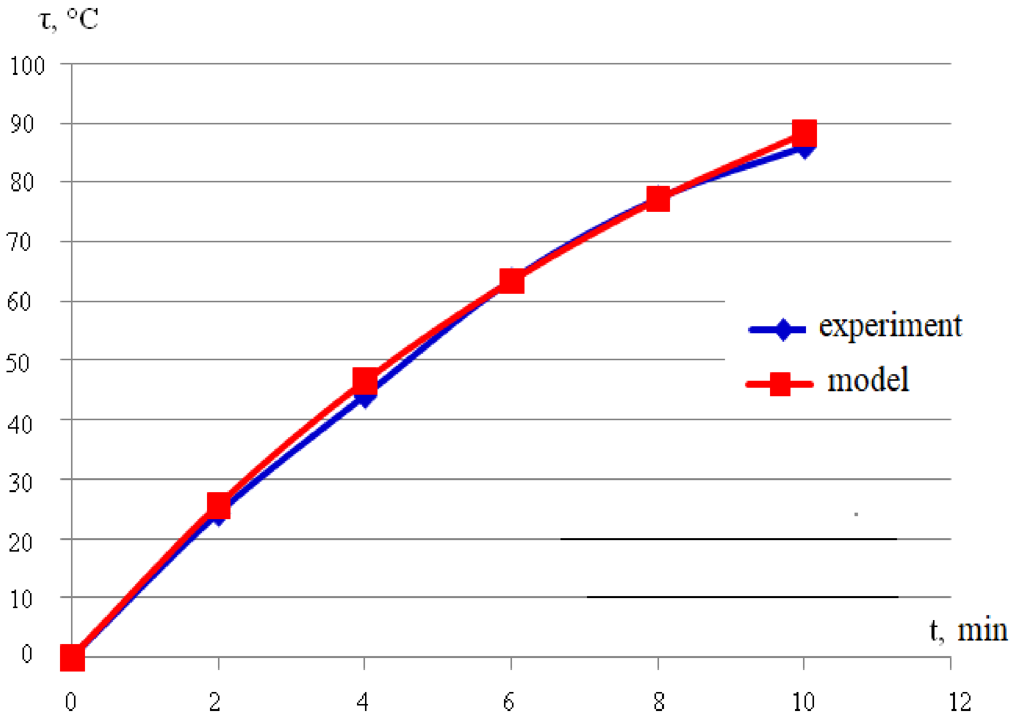


Fig. 54 Curves of motor heating in experiment # 4

Here, the initial values are represented by the parameters of the AM model and an arbitrary-shape curve of supply voltage, applied to calculate the immediate AM power.

In its turn, the latter is used to calculate the degree of losses. In its turn, a value of losses is the input parameter of a thermal dynamic AM model which adequacy is tested.

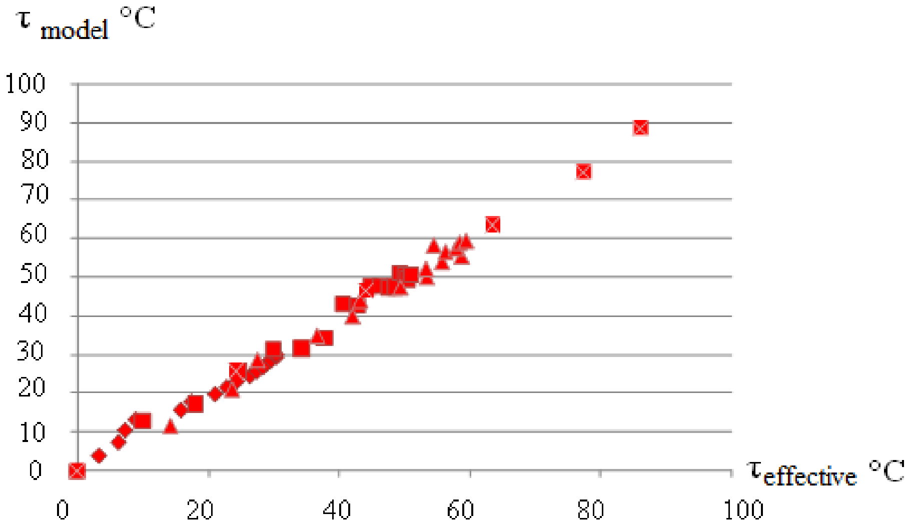


Fig. 55 Relations of the predicted τ_M and experimental τ_{ef} values of the temperature exceedance of AM winding

Next, error of the predicted temperature value in the heating dynamics was calculated. Fig. 55 demonstrates the experimental and calculated (predicted) temperature values for all the performed experiments which are used to test the model adequacy according to the method represented in [65-67]. In this context, different format of markers belongs to the corresponding experiments.

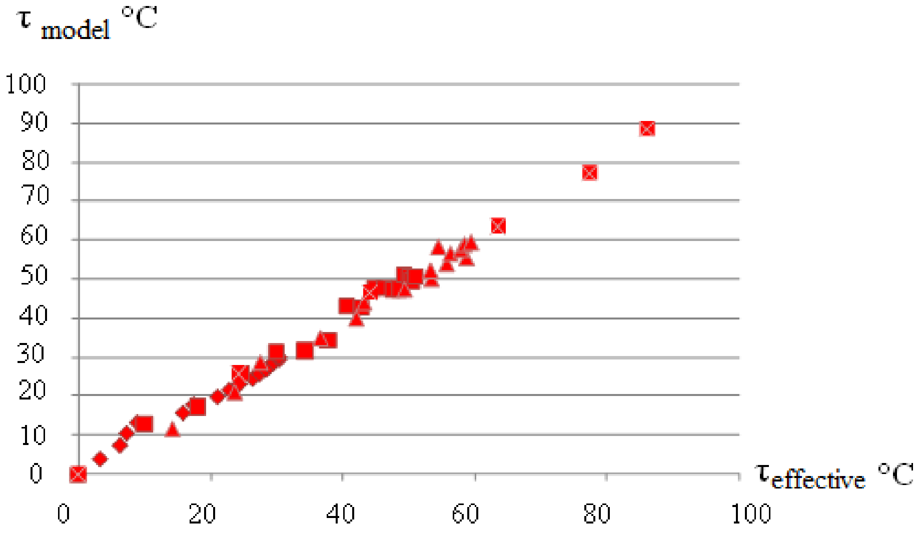


Fig. 56 Relations of the predicted τ_M and experimental τ_{ef} values of the temperature exceedance of AM winding

The carried out test for the adequacy supposes obtaining of the equations (47-53).

Finally, the obtained values are as follows: σ_{Yef} = 21.2 ºC, $\sigma_{Y\text{п}}$ = 20.9 ºC, $r_{YefY\text{п}}$ = 0.99, σ^*_{Yn} = 2.34 ºC, ΔY_n = 0.28 ºC, δ_{Yn} = 3.2%.

Conclusions on chapter 5

The obtained results show the adequacy of the proposed thermal model of an asynchronous motor operating in the mains with poor quality power. Taking into consideration the fact that in terms of many motor types, reference literature does not contain the required data on the coefficients of thermal efficiency and thermal capacity, and only thermal constants of time are given for certain motor types, values of the specified parameters of the model may be obtained basing on the methodology represented in the chapter 1.5.

CHAPTER 6

ALGORITHM FOR IMPROVING THE ENERGY EFFICIENCY OF AN ELECTRIC CONSUMER USING THE EXAMPLE OF AN ASYNCHRONOUS MOTOR OPERATING IN CONDITIONS OF LOW-QUALITY ELECTRICITY

An algorithm is illustrated the comparing of an options for AM protection equipment for making the considered decisions.

Figure 57 illustrates the proposed algorithm for comparing the options.

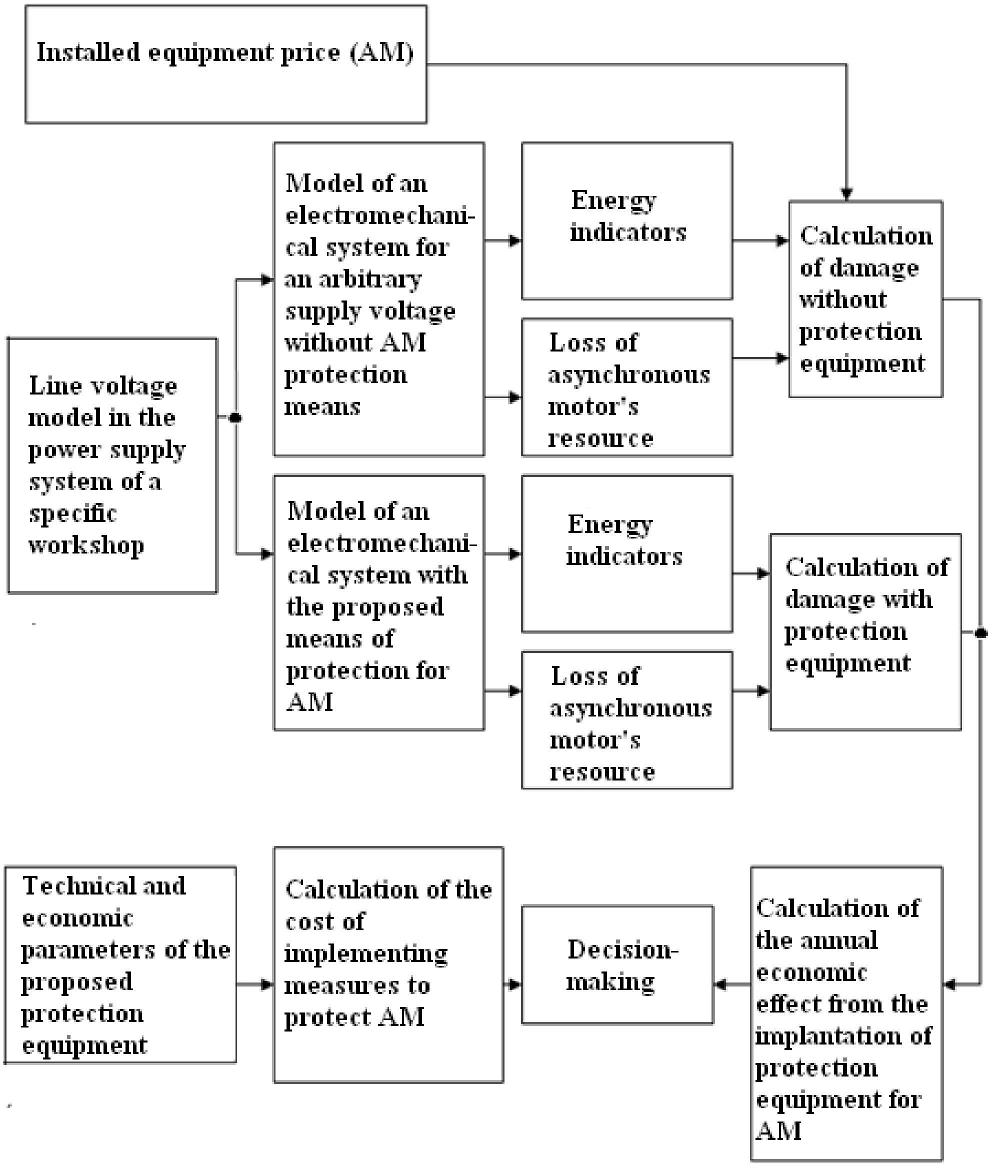


Fig.57 Algorithm for comparing options for AM protection equipment for making a decision on measures to reduce the negative impact of low-quality electricity on technical and economic indicators

Table 40 shows an example of comparing technical and economic indicators for a 7.5 kW motor, which operates for 80% of the operating cycle in conditions of low-quality electricity in the experimental workshop of the Open Joint Stock Company "Ukrspetsservice".

Table 40

An example of calculating the technical and economic indicators of AM

Indicator	**Unit of measurement**	**Value**
Motor rated power	kW	7,5
Sinusoidal distortion factor	%	9
Negative sequence factor	%	3
Annual damage caused by non-sinusoidality	thousand UAH	1,11
Annual damage caused by asymmetry	thousand UAH	1,212
Damage from reduced motor life	thousand UAH	2,600
TOTAL, total damage	thousand UAH	4,922
The cost of passive filters	thousand UAH	0,42
Active filter cost	thousand UAH	6,00

GENERAL CONCLUSIONS

In this work, on the basis of the obtained theoretical and applied results and their systematization, the urgent scientific task of developing elements of the energy-economic model "ELECTRIC NETWORK - ELECTRIC CONSUMER" is solved, which makes it possible to select economically feasible means of increasing the energy efficiency of electrical consumers working in a specific shop network with low-quality electricity.

The research carried out in this work allows us to formulate the following conclusions:

The conducted experimental studies of the analysis of the quality of electricity at industrial enterprises of Ukraine showed that in their shop networks there are exceeded levels of at least one of the standardized indicators of the quality of electricity, while the integral indicators of symmetry and sinusoidality are normal, and the coefficients of individual harmonic components significantly exceed the maximum permissible values.

The expediency of using a unified technical and economic model of an electric consumer, made on the example of an asynchronous motor operating in a network with low-quality electricity, has been proved, allowing to make informed decisions to improve the energy efficiency of an electric consumer.

The universal dynamic electromagnetic model of an asynchronous motor has been improved, which makes it possible to analyze static and dynamic processes in an electromechanical system with non-sinusoidal and asymmetric stator power supply. Checking the adequacy of the above mathematical analogue confirmed its adequacy, which indicates the possibility of its use for the tasks of computational studies of the energy efficiency of an asynchronous motor.

It has been proven that the study of the efficiency of using electrical equipment in electrical networks with low-quality electrical energy is advisable to carry out on the basis of computational studies using a probabilistic model of a workshop electrical network, developed on the basis of the method of statistical tests. In this case, the modeling of line voltages in electrical networks with low-quality electricity by statistical methods, in view of the fact that all their harmonic components have fixed oscillation frequencies, on which only changes in amplitudes and initial phases are superimposed, it is advisable to carry out by generating random sequences of the last-mentioned.

The results of the studies were adopted for use in OJSC "Ukrspecservice", they expand the toolkit of energy management of industrial enterprises and can be used in the educational process.

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SCIENTIFIC EDITION

MONOGRAPH

MODELING OF STRUCTURAL ELEMENTS OF THE ENERGY-ECONOMIC MODEL «ELECTRIC NETWORK - ELECTRIC CONSUMER»

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Monograph published in the author's edition
The monograph is included in International scientometric databases

Authorized for printing 24.12.2024.
Publisher's sheet 8.1.
Order No. MGE07-2024. Contracted price.

Published:
ScientificWorld -NetAkhatAV
Lußstr 13,
Karlsruhe, Germany

e-mail: editor@promonograph.org
https://de.promonograph.org

ISBN 978-3-989240-21-6