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CONTENT

РОЗДІЛ 1. MODELING OF STRUCTURAL ELEMENTS OF THE ENERGY-ECONOMIC MODEL «ELECTRIC NETWORK - ELECTRIC CONSUMER»

ABSTRACT

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.

Keywords: energy-economic model "ELECTRIC NETWORK - ELECTRIC CONSUMER", asynchronous motor, line voltages, harmonic components, dynamic electromagnetic model, low-quality electricity, non-sinusoidal and asymmetric power supply, electrical networks

INTRODUCTION

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 No. 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}:

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

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} :

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

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:

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

U_n – the effective value of the voltage of the nth 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:

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

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% [Sapronov, A.A. Low-quality electric power – additional component of the commercial losses of power enterprise/ A.A. Sapronov, D.S. Goncharov // Modern energy systems and complexes and their control: collection of reports. – Novocherkassk, 2006].

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 chapter were presented at the International scientific and technical conferences: «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 National Metallurgical Academy of Ukraine with a master's degree, who study under the educational-professional program «Electromechanical automation systems and electric drive» 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 National Metallurgical Academy of Ukraine with a master's degree, who study under the educational-professional programs: 122 - Informational-control systems and technologies and 151 Automation and computer-integrated technologies 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 - 151 «Automation and computer-integrated technologies» of discipline – «Identification and modeling of technological objects of automation» and for postgraduate students: educational level - Doctor of Philosophy of specialty - 151 «Automation and computer-integrated technologies» 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».
- for students of the Institute of Integrated Education National Metallurgical Academy of Ukraine, with bachelor 's degree in the disciplines: «Electrical engineering», «Electric drive of metallurgical machines and aggregates», «Heat engineering».

1.1 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 general idea of electromagnetic compatibility of consumers within power supply grids, power quality is the topical problem of modern electric-power supply industry. Its solution effects heavily the improvement of efficiency of electric energy use. Development of basic tendencies intended to improve energy efficiency of electric power supply grid depends upon the identification of the reasons causing degradation of electric energy quality. Electric energy quality is the significant factor effecting performance capability of the efficiency of power system and consumers.

A problem to provide quality of electric energy within power grids is important since a number of new progressive technological processes and systems have been implemented recently. Thus, increase in nonlinear and unsymmetrical energy consumers is also available [2].

Objective is to determine basic reasons of deviation of effecting electric energy quality indices from the specified values.

1.1.1 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.

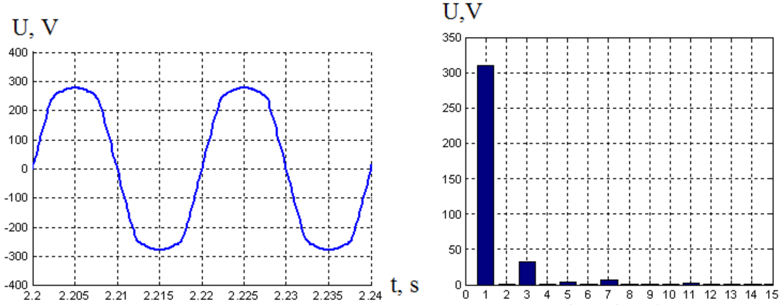
The above does not concern studies of electric energy quality within workshop grids of Alchevsk Metallurgical Integrated Works [3]. Electric drives of rolling mills of roughers and semifinished mills are basic consumers at the enterprise as well as the other similar ones. Power of such drives may be 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.

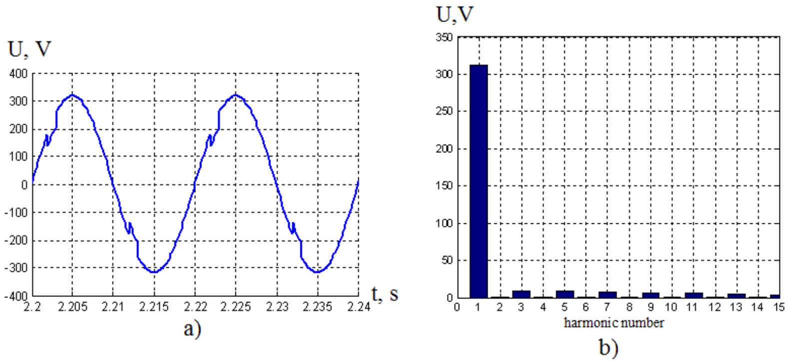


Fig. 2 Shape of a voltage curve if switching noise is available (a) and its spectral structure (b)

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.

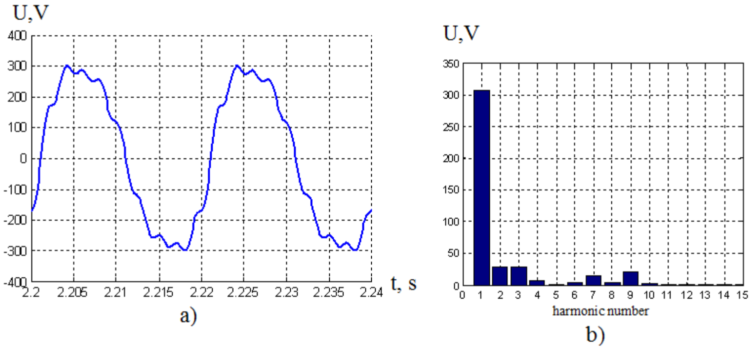


Fig. 3 Voltage curve shape if harmonic two is available (a) and its spectral structure (b)

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

Voltage oscillograms [13], obtained at operating industrial enterprises, confirm availability of poor electric energy within their workshop grids.

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.

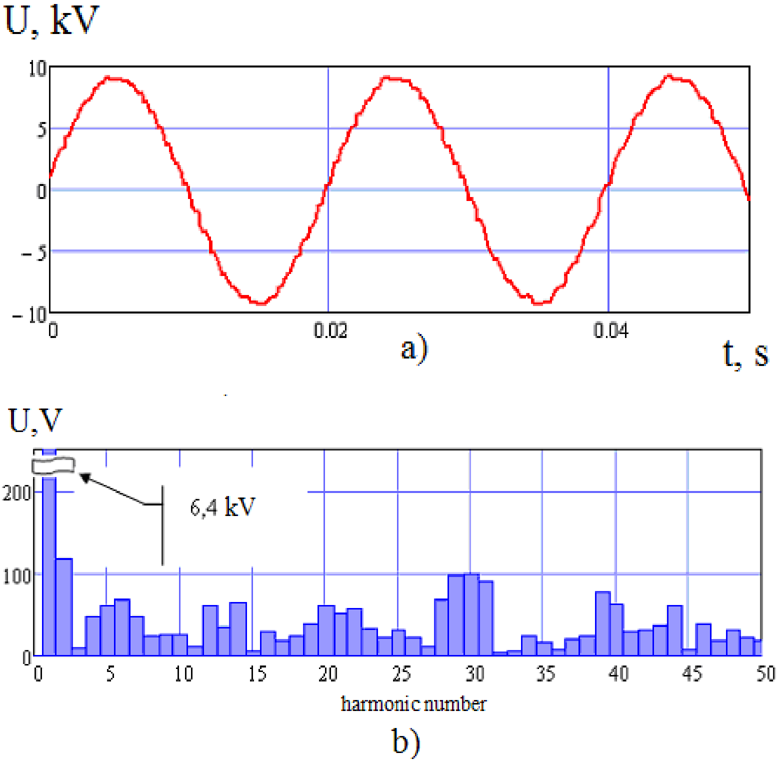


Fig. 4 Oscillogram of linear voltage of substation in a cracking workshop at Ukrtatnafta oil refinery (a) and its spectral structure (b)

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%).

Fig. 5 demonstrates the obtained oscillograms of linear voltages and their spectral structures for the machine workshop of *Zavod Montazhnykh Inzdeli* ltd, city of Dnipro. Such a shape of curves depends upon the workshop substation overload as well as upon the availability of powerful inductive hardening plant.

In the context of the case, to compare with the previous one, high harmonics are within the permissible range; however, voltage waveform distortion factor is 8.4% to be higher than standard permissible value.

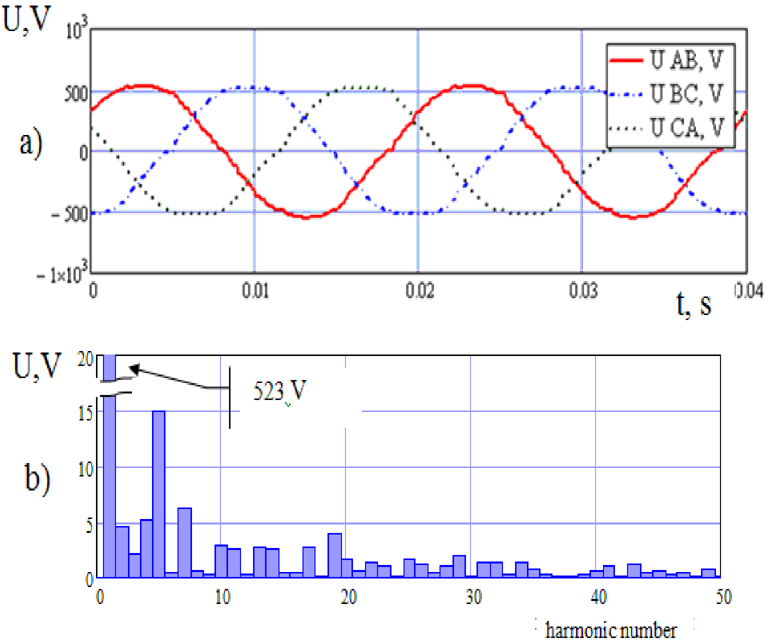


Fig. 5 Oscillograms (a) and spectral structure (b) of linear voltages of mechanical workshop substation of *Zavod Montazhnykh Inzdeli* ltd, city of Dnipro

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 demonstrates quality indices of supplying voltage as for the considered enterprises. Bold type indicates those of them exceeding standard permissible values.

Table 3

Values of power quality indices in workshops of the analyzed enterprises

Enterprise	**Workshop**	**Power quality indices**			
		k_U, %	**$k_{U(\upsilon)}$ %**	**δU,%**	**K_{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.

1.1.3 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].

Hence, solving a problem of efficient power use within grids of non-traction railway consumers is rather topical; like in the previous cases, it should be based upon the results of power quality evaluation right in the process of its transmission and consumption within the grids under study. The problem is independent being equally complex both in theoretical and practical aspects.

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.

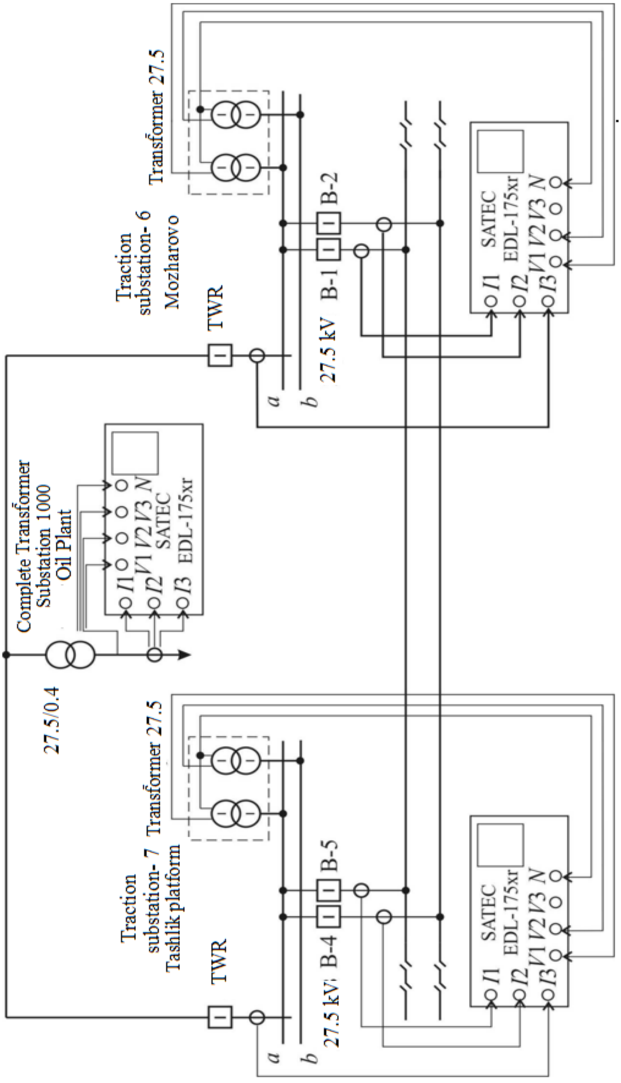


Fig. 6 Measurement plan for industrial object supplied by TWR

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.

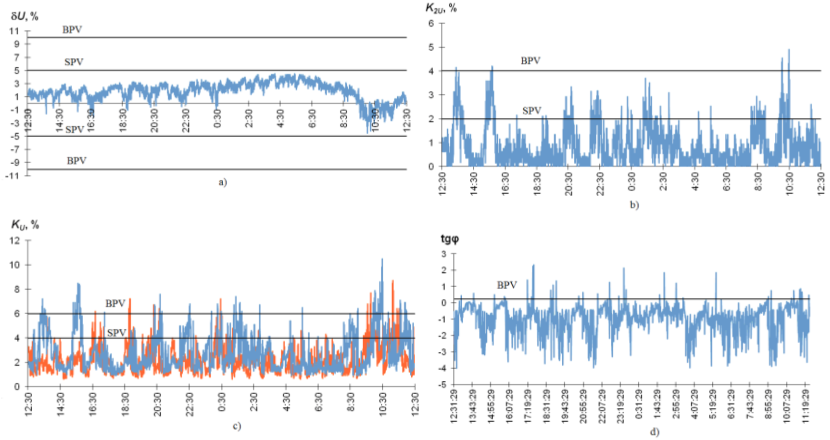


Fig. 7 Changes in power quality indices within 27.5 kV TWR line: a) voltage deviation; b) negative-sequence asymmetry coefficient; c) distortion coefficient of voltage harmonicity; and d) reactive power coefficient

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.

Conclusions on chapter 1.1

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.

1.2 MODELING OF THE “ELECTRIC MAIN – ELECTRIC CONSUMER” SYSTEM

1.2.1 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.

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

Direct simulation of linear voltage within a grid with noisy electricity is complicated by the fact that all harmonic components have fixed frequencies of their oscillations; only random changes in amplitudes and initial phases are superimposed on them. It follows that it is more expedient to generate amplitudes and initial phases of available harmonics, which statistical regularities of changes should be obtained previously, rather than the random voltage sequences [24].

Fig. 8 represents one of the potential variations of the generator of random changes in linear voltages taking into consideration the mentioned above [25].

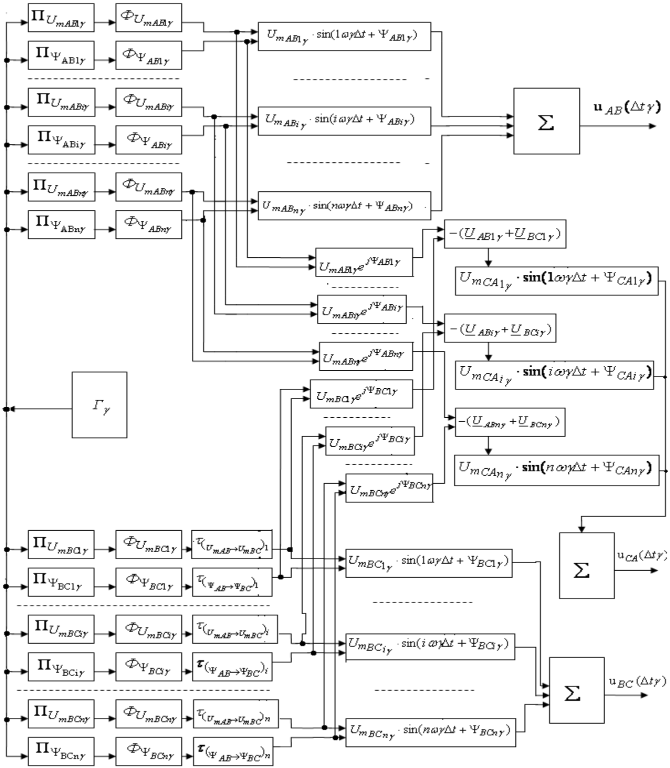


Fig. 8. Generator of linear voltages

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}; $\Phi_{U_{mABi\gamma}}$, and $\Phi_{U_{mBCi\gamma}}$ are filters generating the correlated amplitudes of harmonics of linear voltages U_{AB} , and U_{BC} respectively; $\Phi_{\Psi_{ABi\gamma}}$, and $\Phi_{\Psi_{BCi\gamma}}$ are filters generating the correlated initial phases of harmonics of the same voltages; $\tau_{(U_{mAB}\rightarrow U_{mBC})i}$ 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 $\tau_{(\Psi_{AB}\rightarrow\Psi_{BC})i}$ 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. 8, 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]:

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

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.

1.2.3 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. 9 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).

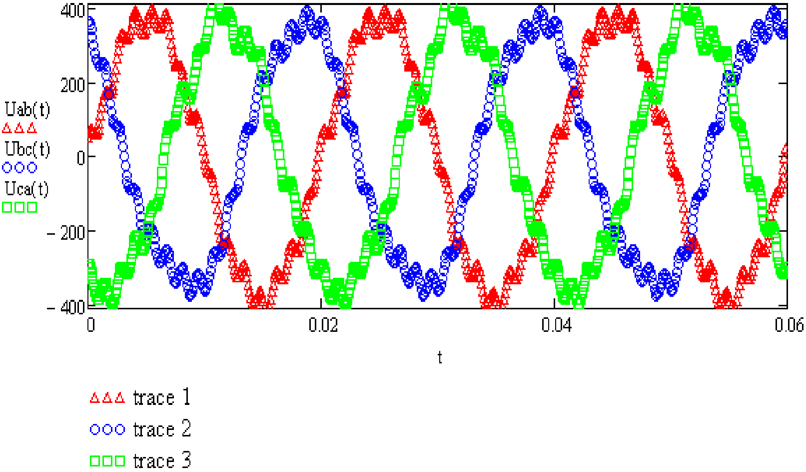


Fig. 9 A fragment of linear voltages u_{AB}, u_{BC}, and u_{CA} within power grid of rolling plant 1 of *Dneprospetsstal* OJSC (Zaporozhie)

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. 10. In this context: ME is mathematical expectation; SFRP and TRP are steady-flow and transient random processes respectively; and CF is correlation function.

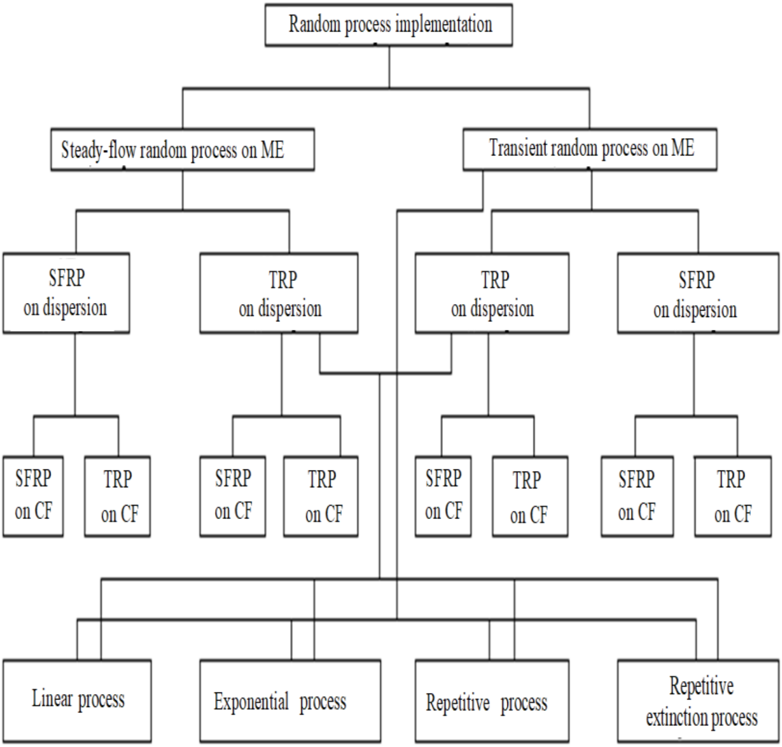


Fig. 10. Classification of random processes

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. 9) 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:

$$[\xi / \sigma_\xi^2] < \Xi(\frac{1+\nu_0}{2}), \tag{6}$$

where ξ is test statistic; σ_ξ^2 is statistic dispersion ξ; Ξ is critical value of a zero hypothesis criterion; ν_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:

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

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

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:

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

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.

Approximation of the calculated curves should be based upon general theoretical factors concerning initiation of random processes. If they are unknown, attention should be paid to common nature of correlation function, and compare them with representative curves. In such cases, certain support points are used where experimental values as well as values, calculated on approximating value, coincide. 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

1.2.4 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:

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

If there is integral in a right side, then:

$$x = F(y). \qquad (13)$$

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

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

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

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

Determine integral in a right side:

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

as well as inverse function:

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

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]:

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

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:

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

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. 11 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.

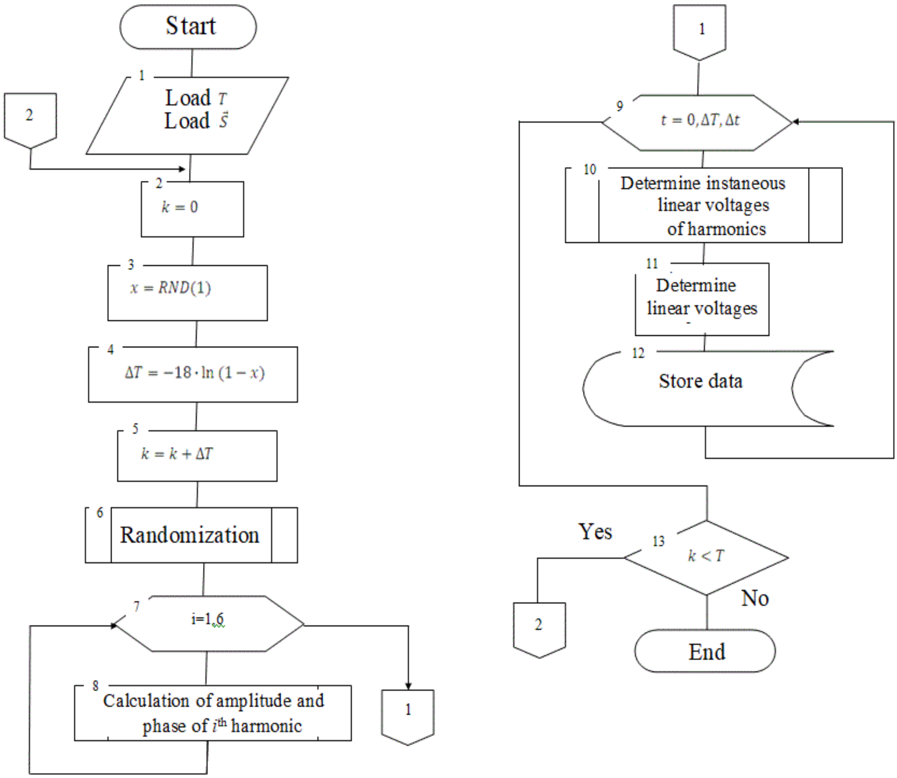


Fig. 11. Algorithm to simulate linear voltages

Fig. 12 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).

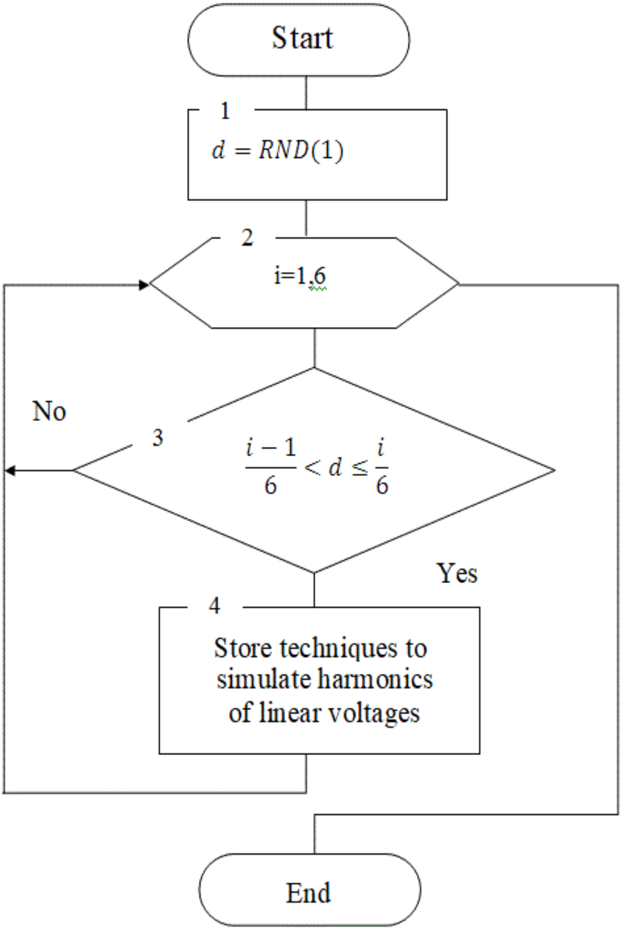


Fig. 12 Randomization algorithm

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 1.2

It is practical to carry out studies, concerning electric equipment efficiency within power grids with noisy electricity, basing upon computational experiments with the use of linear voltage generators developed on the basis of a method of statistical tests.

Since all harmonic components of linear voltages within power grids with noisy electricity have fixed oscillation frequencies, on which changes in amplitudes and initial phases are just superimposed, their modeling by means of statistical methods is expedient while generating random sequences of the latter.

Availability of large intervals between random switching on/switching off of electrical equipment within power grids results in nonstationarity of linear voltages which involves separation of stationary sections.

Randomization of computational sequences of harmonics of linear voltages helps decrease systematic modeling error.

Use of the developed probability model of a workshop power grid with noisy electrical energy helps making correct engineering solutions to provide the prescribed functioning conditions for asynchronous motors basing upon computational studies.

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

1.3.1 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-known fact that the problem solution should be sought at technical-and-economic level involving methods of mathematical modeling. Authors have proposed a technique to make optimum decision as for electric equipment operation under the conditions of noisy power. The technique relies upon economic evaluation of various alternatives to recover supply voltage up to the preset quality indices. According to the technique, power indices of electromechanical transducer are calculated involving the current quality power indices within the enterprise power grid, and basing upon electric model, and thermal model of electrcal consumer. If indices, calculated in such a way, differ substantially from preset ones, various alternatives of engineering solutions, intended to recover electric power supplying the consumer, are considered. Cost of each of the alternatives is estimated and final decision, concerning its further operation, is made [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].

1.3.2 Power and economic model of electric equipment

Fig. 13 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.

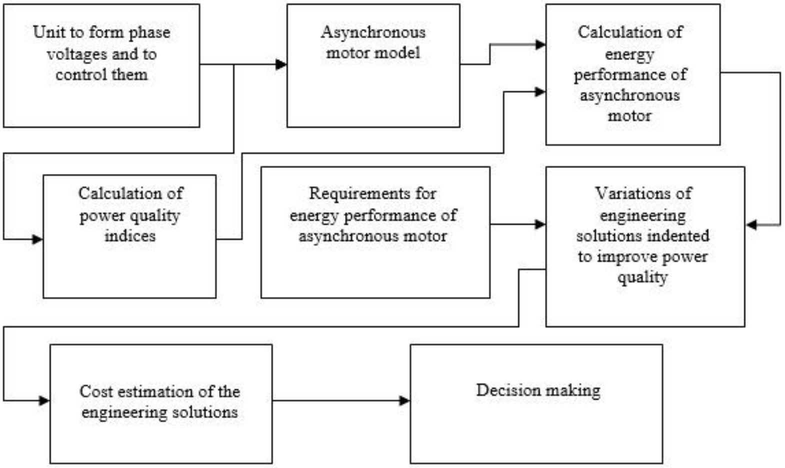


Fig.13 Schematic diagram of power and economic model of electric equipment

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 $\bar{y}(t)$ 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:

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

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

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

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

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

$$\begin{aligned} R_{x,x}[iT,\tau] &= R_{x,x}[(i-1)T,\tau] + \frac{1}{i}((x[(i-1)T] - \bar{x}[(i-1)T]) \times \\ &\times ((x[(i-1)T] - \bar{x}[(i-1)T])) - R_{x,x}[(i-1)T,\tau]) \end{aligned} \tag{35}$$

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

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 $\psi_{BC1}(t)$).

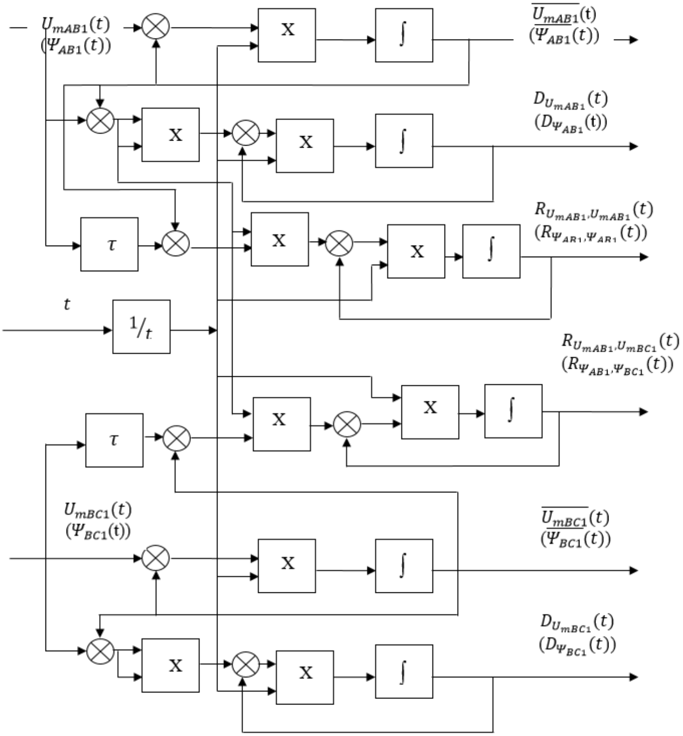


Fig.14 Diagram of analogous control system

Fig. 15 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. 13, can be used in the process of analogous modeling of linear phase voltages; the scheme, shown in Fig. 14, 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].

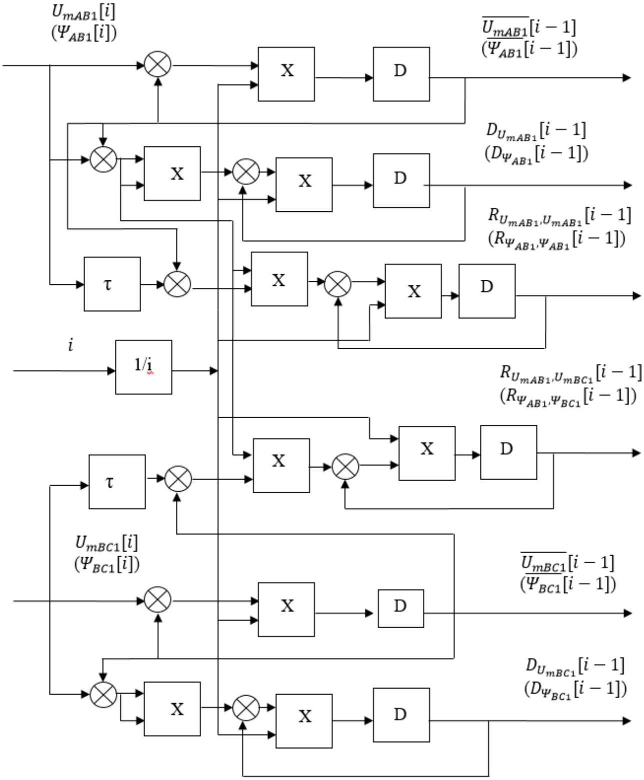


Fig.15 Diagram of discrete control system

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 D_0 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 $\left|U_{observ}\right| < u_{cr}$, 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. 15) if $n = 30$.

Table 28

Checking results of average harmonics of linear voltages

<table>
<tr><th colspan="7">Linear voltage U_{AB}</th></tr>
<tr><th rowspan="2">Harmonic</th><th colspan="3">Amplitude, V</th><th colspan="3">Phase, degrees</th></tr>
<tr><th>Average x_0</th><th>Average $\bar{x}$</th><th>$\left|U_{observ}\right|$</th><th>Average x_0</th><th>Average $\bar{x}$</th><th>$\left|U_{observ}\right|$</th></tr>
<tr><td>1</td><td>529.82</td><td>531.26</td><td>|1.8|</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>4.23</td><td>4.38</td><td>|0.7|</td><td>63</td><td>59.95</td><td>|-1.58|</td></tr>
<tr><td>3</td><td>17.60</td><td>16.85</td><td>|-1.35|</td><td>206</td><td>208.01</td><td>|1.34|</td></tr>
<tr><td>4</td><td>1.51</td><td>1.58</td><td>|1.63|</td><td>92</td><td>94.88</td><td>|1.71|</td></tr>
<tr><td>5</td><td>18.54</td><td>17.75</td><td>|-1.51|</td><td>130</td><td>134.99</td><td>|1.87|</td></tr>
<tr><td>6</td><td>3.05</td><td>2.95</td><td>|-1.02|</td><td>290</td><td>286.24</td><td>|-1.67|</td></tr>
<tr><th colspan="7">Linear voltage U_{BC}</th></tr>
<tr><th rowspan="2">Harmonic</th><th colspan="3">Amplitude, V</th><th colspan="3">Phase, degrees</th></tr>
<tr><th>Average x_0</th><th>Average $\bar{x}$</th><th>$\left|U_{observ}\right|$</th><th>Average x_0</th><th>Average $\bar{x}$</th><th>$\left|U_{observ}\right|$</th></tr>
<tr><td>1</td><td>532.09</td><td>533.38</td><td>|1.70|</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>3.98</td><td>4.41</td><td>|1.88|</td><td>78</td><td>74.63</td><td>|-1.83|</td></tr>
<tr><td>3</td><td>19.13</td><td>18.38</td><td>|-1.44|</td><td>235</td><td>236.7</td><td>|1.33|</td></tr>
<tr><td>4</td><td>1.55</td><td>1.64</td><td>|1.92|</td><td>111</td><td>114.27</td><td>|1.74|</td></tr>
<tr><td>5</td><td>16.77</td><td>17.35</td><td>|1.25|</td><td>114</td><td>109.11</td><td>|-1.85|</td></tr>
<tr><td>6</td><td>4.15</td><td>4.33</td><td>|0.94|</td><td>325</td><td>327.08</td><td>|0.97|</td></tr>
<tr><th colspan="7">Linear voltage U_{CA}</th></tr>
<tr><th rowspan="2">Harmonic</th><th colspan="3">Amplitude, V</th><th colspan="3">Phase, degrees</th></tr>
<tr><th>Average a_0</th><th>Average $\bar{y}$</th><th>$\left|U_{observ}\right|$</th><th>Average a_0</th><th>Average $\bar{y}$</th><th>$\left|U_{observ}\right|$</th></tr>
<tr><td>1</td><td>530.41</td><td>531.85</td><td>|1.90|</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>2</td><td>3.71</td><td>4.07</td><td>|1.78|</td><td>94</td><td>91.23</td><td>|-1.55|</td></tr>
<tr><td>3</td><td>18.27</td><td>19.09</td><td>|1.69|</td><td>182</td><td>182.31</td><td>|0.19|</td></tr>
<tr><td>4</td><td>1.50</td><td>1.57</td><td>|1.63|</td><td>83</td><td>85.42</td><td>|1.77|</td></tr>
<tr><td>5</td><td>16.01</td><td>16.56</td><td>|1.08|</td><td>165</td><td>169.22</td><td>|1.71|</td></tr>
<tr><td>6</td><td>3.82</td><td>3.57</td><td>|-1.88|</td><td>310</td><td>315.34</td><td>|1.89|</td></tr>
</table>

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. 16 and Fig. 17 demonstrate a window of CED Expert software in the process of oscillographic testing of signals during operation of tested electric motor under loading.

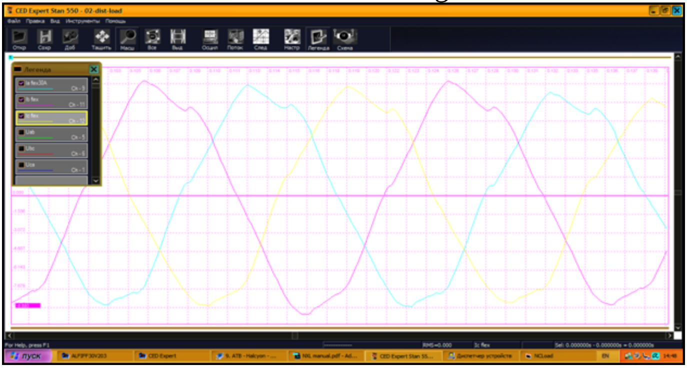


Fig. 16. Oscillograms of currents within the considered electric motor while operating under loading

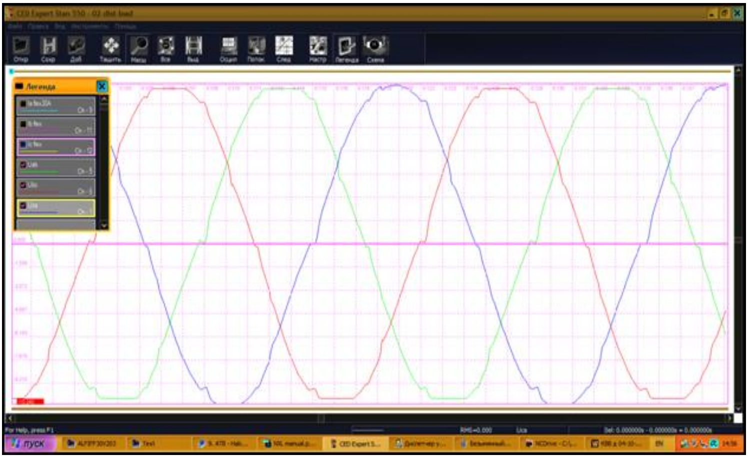


Fig. 17. Oscillograms of voltages within the considered electric motor while operating under loading

Conclusions on chapter 1.3

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.

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

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

It is a well-known fact that modeling of electromechanical systems makes it possible to evaluate all the processes occurring in them during a pre-project stage. The data are the basis for possible correction of the parameters of power units and systems of their control. In terms of asynchronous electric motor that is not the problem anymore with the development of specialized software (CAD-programs). That helps build graphs of transient processes, obtain dependences of the required parameters upon the input factors etc.

However, the situation becomes more complicated when we should consider qualitative indices of the input voltage such as asymmetry and nonsinusoidality. The problem is in the fact that the model itself often becomes inadequate due to certain assumptions. Moreover, if we use more complex analogues, then description of the processes turns to be so complicated that the search for the required dependences is impossible at all.

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.

1.4.2 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:

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

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:

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

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

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.18 [43].

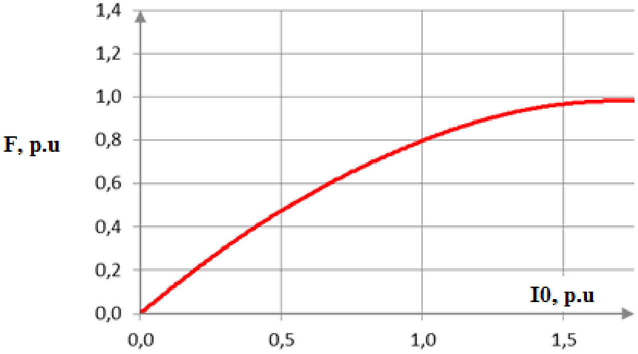


Fig. 18 Dependence of main magnetic flux upon magnetizing current

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.19).

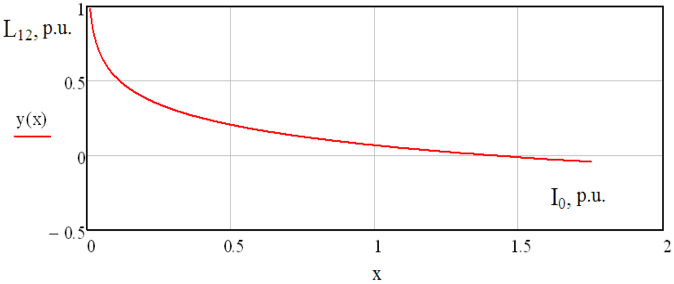


Fig. 19 Dependence of main induction upon magnetizing current

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:

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

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

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

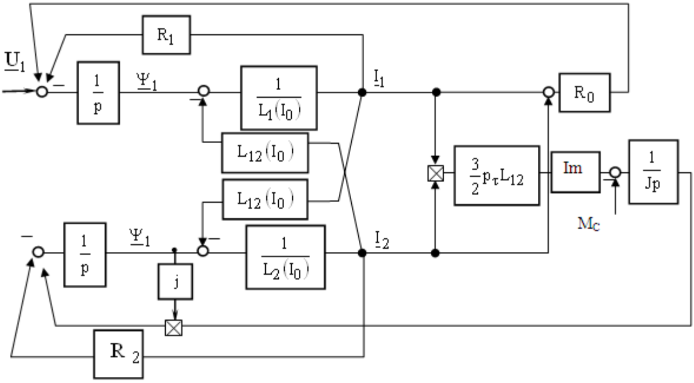


Fig.20 Structural diagram of asynchronous motor as a modeling object

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

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

$$M - M_c = J \frac{d\omega_m}{dt} , \tag{43}$$

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

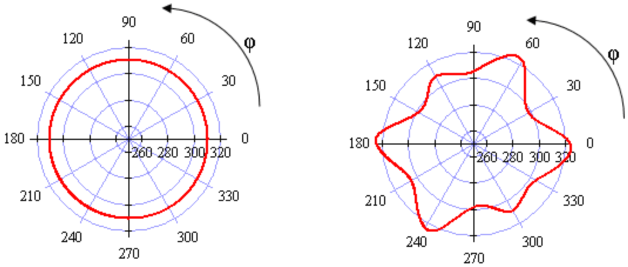
Software implementation of such AM model operating in terms of poor-quality power is tested by describing starting process, load rise, and steady-state mode of the motor of MTKH 112-6 type with the power of 5.3 kW characterized by following values: U_{1n}=310 V, n_n=875 rot/min, J=0.08 kg·m^2, R_1=1.61 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. 21 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.21 Hodographs of space-time voltage complexes corresponding to indices of quality (a) and asymmetric nonsinusoidal voltage (b).

Fig. 22 shows Moment and velocity of AM while starting and load rising in terms of ideal (a) and asymmetric nonsinusoidal (b) supply voltage.

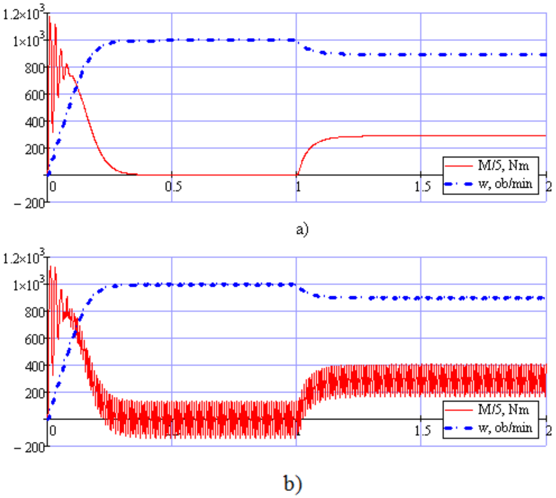


Fig. 22. Moment and velocity of AM while starting and load rising in terms of ideal (a) and asymmetric nonsinusoidal (b) supply voltage

Fig. 23 shows instantaneous currents of stator and rotor.

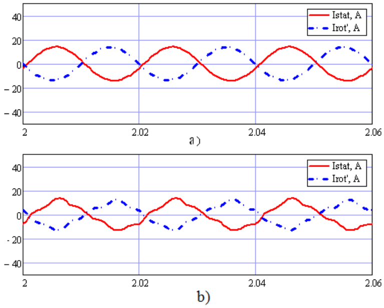
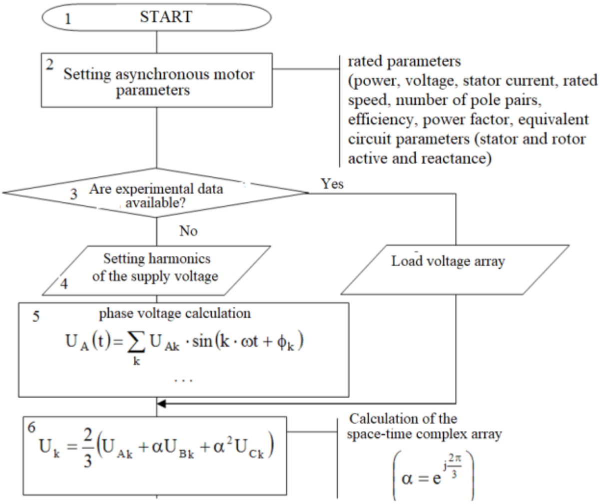
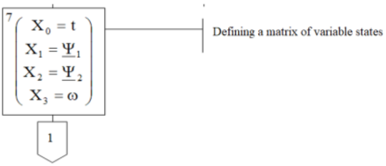
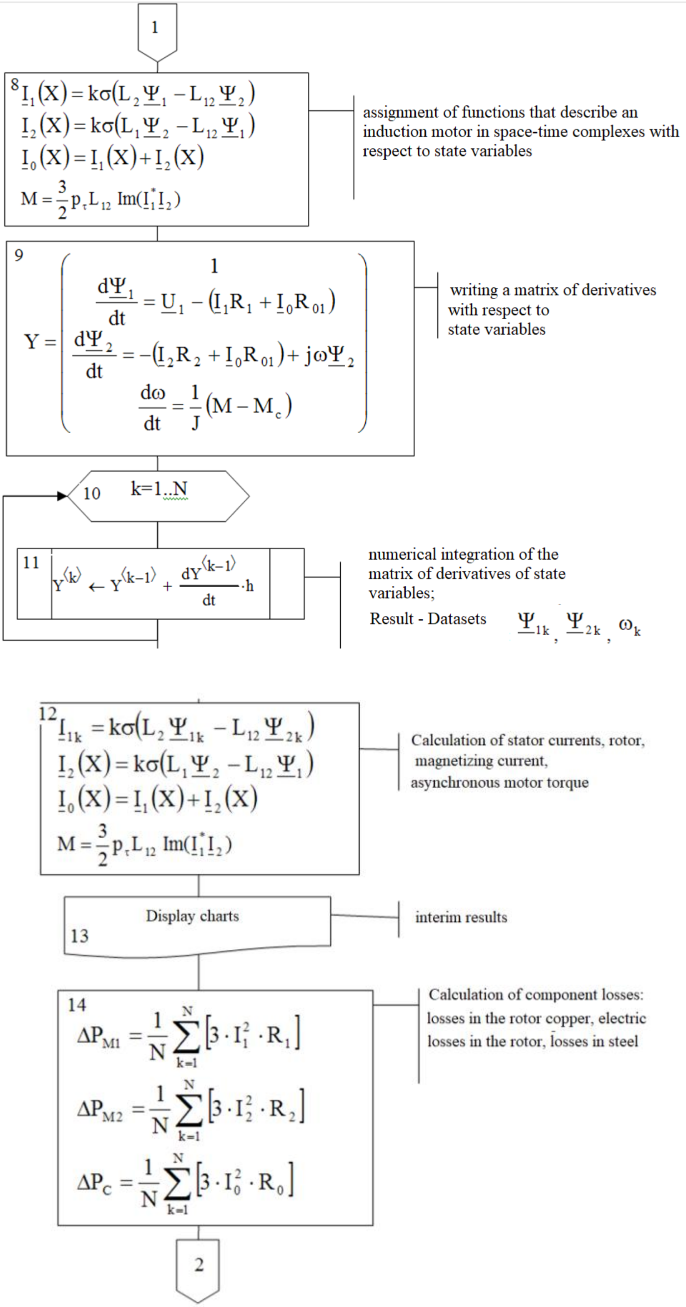


Fig. 23 Currents of stator and rotor in terms of ideal (a) and poor-quality (b) power supply in steady-state mode.

The block diagram of the developed model of the induction motor is presented in Fig. 24. It allows to estimate the considered energy parameters of the induction motor in any mode, at any form of supply voltage.


1 START
2 Setting asynchronous motor parameters
rated parameters (power, voltage, stator current, rated speed, number of pole pairs, efficiency, power factor, equivalent circuit parameters (stator and rotor active and reactance)
3 Are experimental data available?
Yes
No
4 Setting harmonics of the supply voltage
Load voltage array
5 phase voltage calculation
$U_A(t)=\sum_k U_{Ak}\cdot\sin(k\cdot\omega t+\phi_k)$
...
6 $U_k=\frac{2}{3}(U_{Ak}+\alpha U_{Bk}+\alpha^2 U_{Ck})$
Calculation of the space-time complex array
$\left(\alpha=e^{j\frac{2\pi}{3}}\right)$


7
$X_0=t$
$X_1=\Psi_1$
$X_2=\Psi_2$
$X_3=\omega$
Defining a matrix of variable states
1



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

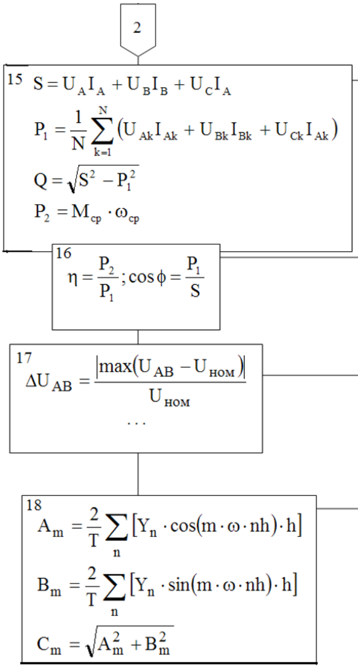
numerical integration of the matrix of derivatives of state variables;

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

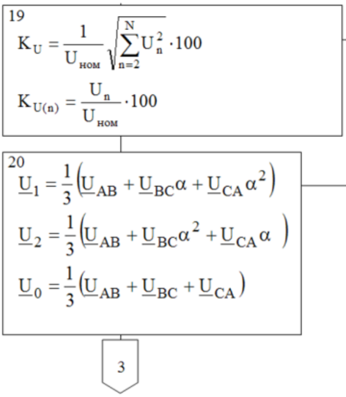


calculation of energy parameters from the supply network: active power, reactive power, apparent power, efficiency

ККД, cos φ

Calculation of voltage deviation for each phase

Spectral stress analysis. Fourier expansion in discrete form (m is the current number of the harmonic component; h is the discretization step)



Calculation of non-sinusoidality indicators: distortion coefficient and harmonic component coefficients

Calculation of the symmetrical components of the supply voltage

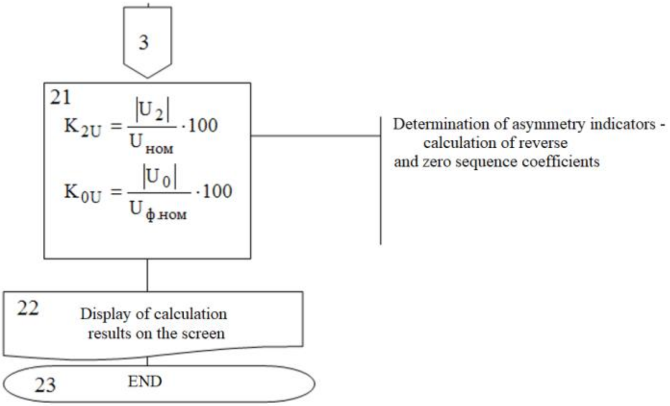


Fig. 24 - Block diagram of the developed combined simulation model of AM

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

1.4.3 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)$P_{ном}$. 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. 25 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	±0.5M3P; max 1M3P
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

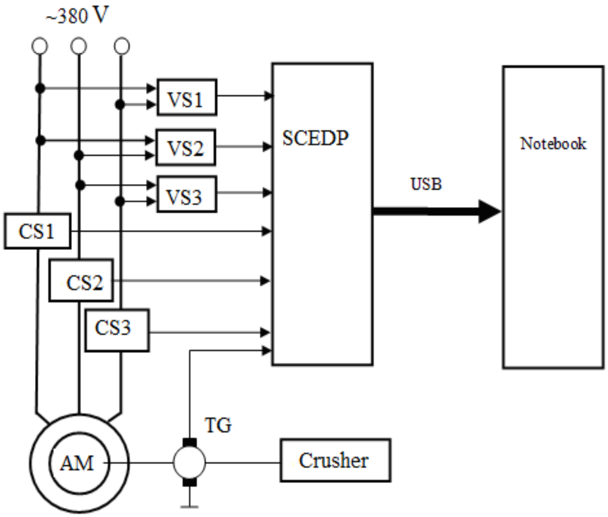


Fig. 25. Diagram of equipment connection to check validity of asynchronous motor model: VS – voltage sensor; CS – current sensor; TG – tachometer generator

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 ith 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 ith 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.26) demonstrates that the model is rather accurate to express real processes in AM. Relative error was not more than 2.4%.

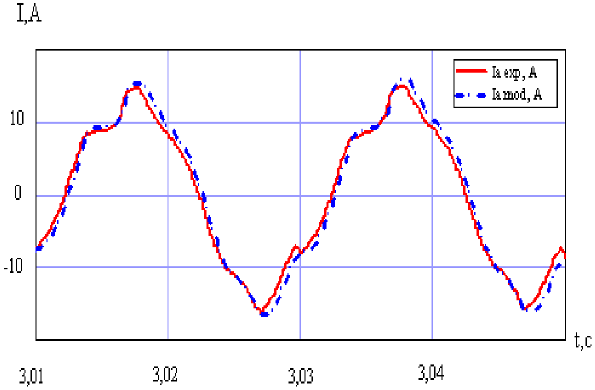


Fig. 26. Current of "A" phase registered experimentally (solid line) and obtained in terms of the model (dot-and-dash line).

Fig.27 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%.

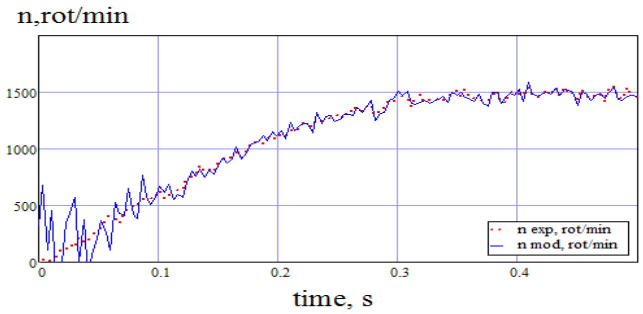


Fig. 27 Motor velocity in terms of idle starting obtained experimentally and by its modeling (solid line)

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. 28. 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.

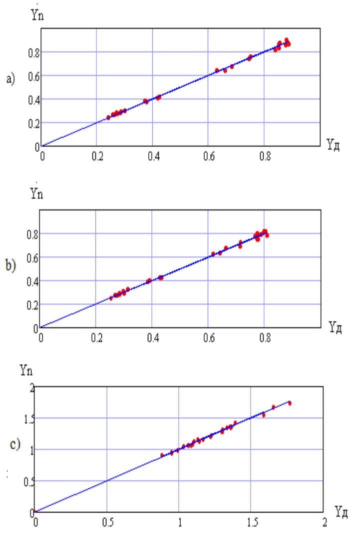


Fig. 28. Correspondence of the experimental data to the modeling results: a) motor efficiency; b) power factor; c) total losses

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

$$Y_n^* = a_0 + a_1 Y_\partial , \tag{47}$$

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

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

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

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

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

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:

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

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 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.

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%

Conclusions on chapter 1.4

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.

1.5 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:

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

Corresponding experiments have been carried out in terms of experimental workshop of Ukrspetsservis Ltd. Asynchronous motor of 4AX80A4У3 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. 29).

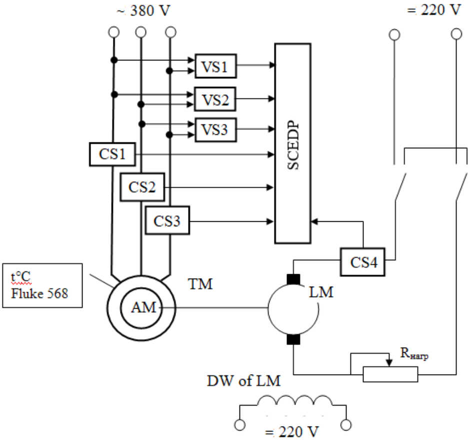


Fig. 29 Schematic of the experience to test adequacy of a thermal model of an asynchronous motor: TM, LM – test machine and loading machine; SCEDP– system to control electric drive parameters (measuring complex); VS – voltage sensor; CS – current sensor ; DW of LM – drive winding of loading machine.

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

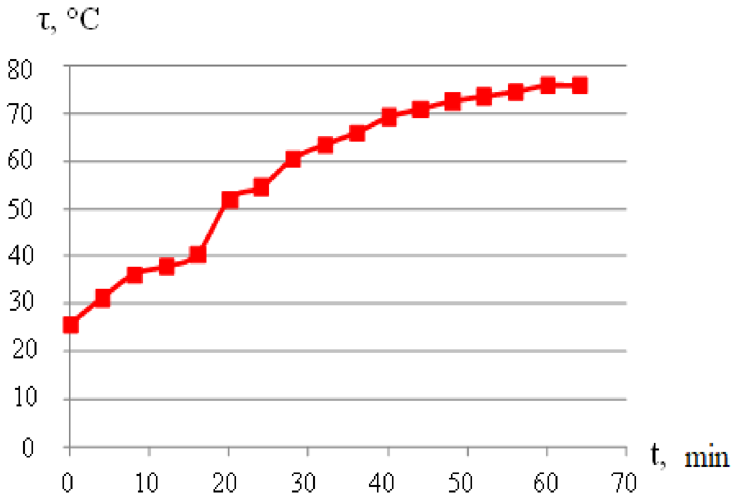


Fig. 30 Curve of motor heating while operating in terms of nominal load and ideal supply voltage

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.

Taking into account the fact that the reference literature contains rather scarce data on thermal parameters of the electric machines (as a rule, there is only the information concerning thermal time constants for motors of certain classes and power ranges), the considered method of their determination while identifying a specific AM model is rather topical.

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 31-36 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.

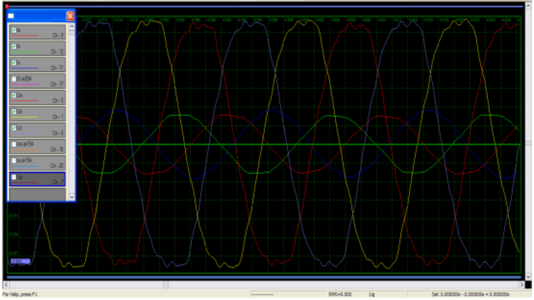


Fig. 31 Oscillograms of voltages and currents (k_U = 6%, ε_2 = 4%) in experiment #2

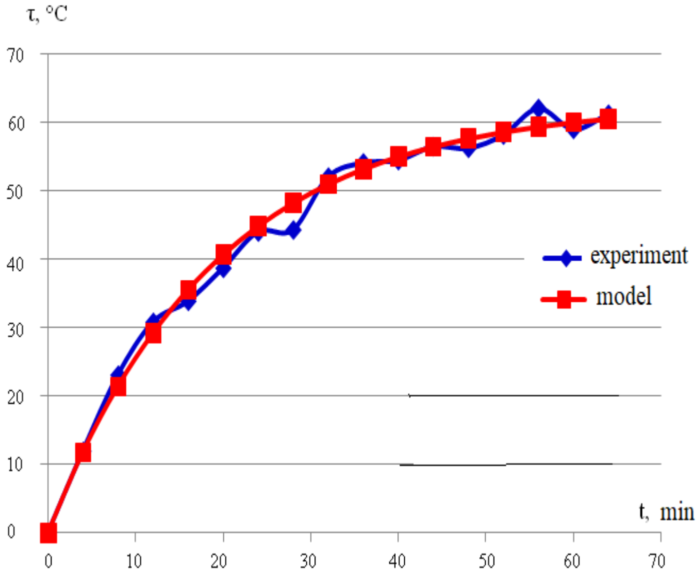


Fig. 32 Curves of motor heating in experiment # 2

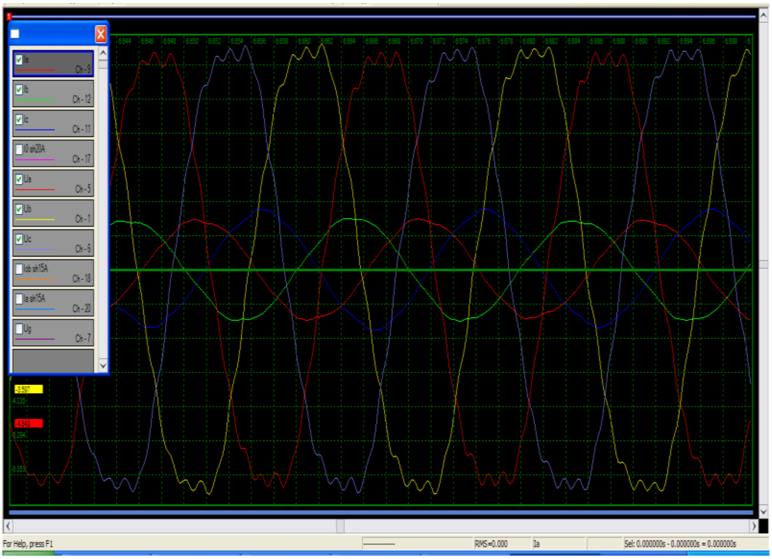


Fig. 33 Oscillograms of voltages and currents (k_U = 8%, ε_2 = 4%) in experiment #3.

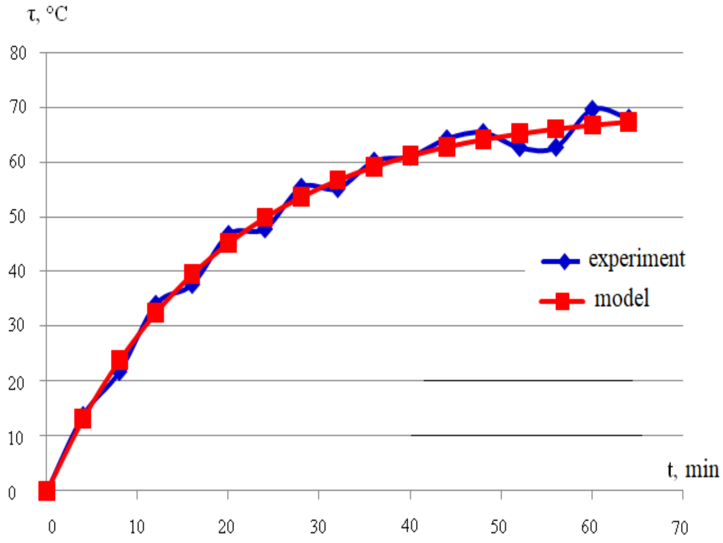


Fig. 34 Curves of motor heating in experiment # 3.

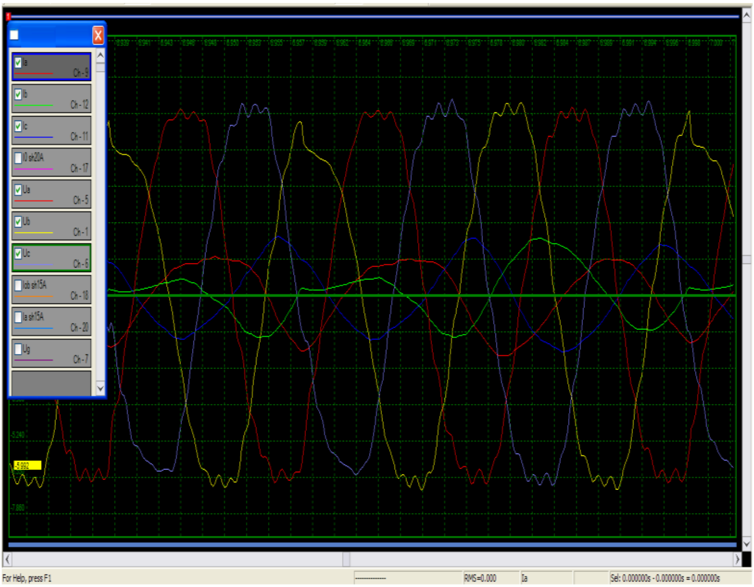


Fig. 35 Oscillograms of voltages and currents (k_U = 13%, ε_2 = 6 %) in experiment 4.

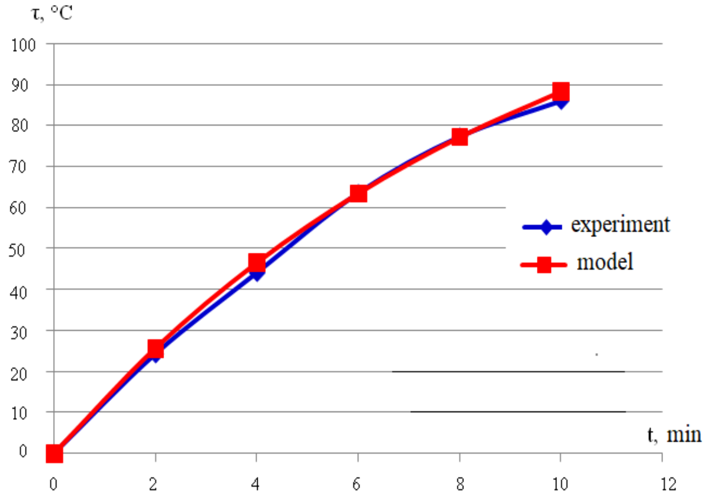


Fig. 36 Curves of motor heating in experiment # 4

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.

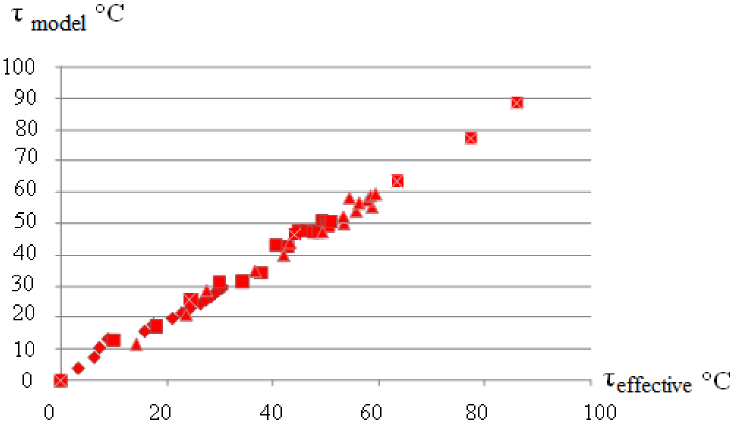


Fig. 37 Relations of the predicted $\tau_{м}$ and experimental τ_{ef} values of the temperature exceedance of AM winding

Next, error of the predicted temperature value in the heating dynamics was calculated. Fig. 37 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.

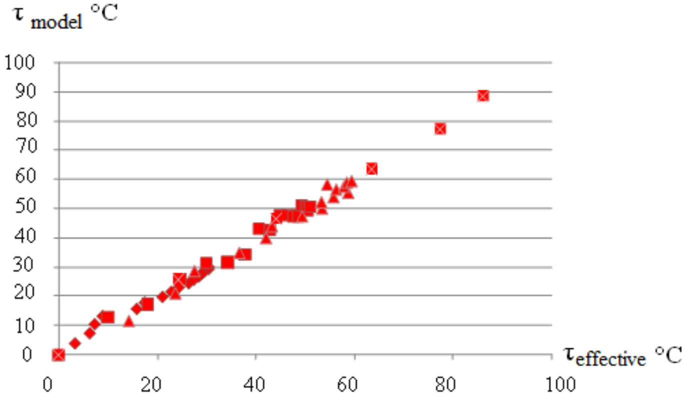


Fig. 37 Relations of the predicted $\tau_{м}$ and experimental τ_{ef} values of the temperature exceedance of AM winding

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, $\sigma_{YП}$ = 20.9 ºC, $r_{YefYП} = 0.99$, σ^*_{Yn} = 2.34 ºC, ΔY_n = 0.28 ºC, δ_{Yn} = 3.2%.

Conclusions on chapter 1.5

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.

1.6 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 38 illustrates the proposed algorithm for comparing the options.

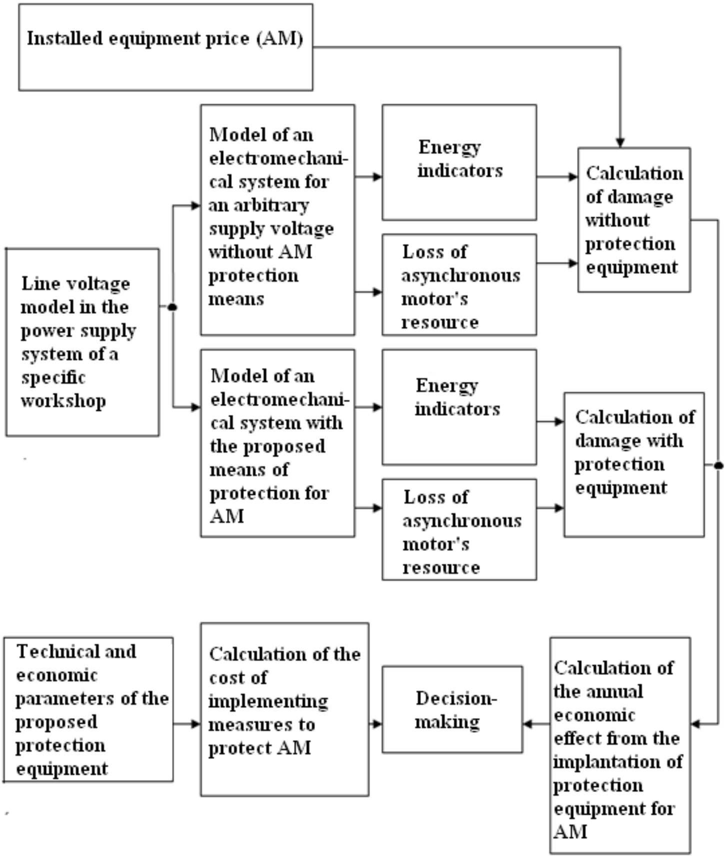


Fig.38 Algorithm for comparing options for AM protection equipment for making a decision on measures to reduce the negative impact of low-quality electricity on technical and economic indicators

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.

REFERENCES

1. Kyrylenko, O. V. (2001) «Modeling of energy processes in energy supply systems in solving energy saving problems», Pratsi Instytutu elektrodynamiky NAN Ukrainy, Elektrodynamika: Zbirnyk naukovykh prats – Kyiv: IED NAN Ukrainy, 2001.– P. 87−91.

2. Sychenko, V. H. (2015) «Influence of electric power processes in traction power supply systems on the quality of electric energy», Hirnycha elektromekhanika ta avtomatyka: Naukovo – tekhnichnyi zbirnyk NHU. −Dnipropetrovsk.: Vypusk: 2015. №1(94).− P.25-30.

3. Polylov, E.V. (2006) «Experimental studies of the quality of electrical energy in the main shops of the "AMK". Analysis of the harmonic composition of the mains voltage», Visnyk KDPU. – Vypusk 3/2006(39). – Chastyna 1.– P.93-97.

4. Zhezhelenko, Y.V. (2000) «Electricity quality indicators and their control at industrial enterprises», Moskva: Energoatomizdat, 2000. – 360 p.

5. Zhezhelenko, Y.V. (2000) «Higher harmonics in power supply systems of industrial enterprises», Moskva: Energoatomizdat, 2000. – 340 p.

6. Zhezhelenko, Y.V. (1996) «Power quality issues in electrical installations», Mariupol: PGTU, 1996. – 173 p.

7. M. Zagirnyak, D. Rod'kin, Iu. Romashykhin, Zh. Romashykhina, A. Nikolenko, “Refined calculation of induction motor equivalent circuit nonlinear parameters by an energy method”, Eastern-European Journal of Enterprise Technologies, Vol. 3, No. 5(87), pp. 4–10, 2017. DOI: 10.15587/1729-4061.2017.104146.

8. Romashykhin Iurii, Rudenko Nikita, Kuznetsov Vitaliy (2017). The possibilities of the energy method for identifying the parameters of induction motor. Proceedings of the International Conference on Modern Electrical and Energy Systems, MEES 2017. Pages: 128 – 131. DOI: 10.1109/MEES.2017.8248869/

9. Zhuk, A. K. (2003) «Analysis of the effect of the thyristor converter on the power supply network, taking into account switching oscillations», Elektromashynobuduvannia ta elektroobladnannia. – 2003. – №60. – P.39-47.

10. Zapalskyi, V. N. (2007) «Spectral analysis of typical semiconductor converters in autonomous electric power systems»,

Zbirnyk naukovykh prats Dniprodzerzhynskoho derzhavnoho tekhnichnoho universytetu (tekhnichni nauky). – Tematychnyi vypusk «Problemy avtomatyzovanoho elektropryvoda. Teoriia y praktyka». – Dniprodzerzhynsk, DDTU, 2007. – P. 230-231.

11. Serdiuk Tetiana, Kuznetsov Vitaliy, Kuznetsova Yevheniia. About electromagnetic compatibility of rail circuits with the traction supply system of railway //2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS). – September 10 - 14, 2018 Kharkiv, Ukraine. – P. 59 – 63.

12. Kuznetsov, V., Nikolenko, A. (2015). Models of operating asynchronous engines at poor-quality electricity, EasternEuropean Journal of Enterprise Technologies. VOL 1, NO 8(73) (2015): ENERGY-SAVING TECHNOLOGIES AND EQUIPMENT. Pages: 37 - 42. DOI: 10.15587/1729-4061.2015.36755.

13. Kachan, Yu. H. (2010) «On the quantitative assessment of the quality of electrical energy in the networks of industrial enterprises», Hirnycha elektromekhanika ta avtomatyka: naukovo-tekhnichnyi zbirnyk – Vypusk 84. – Dnipropetrovsk, 2010. – P.9-16.

14. GOST 13109-97. «Normy kachestva elektricheskoy energii v sistemakh elektrosnabzheniya obshchego naznacheniya», IPK. – Moskva: Izdatelstvo standartov. –1998.– 15 p.

15. Ratner, M.P. (1985) «Elektrosnabzheniye netyagovykh potrebiteley zheleznykh dorog», Moskva: Transport. 1985. – 295 p.

16. Analysis of the operation of the economy of electrification and power supply in 2014. – Kyiv. Ukrzaliznytsia, 2015. – 240 p.

17. Temerbaev, S. A. «Analysis of the quality of electricity in urban distribution networks of 0.4 kV», Electronic resource access mode: http://elib.sfu-kras.ru/bitstream/2311/9644/1/12_Temerbaev.pdf

18. Sychenko, V. H. (2015) «Quality of electric energy in traction networks of electrified railways», Dnipropetrovsk: PF Standart-Servis, 2015. – 344 p.

19. IEEE Std 519-1992, “IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems,” Institute of Electrical and Electronics Engineers, Inc. 1993.

20. Kuznetsov Vitaliy, Tryputen Nikolay, Kuznetsova Yevheniia "Evaluating the Effect of Electric Power Quality upon the Efficiency of Electric Power Consumption," *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON)*,

Lviv, Ukraine, 2019, pp. 556-561, doi: 10.1109/UKRCON.2019.8879841.

21. Kachan Yu., Nikolenko A.V., Kuznetsov V.V. Thermal component of economic damage from asynchronous motor operations under conditions of low-quality electric power. Mining electromechanics and automation: Scientific and technical collection. Volume 85. Pp. Pages 113-118. 2010.

22. Borky , J., Bradley, Th.: Effective Model-Based Systems Engineering. 1st ed. 779 p. Springer International Publishing AG. Cham, Switzerland (2019).

23.Dori, D. Model-Based Systems Engineering with OPM and SysML. 1st ed. 411 p. Springer-Verlag New York Inc. New York, United States (2016).

24. M. Tryputen, V. Kuznetsov, A. Kuznetsova, K. Maksim and M. Tryputen, "Developing Stochastic Model of a Workshop Power Grid," 2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP), Kremenchuk, Ukraine, 2020, pp. 1-6, doi: 10.1109/PAEP49887.2020.9240898.

25. Kawano, S., Yoshizawa, S. and Hayashi, Y.:Centralized voltage control method using voltage forecasting by JIT modeling in distribution networks 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), Dallas, TX, 2016, pp. 1–5.

26. Udagawa, T., Yasuhiro, H., Takahashi, N., Matsuura, Y., Morita, T. & Minami, M.) Evaluation of Voltage Control Effect for Data Acquisition Period Length from SCADA with IT Switches, Journal of International Council on Electrical Engineering. Vol. 3, No. 2, 146 –152 (2013).

27. Yaglom, A.M. Correlation Theory of Stationary and Related Random Functions : Supplementary Notes and References. (Springer Series in Statistics). Softcover reprint of the original 1st ed. 1987 edition. 287 p., Springer, New York; (October 13, 2011).

28. Bendat, J.S., Piersol, A.G. Random Data: Analysis and Measurement Procedures: Fourth Edition (2012) Random Data: Analysis and Measurement Procedures: Fourth Edition, pp. 1–613.

29. Hastie, T., Tibshirani, R., Friedman, J.: The Elements of Statistical Learning: Data Mining, Inference, and Prediction, Second Edition. 745 p., Springer Science+Business Media, Ney York, USA (2017).

30. Neylor, G. Mashinnyie imitatsionnyie eksperimentyi s modelyami ekonomicheskih sistem – M.: Mir, 1975. – 412.

31. Gmurman, V.: Guidance on to solving problems in probability theory and mathematical statistics: scholarship for studio vtuzov. 400 p. Graduate School. Moscow (1979).

32. Kendall, M., Gibbons, J.: Rank Correlation Methods. 260 pp. 5th edn., Edward Arnold, London, (1990).

33. Bonett, Douglas G.; Wright, Thomas A. (2000). "Sample size requirements for estimating Pearson, Kendall, and Spearman correlations". Psychometrika. 65 (1): 23–28.

34. Sayenko, D. Kalyuzhniy, "Analytical methods for determination of the factual contributions impact of the objects connected to power system on the distortion of symmetry and sinusoidal waveform of voltages", Przegląd elektrotechniczny, vol. 91, pp. 81-85, 2015.

35. Zhezhelenko, I.V. Selected problems of nonsinusoidal modes within power grids of enterprises [Text] / I.V. Zhezhelenko, Yu.L. Saenko, T.K. Baranenko, A.V. Gorpinich, & V.V. Nesterovich. – M.: Energoatomizdat, 2007. − 294 pp.

36. Pedra, J. Estimation of typical squirrel-cage induction motor parameters for dynamic performance simulation [Text] / J. Pedra // IEEE Proceedings on Generation, Transmission and Distribution. – 2006. – Vol. 153, Issue 2. – P. 197. doi: 10.1049/ip-gtd:20045209.

37. G. C. Seritan, C. Cepişcã, P. Guerin, "The analysis of separating harmonics from supplier and consumer", Electrotehnicã Electronicã Automaticã (EEA), vol. 55, no. 1, pp. 14-18, 2007.

38. Yevheniia Kuznetsova, Vitaliy Kuznetsov, Mykola Tryputen, Alisa Kuznetsova, Maksym Tryputen "Development and Verification of Dynamic Electromagnetic Model of Asynchronous Motor Operating in Terms of Poor-Quality Electric Power," 2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES), Kremenchuk, Ukraine, 2019, pp. 350-353. doi: 10.1109/MEES.2019.8896598

39. Tryputen, M., Kuznetsov, V., Kuznetsova, A., Tryputen, M., Kuznetsova, Y., Serdiuk, T. Improving the Reliability of Simulating the Operation of an Induction Motor in Solving the Technical and Economic Problem (2021) Advances in Intelligent Systems and Computing, 1247 AISC, pp. 143-152. DOI: 10.1007/978-3-030-55506-1_13

40. Gmurman V. “Theory of Probability and Mathematical Statistics” M.: Vysshaya shkola, 2003.

41. Kommaev V., Kalinina V. “Theory of Probability and Mathematical Statistics” M.: INFA-M, 2001.

42. Bessonov, L.A. Theoretical foundations of electrotechnics [Text] / L.A. Bessonov. – M.: Vysshaia shkola, 1973.

43. Vazhnov, A.I. Electric equipment [Text] /A.I. Vazhnov. – L.: Energia, 1968. – 768 pp.

44. Rodkin, D.I. Systems of dynamic load of electric motors during their testing (theory, research, and development) [Text]: Thesis for a Degree of Doctor of Engineering: 05.09.03 / D.I. Rodkin. – Krivoi Rog: Krivoi Rog Technical University, 1994. – 307pp.+204 pp appendix.

45. Syromiatnikov, I.A. Operation modes of asynchronous motors and synchronous motors [Text] / I.A. Syromiatnikov. – M.: Energoatomizdat, 1984. – 396 pp.

46. Ogar, V.A. Estimation of nonlinearity of inductance of a winder with steel using energy method [Text] / V.A. Ogar //Messenger of KrSPU. – 2004. – Publication 2/2004 (25). – Pp.78-84.

47. Veshenevski, S. N. Characteristics of motors in electric drive [Text] / S. N. Veshenevski – Edition 6, corrected. – M.: Energia, 1977. – 431pp.

48. GOST 7217-87 Electric rotating equipment. Asynchronous motors. Testing procedures.

49. Kerkman O, Russel J. Steady-State and Transient Analyses of an Induction Machine with Saturation of the Magnetizing Branch //IEEE Transactions on Industry Applications. – 1985. – Vol. 21. – Pp.226-234.

50. Basharin, A.V., & Postnnikov, Yu.V. Calculation examples for automated electric drive using computer [Text]: Manual for University students/A.V. Basharin, & Yu.V. Postnikov. – L.: Energoatomizdat, Leningrad branch, 1990.

51. Ivanov-Smolenski, A.V. Electric equipment [Text] / A.V. Ivanov-Smolenski. – M.: Energia, 1980.

52. Kachan, Yu.G., Nikolenko, A.V., & Kuznetsov, V.V. Implementing asynchronous motor model for the conditions of noisy power supply// Yu.G. Kachan, A.V Nikolenko, & V.V Kuznetsov. Messenger of Kremenchuk State Polytechnical University: #3. – Kremenchuk, 2009. ─ Pp.56-58.

53. Kachan, Yu.G., Nikolenko, A.V., & Kuznetsov, V.V. Estimating adequacy of mathematical model of asynchronous motor under the conditions of noisy power supply [Text] / Yu.G. Kachan, A.V Nikolenko, & V.V Kuznetsov. // Integrated technologies and energy saving. Quaterly scientific and applied journal. – #3. – Kharkiv: NTU "KhPU", 2009. – Pp..70-74.

54. Adler, Yu. P., Markova, E. V., & Granovski, Yu. V. Planning the experiment while searching for optimum conditions [Text] / Yu.P. Adler, E.V. Markova, & Yu. V.Granovski. – M.: Nauka, 1976. – 183 pp.

55. Tytiuk V., Chornyi O., Zachepa Yu., Kuznetsov V., Tryputen M. Control of the start of high-powered electric drives with the optimization in terms of energy efficiency. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2020, № 5, pp.101-108. https://doi.org/10.33271/nvngu/20205/101.

56. M. Zagirnyak, D. Rod'kin, Iu. Romashykhin, Zh. Romashykhina, A. Nikolenko, "Refined calculation of induction motor equivalent circuit nonlinear parameters by an energy method", Eastern-European Journal of Enterprise Technologies, Vol. 3, No. 5(87), pp. 4–10, 2017. DOI: 10.15587/1729-4061.2017.104146.

57. Sychenko V., Kuznetsov V., Pulin N., Kosarev Y., Hubskyi P., Kuznetsov V. New concept of DC traction network reinforcement // The Fourth International Conference on Railway Technology: Research, Development and Maintenance. Session E4: R03 - Energy Efficiency and Storage in Railway Operations. – 3-7 September 2018 , Sitges, Barcelona, Spain. Available at: https://elsevier.conference-services.net/viewsecurePDF.asp?conferenceID=4218&abstractID=1021263.

58. Sharuda V.H., Tkachov V.V., Filkin M.P. Metody analizu i syntezu system avtomatychnoho keruvannia: Navch. posib. – Dnipro., Nats. hirnych. un-t, 2008.-543 s.

59. Zhezhelenko, I. V. (2000). Vysshie garmoniki v sistemah jelektrosnabzhenija prompredprijatij. – M.: Jenergoatomizdat, 340 .

60. Chystiakov, P., Chornyi, O., Zhautikov B. and Sivyakova, G. Remote control of electromechanical systems based on computer simulators, 2017 International Conference on Modern Electrical and Energy Systems (MEES), Kremenchuk, 2017, pp. 364-367, doi: 10.1109/MEES.2017.8248934.

61. Tuys, A., Meyer, F., Steichen, M., Zwyssig, Ch. and Kolar, J. W. Advanced Cooling Methods for High-Speed Electrical Machines, 2017 IEEE Transactions on Industry Applications, Vol. 53, No. 3, pp. 2077--2087, May/June 2017 .

62. Schrittwieser, M., Marn, A., Farnleitner, E., Kastner, G. Numerical analysis of heat transfer and flow of stator duct models, IEEE Trans. Ind. Appl., vol. 50, no. 1, pp. 226–233, Jan. 2014.

63. Boglietti, A., Cavagnino, A., Staton, D. Determination of critical parameters in electrical machine thermal models, IEEE Trans. Ind. Appl., vol. 44, no. 4, pp. 1150–1159, Jul. 2008.

64. Boglietti, A., Cavagnino, A., Staton, D., Shanel, M., Mueller, M., Mejuto, C. Evolution and modern approaches for thermal analysis of electrical machines, IEEE Trans. Ind. Electron., vol. 56, no. 3, pp. 871–882, Mar. 2009.

65. Adler, Yu. Planning an experiment in finding optimal conditions. Moscow: Science, 1976, 183 p.

66. Ivobotenko, B., Iliinskyi, I., Kopylov, I. Experiment planning in electromechanics. Moscow: Energiya, 1975. 184 p.

67. Korn, G. Mathematics Handbook for Scientists and Engineers: Definitions, Theorems, Formulas. Moscow: Book on Demand, 2014, 832 p.

68. Sapronov, A.A. Low-quality electric power – additional component of the commercial losses of power enterprise/ A.A. Sapronov, D.S. Goncharov // Modern energy systems and complexes and their control: collection of reports. – Novocherkassk, 2006.

69. 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.

70. The Law of Ukraine “On electric energy market” as in force on 17.10.2020

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Для нотаток

НАУКОВЕ ВИДАННЯ

СУЧАСНІ РЕАЛІЇ ФІНАНСОВО-ЕКОНОМІЧНОГО РОЗВИТКУ РЕГІОНІВ, ГАЛУЗЕЙ, ПІДПРИЄМСТВ, БІЗНЕСУ

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