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INCREASING THE RELIABILITY OF SIMULATION OF ASYNCHRONOUS MOTOR OPERATION BASED ON AN ADAPTIVE APPROACH

Abstract. *This research focuses on improving the reliability of simulating the operation of induction motors when solving technical and economic problems related to the selection of protection systems for electric drives operating in industrial power networks with poor power quality. The presence of voltage asymmetry, harmonic distortions, and other power quality issues in workshop networks significantly affects the performance and service life of induction motors, increasing energy losses and maintenance costs.*

The article proposes a power and economic model that allows conducting computational experiments to determine the optimal solution for improving power supply quality. A key element of the model is the system for generating and controlling linear voltage parameters, which ensures compliance of the simulated signals with their statistical regularities observed in real industrial conditions.

The research introduces adaptive algorithms for the continuous and simultaneous assessment of average values, variances, autocorrelation, and cross-correlation functions of voltage harmonics. Mathematical expressions for their correction during the accumulation of information are presented. Structural schemes of control systems for both analog and digital modeling of voltage processes are proposed, allowing for real-time monitoring of the reliability of generated data.

The simulation results were verified through statistical hypothesis testing for the average values and variances of the generated voltage harmonics. Experimental studies were carried out in the rolling shop No. 1 of Dneprospetsstal LLC, where significant voltage distortions are caused by the operation of powerful semiconductor converters. The results confirmed the adequacy of the proposed modeling approach and its applicability for making economically sound decisions regarding the choice of technical solutions for voltage quality improvement.

This work contributes to the field of energy efficiency in industrial enterprises by providing a methodological basis for the reliable simulation of induction motor operation

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in the presence of distorted power supply conditions. The proposed approach allows reducing the cost and duration of experimental studies by replacing them with validated computational modeling.

Keywords: *Induction Motor, Electric Networks, Linear Voltages, Protection Tools, Economic Model, Electric Energy*

Introduction

In the current context, induction motors are the primary devices for converting electrical energy into mechanical energy and form the foundation of the drive systems of most industrial mechanisms. This position has been earned due to a successful combination of operational and structural characteristics — the ability to automatically adjust torque in response to changes in load torque on the shaft, high efficiency, simple construction, and relatively low manufacturing cost compared to other electromechanical converters [1]. Moreover, it should be emphasized that induction motors, despite their numerous advantages and widespread application in various industries, remain the largest consumers of electrical energy on a global scale. Their extensive use in industrial enterprises, transport systems, municipal infrastructure, and household appliances has led to an exceptionally high share of total electricity consumption attributed to electric drive systems. According to expert estimates and international energy studies, the share of electric motors in the global structure of electricity consumption ranges from 43% to 46%, making them the most energy-intensive class of electrical equipment.

Such a significant consumption of energy resources by electric motors is a key factor influencing the development of modern energy policy, especially in the context of the growing need for energy saving, reducing operational costs, and minimizing negative environmental impacts. If no systematic and effective measures are taken to increase energy efficiency, optimize the operation of drive systems, and modernize the power infrastructure, then according to analytical forecasts, electricity consumption by induction motors could increase to a critical level — up to 13,360 TWh per year by 2030. This scenario takes into account the projected growth of industrial production volumes, the increase in the number of automated technological lines, and the expansion of the global industrial sector.

Currently, end-users of electric motors - industrial enterprises, commercial facilities, and residential consumers - collectively spend approximately 565 billion

US dollars annually on electricity costs for the operation of electric motor-driven systems. These costs include not only direct energy expenses but also additional operational costs associated with low energy efficiency, equipment wear, and losses in power networks. If comprehensive programs aimed at improving the energy efficiency of electric drives, implementing smart control systems, and using modern energy-saving technologies are not implemented at the national and international levels, it is expected that by 2030 these annual expenditures may increase dramatically - reaching almost 900 billion US dollars. This will place a considerable burden on both industrial enterprises and national economies, underscoring the urgent need to develop and apply technical and organizational measures to improve the energy performance of electric motors across all sectors of their use [2].

Modern electric drive systems, which implement electromechanical energy conversion processes and are mainly based on squirrel-cage induction motors, are not structurally complex. However, the operation of this class of motors today is associated with a number of challenges. One of the most pressing problems is the supply of poor-quality electric power to induction motors. It is well established that even minor deviations in supply voltage quality lead to adverse effects, including insulation aging and reductions in energy performance indicators such as efficiency and power factor [3]. The quality of electric power supply significantly affects the reliability, efficiency, and service life of these motors [4]. Therefore, one of the urgent problems influencing the operation of induction motors is the deterioration of power quality — the presence of asymmetry, waveform distortion, frequency instability, and other deviations from standard values [5, 6, 7].

It is known [8] that harmonic voltage distortions arise due to the operation of thyristor converters, switching power supplies, and other nonlinear loads, which lead to voltage and current waveform distortion in motor windings. In [9], the authors showed that voltage containing harmonic components on the stator causes significant changes in the motor's electromagnetic parameters (torque, currents, losses, etc.) and affects the mechanical part of the drive. The study concluded that electric motors operating under harmonic distortion suffer from reduced efficiency and shorter service life due to increased iron and copper losses. Additionally, voltage and current harmonics can influence the torque developed by the motor. Harmonic components in rotating machines can also cause vibrations and noise. For example,

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harmonics of negative sequence create a counteracting torque that opposes the main motor torque, thereby reducing overall motor efficiency. Odd harmonics generate a reverse magnetic field (negative sequence) in the motor, which produces a negative torque and further reduces the useful output torque of the induction motor.

The study by the author in [10] investigates the relationship between supply voltage variations and the operating characteristics of induction motors, particularly their effects on torque, current, power factor, heating, and overall efficiency. The author concluded that voltage deviations significantly affect the reliability and performance of electric motors. To ensure stable operation and extend motor service life, system voltage must be maintained as close to the nominal value as possible [10]. A special case is voltage asymmetry in induction motors, when deviation occurs in only one phase of the supply network, as studied in [11]. The researchers modeled situations in which the voltage in one phase exceeded the nominal value by 10% and 20%, while the other two phases remained at nominal levels. The simulations on the synthesized model [11] demonstrated that even a minor overvoltage in one phase (10–20%) has a substantial impact on the performance of a three-phase induction motor — leading to increased winding temperatures and reduced performance metrics, which may result in premature motor failure.

Other researchers [12, 13] note that short-term overvoltages caused by switching processes can lead to insulation breakdown in motors. Modeling results presented in [13] confirm that overvoltages reduce insulation lifespan and can cause premature inter-turn insulation failures. Practical recommendations include the use of surge protection devices (such as surge arresters, varistors, etc.) and maintaining voltage levels within acceptable limits, as any exceedance of 10% or more should be considered an emergency condition.

Industrial enterprises, especially those with a large number of electromechanical systems, often face a serious problem related to the deterioration of power supply quality within workshop electrical networks. In particular, induction motors - widely used in production processes - are highly sensitive to deviations of electrical parameters from nominal values. The so-called "noisy electricity", which includes voltage asymmetry, harmonic distortions, and a general deviation from the sinusoidal form of the supply voltage, negatively affects the stable operation of such motors.

Unsymmetrical load distribution between phases, the presence of higher harmonics in the power grid, and frequent voltage fluctuations lead to a whole complex of undesirable phenomena in the operation of induction motors. These factors cause overheating of motor windings, which provokes premature insulation wear and increases the risk of failures. In addition, a decrease in power factor and energy efficiency is observed, along with a significant increase in reactive power consumption. Over time, these processes not only reduce the overall efficiency of production equipment but also contribute to its accelerated wear and shortening of service life, increasing the frequency of repairs and maintenance.

Therefore, the problem of reducing the negative influence of poor-quality power supply on electromechanical systems becomes particularly relevant for modern industrial enterprises seeking to increase energy efficiency and minimize downtime losses. To neutralize or mitigate the harmful effects of distorted voltage, several technical solutions are used in practice. These include, for example, "individual" LC-filters installed directly at the input of a specific electric motor, or more powerful "cluster" devices for compensation of voltage distortion installed at the level of an entire workshop or production section.

An alternative strategy involves the control and correction of power supply quality directly in the zones of distortion formation — in other words, preventive actions aimed at eliminating the causes of noise at the earliest stages. However, each of the mentioned approaches has not only a certain technical potential but also requires significant financial investments for its implementation, as well as subsequent maintenance costs.

Choosing the optimal solution among these alternatives is a complex technical and economic task. It requires consideration of many factors - from the characteristics of the technological process and the degree of power supply quality deviation to the costs of implementing and operating compensating devices. Conducting real industrial experiments to compare these options is extremely costly and time-consuming. Therefore, a promising direction is the use of mathematical modeling and computer simulations. They make it possible to evaluate in advance the effectiveness of various technical solutions, predict their impact on energy consumption, equipment operation, and the overall economic efficiency of production. Simulation experiments allow companies to minimize financial risks and

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make informed decisions regarding the modernization of workshop electrical networks.

Literature review and problem statement. It is a well-established and widely recognized fact in the field of electrical engineering that poor-quality power supply has a significant and often detrimental impact on the operational characteristics and performance parameters of induction motors (IM), which are among the most commonly used types of electric motors in industrial applications. The stability, reliability, and efficiency of induction motors directly depend on the quality of the supplied voltage. Any deviations of power supply parameters from the nominal values — including voltage fluctuations, asymmetry between phases, frequency instability, or the presence of harmonic distortions — inevitably lead to unfavorable operating conditions for the motor.

Such distortions in the supply voltage negatively influence the electromagnetic processes occurring within the motor, altering its torque characteristics, increasing energy losses, and provoking the emergence of additional heating in motor windings. As a result, the service life of the insulation system is reduced, and the probability of premature failures grows substantially. Moreover, poor power quality affects not only the energy efficiency indicators of induction motors — such as efficiency, power factor, and reactive power consumption — but also leads to mechanical problems, such as increased vibration, noise, and even mechanical stress on the motor shaft and bearings.

Given that induction motors often operate in critical technological processes in industrial enterprises, where stable and uninterrupted functioning of equipment is required, ensuring high-quality power supply becomes an essential prerequisite for maintaining operational reliability and extending the service life of electric drives. Therefore, analyzing the negative impact of poor-quality power supply on induction motors and developing effective methods to mitigate this influence remains one of the key areas of research in modern energy engineering and industrial automation [14 - 16].

Reduced quality of power voltage results in pulsation of the moment generated by the motor, drop of starting and critical IM moment, increase in vibration, early wear of bearing and gear components, increased steel losses due to higher harmonic field constituents in a gap, reduction in such power indices of induction motor operation as efficiency coefficient and power coefficient. 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. Paper [17] has shown that the problem solution should be sought at technical-and-economic level involving methods of mathematical modeling. Papers [17 and 18] 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. Moreover, its suitability has been demonstrated in terms of induction motor operation. According to the technique, power indices of electromechanical transducer are calculated involving the current quality power indices within the enterprise power grid [19, 20, and 21], and basing upon electric model, and thermal model [22]. If indices, calculated in such a way, differ substantially from preset ones, various alternatives of engineering solutions, intended to recover electric power supplying the motor, are considered. Cost of each of the alternatives is estimated and final decision, concerning its further operation, is made.

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 [23].

Power and economic model of electric equipment. Fig. 1 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

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regularities. Basing upon specific features of linear voltage simulation [23] 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:

$$\bar{x}(t) = \frac{1}{t}\int_0^t x(t)dt \tag{1}$$

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

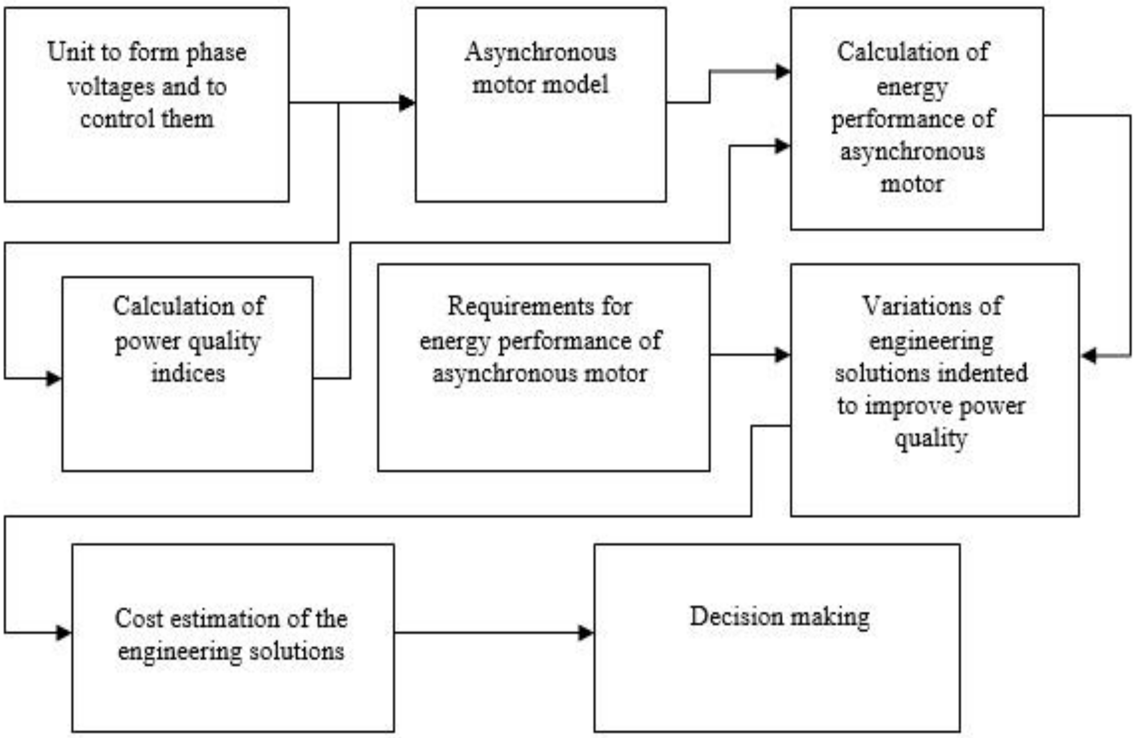

Figure 1 - Schematic diagram of power and economic model of electric equipment

Differentiate left side and right side of expression (1) with respect to t:

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

or:

$$\frac{d\bar{x}(t)}{dt} = -\frac{1}{t}\bar{x}(t) + \frac{1}{t}x(t)\frac{1}{t}(x(t) - \bar{x}(t)). \quad (2)$$

If the random process is represented by a discrete (impulse) function, then expression (2) is:

$$\bar{x}[iT] - \bar{x}[(i-1)T] = \frac{1}{i}(x[iT] - \bar{x}[(i-1)T]) \quad (3)$$

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 (3) as follows:

$$\bar{x}[iT] = \bar{x}[(i-1)T] + \frac{1}{i}(x[iT] - \bar{x}[(i-1)T]) \quad (4)$$

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

$$D_x(t) = \frac{1}{t}\int_0^t (x(t) - \bar{x}(t))^2 dt \quad (5)$$

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

$$R_{x,x}(t,\tau) = \frac{1}{t}\int_0^t ((x(t) - \bar{x}(t))(x(t-\tau) - \bar{x}(t)))dt \quad (6)$$

$$R_{x,y}(t,\tau) = \frac{1}{t}\int_0^t ((x(t) - \bar{x}(t))(y(t-\tau) - \bar{y}(t)))dt \quad (7)$$

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

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After performing transformation of (5), (6), and (7) expressions, being analogous to the above mentioned ones, we obtain the following for continuous random functions:

$$\frac{dD_x(t)}{dt}=\frac{1}{t}((x(t)-\bar{x}(t))^2-D_x(t)) \tag{8}$$

$$\frac{dR_{x,x}(t,\tau)}{dt}=\frac{1}{t}((x(t)-\bar{x}(t))(x(t-\tau)-\bar{x}(t))-R_{x,x}(t,\tau)) \tag{9}$$

$$\frac{dR_{x,y}(t,\tau)}{dt}=\frac{1}{t}((x(t)-\bar{x}(t))(y(t-\tau)-\bar{y}(t))-R_{x,y}(t,\tau)) \tag{10}$$

In a digital form, (8), (9), and (10) expressions are:

$$D_x[iT]=D_x[(i-1)T]+\frac{1}{i}((x[(i-1)T]-\bar{x}[(i-1)T])^2-D_x[(i-1)T]) \tag{11}$$

$$\begin{aligned}R_{x,x}[iT,\tau]&=R_{x,x}[(i-1)T,\tau]+\frac{1}{i}((x[(i-1)T]-\bar{x}[(i-1)T])\times\\&\times((x[(i-1)T]-\bar{x}[(i-1)T]))-R_{x,x}[(i-1)T,\tau])\end{aligned} \tag{12}$$

$$\begin{aligned}R_{x,y}[iT,\tau]&=R_{x,y}[(i-1)T,\tau]+\frac{1}{i}((x[(i-1)T]-\bar{x}[(i-1)T])\times\\&\times((y[(i-1)T]-\bar{y}[(i-1)T]))-R_{x,y}[(i-1)T,\tau])\end{aligned} \tag{13}$$

Fig. 2 represents structural scheme of a control system implementing (2), (8), (9), and (10) 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 $\psi_{BC1}(t)$).

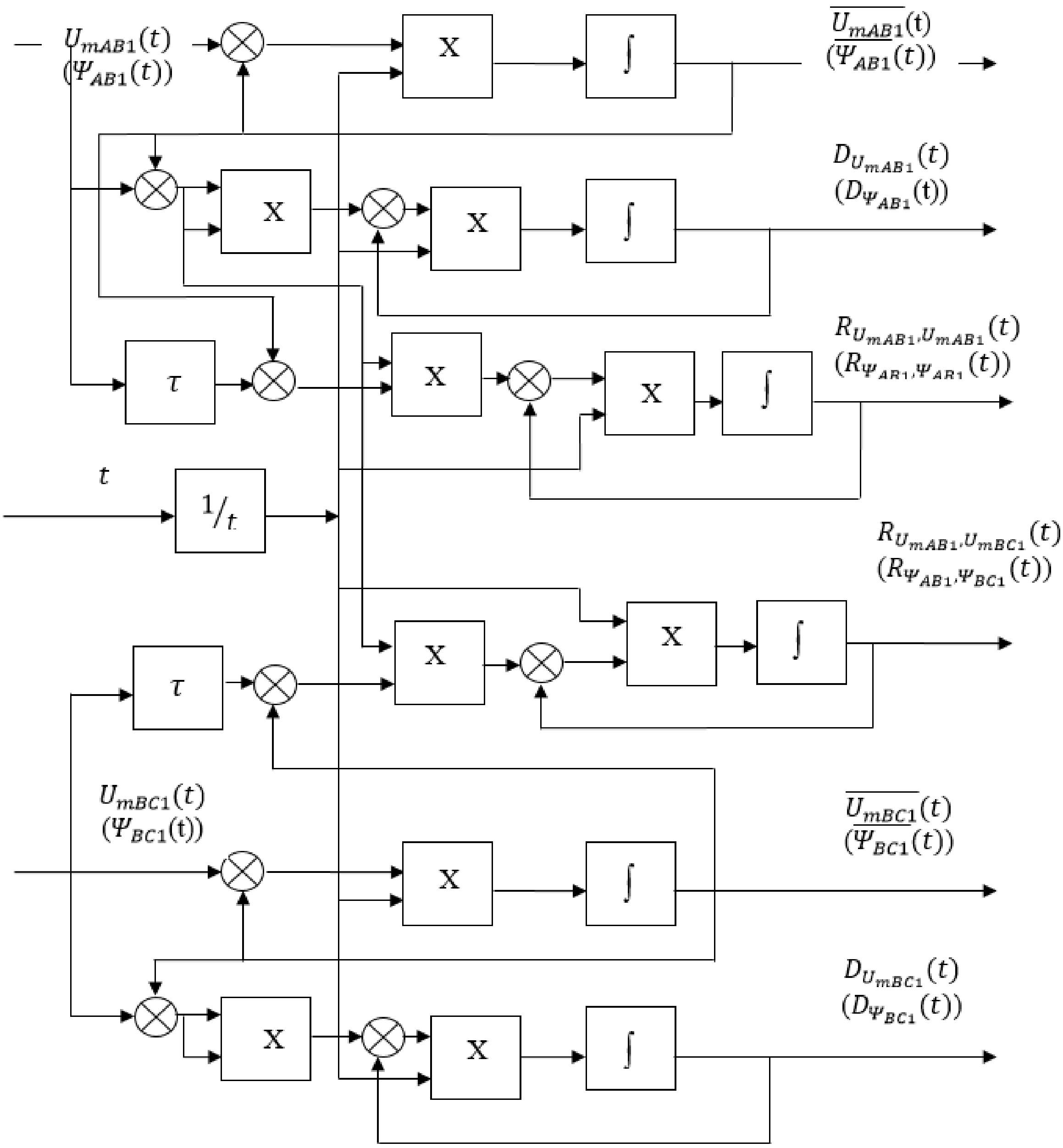

Figure 2 - Diagram of analogous control system

Fig. 3 represents structural scheme of a control system implementing (4), (11), (12), and (13) algorithms to evaluate statistic characteristics of discrete implementations of the same random functions according to [3,24].

The control system scheme, shown in Fig. 2, can be used in the process of analogous modeling of linear phase voltages; the scheme, shown in Fig. 3, is

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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 [3, 24].

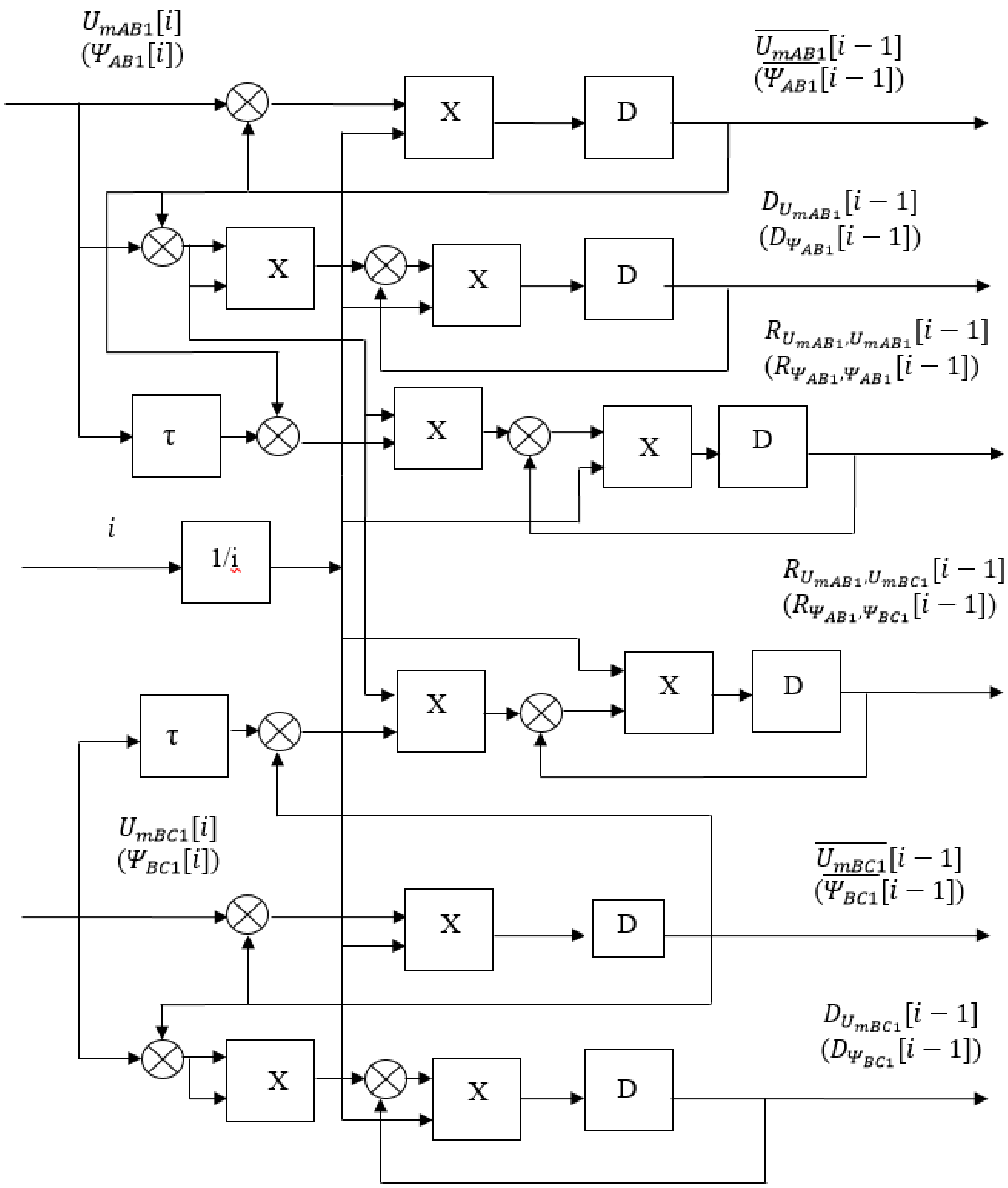

Figure 3 - Diagram of discrete control system

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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 [25-27]:

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

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

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

In this context, n is the number of observations.

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

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

Table 1 demonstrates checking results of the average random sequences of harmonics of linear voltages generated according to [25-27] and evaluated with the help of a control system (Fig. 3) if $n = 30$.

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Table 1

Checking results of average harmonics of linear voltages

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

Zero hypothesis checking in terms of α $H_0 : D_x = D_0$ significance level concerning equality between unknown overall dispersion D_x with the known dispersion D_0 and hypothetic value D_0 in terms of a competing hypothesis $H_1 : D_x \neq D_0$, has been performed basing upon the criterion value [25-27].

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

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

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.

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Table 2

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
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

Fig. 4 demonstrates a window of CED Expert software in the process of oscillographic testing of signals during operation of tested electric motor under loading.

Figure 4 - Oscillograms of currents (from above) and voltages (from below) within the considered electric motor while operating under loading

Conclusions

The analysis of complex processes through computer-based experiments inherently involves the emergence of errors that stem from multiple sources. One major source of such errors lies in the fact that a discrete function is often represented as a finite set of its values corresponding to different groups of arguments. This inherently discrete nature leads to approximation inaccuracies because the continuous behavior of a system can only be imitated by a limited number of sampled points. In addition to sampling errors, computational procedures often involve rounding of numerical results, either deliberately to conform to specified precision levels or inherently due to hardware and software limitations. Further compounding the situation are errors that arise during the conversion of numbers between different numerical formats, such as from decimal to binary systems, and particularly when employing floating-point representations, which are well known for their limited precision and susceptibility to cumulative rounding errors.

These cumulative and interdependent sources of errors may, under certain circumstances, cause the generation of completely unexpected or even paradoxical results during the simulation or computational experimentation processes. For

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instance, subtle inaccuracies in the representation of harmonic components of voltage waveforms can result in significant deviations when assessing power quality metrics or motor behavior characteristics. Consequently, careful management of computational errors becomes critically important when high-precision modeling and decision-making are required.

To address these issues within the context of analyzing electric motors, particularly asynchronous (induction) motors, a significant improvement was achieved by complementing the existing power-economic model with a dedicated control system aimed at managing the static characteristics of the motor's linear voltages. The addition of this control system enables the regulation and correction of random sequences generated during computational experiments, thereby improving the reliability and correctness of the simulated data. This, in turn, facilitates the selection of more cost-effective alternatives for restoring and maintaining the quality of the electric power supplied to electric motors.

The control systems were synthesized based on the concept of adaptation, employing mathematical expressions derived from a thorough analysis of the system behavior and error propagation characteristics. These adaptation-based control systems dynamically adjust key parameters during the simulation process to compensate for observed deviations, thereby enhancing the overall robustness of the modeling results.

The paper presents comprehensive results of the evaluation regarding the control of averages, amplitude dispersions, and phases associated with six harmonics of linear voltages obtained through extensive computer-based modeling. The assessments include not only the calculation of statistical parameters of the generated random sequences but also a critical verification step. This verification involves checking the extent to which the empirical averages and dispersions differ from their respective hypothetical (theoretical) values. Special emphasis is placed on quantifying these differences and analyzing their impact on the overall fidelity and validity of the computational experiments.

Through this rigorous approach, the study highlights both the necessity and the effectiveness of incorporating adaptation-based control systems into computational models to minimize error accumulation and to maintain the statistical integrity of simulation outputs. Such improvements are essential for advancing the precision and reliability of computer-based analysis in the context of complex electrotechnical systems.

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ПІДВИЩЕННЯ НАДІЙНОСТІ МОДЕЛЮВАННЯ РОБОТИ АСИНХРОННОГО ДВИГУНА НА ОСНОВІ АДАПТИВНОГО ПІДХОДУ

Анотація. *Дослідження присвячене підвищенню надійності моделювання роботи асинхронних двигунів під час розв'язання техніко-економічних завдань, пов'язаних із вибором систем захисту електроприводів, що працюють у промислових електричних мережах зі зниженою якістю електроенергії. Наявність напругових асиметрій, гармонічних спотворень та інших проблем якості електроенергії в цехових мережах істотно впливає на ефективність роботи і тривалість служби асинхронних двигунів, збільшуючи втрати енергії та витрати на технічне обслуговування.*

У статті запропоновано енергетико-економічну модель, яка дозволяє проводити обчислювальні експерименти з метою визначення оптимальних технічних рішень для поліпшення якості енергопостачання. Ключовим елементом моделі є система генерації та контролю параметрів лінійних напруг, яка забезпечує відповідність змодельованих сигналів їх статистичним закономірностям, що спостерігаються у реальних умовах роботи промислових підприємств.

Вперше впроваджено адаптивні алгоритми для безперервної та одночасної оцінки середніх значень, дисперсій, автокореляційних і взаємокореляційних функцій гармонік напруги. Наведено математичні вирази для корекції цих характеристик у процесі накопичення інформації. Запропоновано структурні схеми систем керування для аналогового та цифрового моделювання процесів зміни напруги, що дозволяють здійснювати моніторинг достовірності отриманих даних у реальному часі.

Отримані результати моделювання були верифіковані за допомогою перевірки статистичних гіпотез щодо середніх значень і дисперсій гармонік напруги. Експериментальні дослідження проводилися у прокатному цеху №1 ПАТ "Дніпроспецсталь", де функціонування потужних напівпровідникових перетворювачів спричиняє значні спотворення напруги в цехових мережах. Результати досліджень підтвердили адекватність запропонованого підходу до моделювання та його придатність для обґрунтування економічно ефективних рішень щодо поліпшення якості електроенергії.

Робота робить вагомий внесок у підвищення енергоефективності промислових підприємств, надаючи методичну основу для достовірного моделювання роботи асинхронних двигунів в умовах спотвореної якості енергопостачання. Запропонований підхід дозволяє істотно скоротити витрати і тривалість експериментальних досліджень

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за рахунок заміни їх на валідоване обчислювальне моделювання. Окрім цього, розроблена система адаптивного керування забезпечує мінімізацію накопичення похибок у процесі чисельного моделювання та підвищення точності аналізу складних електротехнічних систем. Проведене дослідження підкреслює важливість комплексного підходу до врахування реальних умов роботи електроприймачів у процесі створення моделей для оптимізації енергоспоживання та забезпечення надійності електроприводів у промислових мережах.

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