Разработан аппаратно-программный комплекс измерения и мониторинга коэффициента несимметрии трехфазной системы напряжений. Предложена структурная схема микропроцессорной системы измерения коэффициента несимметрии напряжения в судовой трехфазной сети, в которой используются действующие значения фазных напряжений. Предложена оптимизированная структура цифрового фильтра для расчета действующего значения детерминированного периодического сигнала при оптимальном быстродействии дискретной системы

Ключевые слова: качество электроэнергии, коэффициент несимметрии, судовая электростанция, мониторинг напряжения, цифровой автомат

Розроблено апаратно-програмний комплекс вимірювання і моніторингу коефіцієнту несиметрії трифазної системи напруг. Запропоновано структурну схему мікропроцесорної системи вимірювання коефіцієнту несиметрії напруги в судновій трифазній мережі, в якій використовуються діючі значення фазних напруг. Запропоновано оптимізовану структуру цифрового фільтру для розрахунку діючого значення детермінованого періодичного сигналу при оптимальній швидкодії дискретної системи

Ключові слова: якість електроенергії, коефіцієнт несиметрії, суднова електростанція, моніторинг напруги, цифровий автомат

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DEVELOPMENT OF HARDWARE AND SOFTWARE FOR CALCULATION AND MONITORING OF THE UNBALANCE FACTOR IN THREE-PHASE VOLTAGE SYSTEM

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1. Introduction

At present, much attention is paid to power quality control in ship power systems (SPS). Power quality is characterized by such parameters as total harmonic distortion, the presence of reactive power, load unbalance [1]. Ideally, the supply voltage must have a sinusoidal waveform with constant amplitude and frequency [1, 2]. However, the presence of a non-zero impedance of the power source, different loads in the three-phase system may cause voltage unbalance.

The ship power system is a complex set of power sources and consumers that have various operating modes – from continuous to short-term and intermittent. Each consumer is characterized by the operating schedule, which is independent of operating modes of other consumers. In ships with a power plant with the capacity of up to 2,000 kW, the main switchboard (MSB) usually consists of 12–17 sections, most of which provide switching of up to two dozen consumers of different capacities. The most common sources of voltage unbalance in SPS are such power consumers, the symmetric polyphase implementation of which is either impossible, or impractical for technical and economic reasons. Also, voltage unbalance may be caused by the unbalance of the power supply (generator). The voltage of ship power generators often has a trapezoidal waveform. The voltage waveform is very distorted in systems with semiconductor controlled rectifiers. Voltage unbalance of 2 % reduces the engine life by 10.8 %. With a 4 % voltage unbalance, the service life is halved. For synchronous motors, life reduction with unbalance of 2 % is 16.2 %, transformers – 4 %, capacitors – 20 %. With a 2 % voltage unbalance, the negative sequence current of the induction motor increases to 15 %, power loss – by 8 %. Also, voltage unbalance leads to higher losses in the neutral wire during power transmission. At the same time, power supply disruption, failures of computers, navigation and other equipment are possible [3]. Therefore, the problem of power quality in relation to ship power systems is extremely relevant. Regulatory documents (IEC 60092-101:1995, IEC 60533:1999, GOST 13109-97) set the values of negative (K_{2U}) and zero (K_{0U}) sequence voltage unbalance factors. The allowable value is 2 %, and the maximum allowable value is 4 %. In some cases, separate power sources or converters, LC filters, stabilizers, compensators must be used to provide the required power quality on ships.

When assessing the power quality, there are a number of unresolved or insufficiently resolved problems of measuring the unbalance factors. These problems are related to mathematical, algorithmic and software support. The solution of them has not yet started due to restrictions of the corresponding algorithmic and hardware support. The high cost of ship electric equipment, as well as the complexity of repair in navigation conditions, create the prerequisites for developing modern power quality control systems.

2. Literature review and problem statement

Ship power systems are isolated and autonomous. An analysis of the requirements for the quality of power for SPS has been carried out in [1]. It has been noted that due to the presence of semiconductor power converters in the network, power quality control systems must meet the requirements of electromagnetic compatibility. However, in [1] the author has not proposed technical solutions for accurate measurements in the presence of interference. The unresolved problem of the influence of voltage fluctuations on the measurement accuracy has been also noted. In particular, voltage deviation from 50 Hz is characteristic for ship power systems. This may introduce an error when calculating the unbalance factor due to incorrect determination of effective voltage values. Therefore, it is important to develop a structure of the digital signal processing subsystem, which would minimize the impact of input voltage fluctuations on the measurement accuracy.

In [2], the analysis of the problem of power quality on ships has been carried out and prospects and ways of its improvement have been considered. One solution is to improve measurement means. Staff development is equally important. This requires the development of monitoring systems with human-machine interface elements. At the same time, software for monitoring the power quality, in particular, the unbalance factor, should be informative and easy to use. This will reduce the risk of emergencies due to equipment failures caused by poor power quality.

In [3], the algorithm for calculating the unbalance factor based on the Fortescue theorem application has been proposed. This algorithm is convenient for the calculation and analysis of power quality in SPS. However, the author has not considered the features of technical implementation of the calculation procedure.

In [4], it has been noted that not all manufacturers of power quality measuring equipment met the standards (IEC 61000-4-30, IEC 61000-4-7, IEC 61000-4-15) when developing their devices. In particular, when determining the unbalance factor using the discrete Fourier transform [5], an insufficient number of harmonics are taken into account to ensure the required measurement accuracy. In addition, as noted in [5], if the signal sampling rate does not match the line frequency, signals are digitized incoherently. The solution proposed in [5], obtained in an analytical form, is characterized by high calculating costs. In this case, for the real-time operation of the system, it is necessary to minimize the number of calculations during digital signal processing. Therefore, the development of the optimized high-speed digital filter for the calculation of root-mean-square voltage values used when calculating the unbalance factor is relevant.

A number of authors propose hardware-software solutions for power quality monitoring, based on the use of special data collection systems and virtual tools LabView [6–8]. Such systems are characterized by high cost and redundancy. At the same time, information is displayed numerically and as voltage waveforms. Such solutions are convenient for conducting scientific research. However, vector diagrams are preferably used to monitor voltage unbalance. Therefore, the issue of developing the structure of the unbalance factor measuring system, which would be characterized, on the one hand, by simplicity and, as a consequence, low cost, and, on the other hand, by the maximum use of microprocessor technology and digital signal processing algorithms remains open.

In [9], the methodology for installing power quality monitoring systems on ships to optimize power consumers has been proposed. The devices proposed in [9] are designed for installation of oil tanker pumps on engines, and measure both currents and voltages. Such systems are used to control power quality in dynamic operation modes of consumers. However, the issues related to power quality monitoring, in particular, measurement of the unbalance factor in the statics, have not been considered.

Literature review has shown that in existing measuring means of power quality indicators of three-phase networks, there are opportunities to improve them and ensure more effective measurement of the required indicators. Therefore, it is necessary to develop the structure of the unbalance factor measuring system, taking into account modern capabilities of hardware and algorithmic support. To minimize hardware utilization, it is advisable to measure the characteristics of phase voltages with the sequential calculation of effective line voltages. Synthesis of modern microprocessor control systems involves the development of algorithms for processing the signals taken from transducers. At the same time, the methods used for analogue control systems are sometimes ineffective for digital systems. In this regard, there is also a problem of synthesizing a digital structure for calculating the RMS value of the deterministic periodic signal at the optimum speed of a discrete system.

3. The aim and objectives of the study

The aim of the study is to develop and improve the methods and devices for control, analysis and monitoring of power quality indicators in ship power systems, one of which is the unbalance factor of three-phase voltages.

To achieve this aim, it is necessary to accomplish the following objectives:

– to perform the analysis of expressions for calculating the unbalance factor and their conversion to minimize the utilization of hardware necessary to obtain the required signals and the possibility of using the effective values of phase voltages in calculations;

– to develop the optimized structure of the digital signal processing subsystem for calculating the RMS voltage value, the distinctive feature of which is the independence of the number of calculations to obtain the output reading of the input signal sampling rate;

– to design a block diagram of the microprocessor system for measuring the unbalance factor, highlighting the system elements that cannot be implemented by software;

– to develop a transition graph of the digital automation for software implementation of the unbalance factor calculation algorithm and software for the unbalance factor monitoring.

4. Design of the measuring and monitoring system of the unbalance factor of the three-phase network

4. 1. Conversion of analytical expressions for the asymmetry factor calculation

One of the tasks of the SPS power quality monitoring system is the calculation and transmission of zero sequence:

$$K_{0U}=\sqrt{\frac{\sum_{i=1}^{N}K_{0U(i)}^{2}}{N}}, \tag{1}$$

and negative sequence:

$$K_{2U}=\sqrt{\frac{\sum_{i=1}^{N}K_{2U(i)}^2}{N}}, \quad (2)$$

unbalance factors to the computerized control system (CCS) at the operator's request, where $K_{0U(i)}$ and $K_{2U(i)}$ are the corresponding factors derived from the i-th observation data;

N is the number of observations on the averaging interval (according to [3], the averaging interval is 3 seconds and N must be at least 9).

The calculation of the effective values of unbalance factors is performed using the formulas (1) and (2) in accordance with the expressions:

$$K_{0U(i)}=\frac{\sqrt{3}\cdot U_{0(i)}}{U_{1(i)}}\cdot 100\,\%, \quad (3)$$

$$K_{2U(i)}=\frac{U_{2(i)}}{U_{1(i)}}\cdot 100\,\%, \quad (4)$$

where $U_{0(i)}$, $U_{1(i)}$ and $U_{2(i)}$ are the effective values of zero, positive and negative sequence voltages, respectively, in the i-th observation. To calculate them, the following expressions can be used:

$$U_{a(i)}=U_{AB(i)}-\frac{U_{BC(i)}^2-U_{CA(i)}^2}{U_{AB(i)}},$$

$$U_{b(i)}=U_{AB(i)}-\frac{U_{B(i)}^2-U_{A(i)}^2}{U_{AB(i)}},$$

$$U_{0(i)}=\frac{1}{6}\cdot\sqrt{\left[\frac{U_{BC(i)}^2-U_{CA(i)}^2}{U_{AB(i)}}-3\cdot\frac{U_{B(i)}^2-U_{A(i)}^2}{U_{AB(i)}}\right]^2+\left[\sqrt{4\cdot U_{BC(i)}^2-U_{a(i)}^2}-3\cdot\sqrt{4\cdot U_{B(i)}^2-U_{b(i)}^2}\right]^2}, \quad (5)$$

$$U_{1(i)}=\sqrt{\frac{1}{12}\cdot\left[\left(\sqrt{3}\cdot U_{AB(i)}+\sqrt{4\cdot U_{BC(i)}^2-\left(\frac{U_{BC(i)}^2-U_{CA(i)}^2}{U_{AB(i)}}+U_{AB(i)}\right)^2}\right)^2+\left(\frac{U_{BC(i)}^2-U_{CA(i)}^2}{U_{AB(i)}}\right)^2\right]}, \quad (6)$$

$$U_{2(i)}=\sqrt{\frac{1}{12}\cdot\left[\left(\sqrt{3}\cdot U_{AB(i)}-\sqrt{4\cdot U_{BC(i)}^2-\left(\frac{U_{BC(i)}^2-U_{CA(i)}^2}{U_{AB(i)}}+U_{AB(i)}\right)^2}\right)^2+\left(\frac{U_{BC(i)}^2-U_{CA(i)}^2}{U_{AB(i)}}\right)^2\right]}, \quad (7)$$

where $U_{AB(i)}$, $U_{BC(i)}$ and $U_{CA(i)}$ are the effective values of line voltages in the i-th observation.

To calculate the voltage unbalance factor, the following expression can be used:

$$K_U=\sqrt{A^2+B^2},$$

$$A=\frac{2U_{AB}-U_{BC}-U_{CA}}{U_{AB}+U_{BC}+U_{CA}},$$

$$B=\frac{\sqrt{3}(U_{BC}-U_{CA})}{U_{AB}+U_{BC}+U_{CA}},$$

where U_{AB}, U_{BC} and U_{CA} are the measured effective values of line voltages.

If necessary, the unbalance factor argument value can be calculated:

$$\Delta\phi=arctg\frac{B}{A}.$$

Thus, one of the requirements for the hardware of the power quality monitoring system is the ability to measure line voltages. However, to ensure the unbalance visualization, it is necessary to have the value of at least one of the angles between phase voltage vectors. Since there is an unambiguous relationship between phase and line voltage vectors, it is proposed to measure the characteristics of phase voltage vectors with the subsequent calculation of the effective values of line voltages to minimize hardware utilization:

$$U_{AB(i)}=\sqrt{U_{A(i)}^2-2U_{A(i)}U_{B(i)}\cos\phi_{AB(i)}+U_{B(i)}^2}, \quad (8)$$

$$U_{BC(i)}=\sqrt{U_{B(i)}^2-2U_{B(i)}U_{C(i)}\cos\left(\phi_{AB(i)}-\phi_{AC(i)}\right)+U_{C(i)}^2}, \quad (9)$$

$$U_{CA(i)}=\sqrt{U_{C(i)}^2-2U_{A(i)}U_{C(i)}\cos\phi_{AC(i)}+U_{A(i)}^2}, \quad (10)$$

where $U_{A(i)}$, $U_{B(i)}$ and $U_{C(i)}$ are the effective values of phase network voltages; $\varphi_{AB(i)}$, $\varphi_{BC(i)}$ and $\varphi_{CA(i)}$ are the angles of shifts between phase voltages in the i-th observation.

4. 2. Optimized structure of the digital filter for the RMS value calculation

The arithmetic mean of an alternating signal with the period T is calculated by the formula

$$u_{avg}=\frac{1}{T}\int_0^T|u(t)|\,\mathrm{d}t.$$

If the $u(t)$ curve is symmetric about the x-axis, then:

$$u_{avg}=\frac{2}{T}\int_0^{T/2}|u(t)|\,\mathrm{d}t.$$

A continuous input signal can be converted into a sequence of discrete values by taking the input signal values at regular intervals $t_n=n\cdot T_s$ using a sample and hold circuit. Here,

$$f_s=\frac{1}{T_s}$$

is the sampling rate.

Then, the expression for calculating the mean value can be represented in a discrete form as follows:

$$u_{avg}(t)=\frac{1}{N}\sum_{n=0}^{N-1}|u(t-nT_s)|,$$

where

$$N=\frac{T}{2\cdot T_s}.$$

Let us introduce the following notations: $Y = u_{avg}$, $X = |u|$. By rewriting this equation, introducing the

$$\frac{1}{N} = h$$

constant under the index of summation and passing to discrete time, we obtain the expression:

$$Y(kT_s) = \sum_{n=0}^{N-1} h \cdot X\left[(k-n)T_s\right].$$

This equation describes a linear finite impulse response filter of the $N-1$ order (Fig. 1).

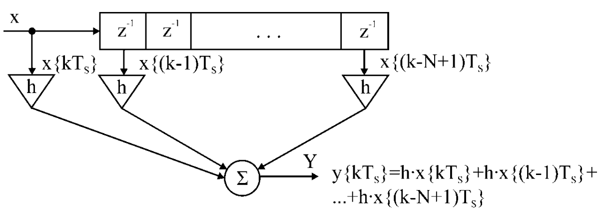

Fig. 1. Structure of the digital filter for the mean voltage value calculation

The expression for calculating the mean value in an expanded form is:

$$y(kT_S) = \\ = h\left[x\{kT_S\} + x\{(k-1)T_S\} + \ldots + x\{(k-N+1)T_S\}\right].$$

For the next reading of time $kT_S + 1$, the following expression is valid:

$$y(kT_S+1) = \\ = h\left[x\{kT_S+1\} + x\{kT_S\} + \ldots + x\{(k-N)T_S\}\right].$$

By combining both expressions, we obtain the equation for the output reading $y(kT_S+1)$, expressed through its previous value $y(kT_S)$:

$$y(kT_S+1) = y(kT_S) + \\ + h \cdot x\{kT_S+1\} - h \cdot x\{(k-N+1)T_S\}.$$

Using the given expression, the optimized structure of the transversal digital filter with equal weighting factors can be proposed (Fig. 2).

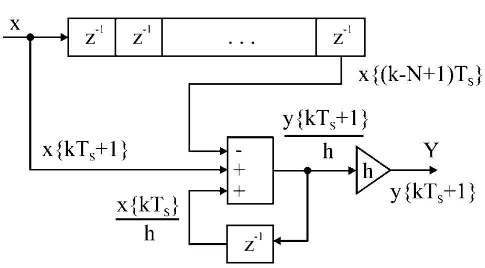

Fig. 2. Optimized structure of the digital filter for the mean voltage value calculation

By introducing additional functional units A^2 and $\sqrt{A}$ (Fig. 3), the optimized structure of the digital filter with equal weighting factors can be used to calculate the effective (RMS) value of the input signal used in the expressions (3)–(10).

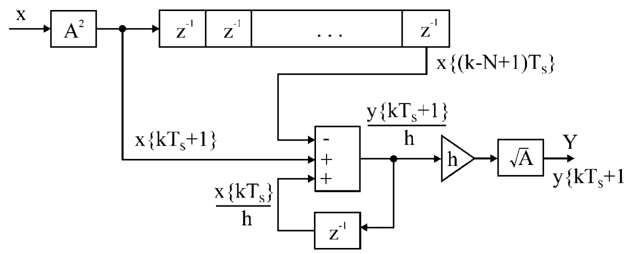

Fig. 3. Optimized structure of the digital filter for the effective voltage value calculation

To calculate the next output reading of the optimized digital filter, it is necessary to perform 3 addition operations and one multiplication operation, against N addition operations and N multiplication operations. Reduction of the number of arithmetic calculations leads to the increased length of the digital delay line by one memory element and allocation of an additional memory element to store the intermediate result.

4. 3. Design of the block diagram of the unbalance factor measuring system and digital automation

The requirements for the hardware of the unbalance factor measuring and monitoring system are as follows: the presence of three inputs for voltage measurement in the range of 0–250 V; the availability of the network interface for communication with the CCS. In accordance with the above requirements, the block diagram of the system was developed (Fig. 4), where 1, 2, 3 – measuring transformers and signal processing subsystems that form the effective values of phase voltages of the busbar of the main switchboard; 4 – proportionality coefficient; 5 – rectifier; 6 – integrator; 7 – low-pass filter; 8 – pulse shaper (null detector); 9 – multiplexer; 10 – ADC; 11 – high-frequency pulse shaper; 12 – counter timer circuit; 13 – microcontroller input/output ports; 14 – serial receiver/transmitter unit; 15 – LEDs for the operation mode indication; 16 – interface converter from RS232 to RS485; MPU – microcontroller.

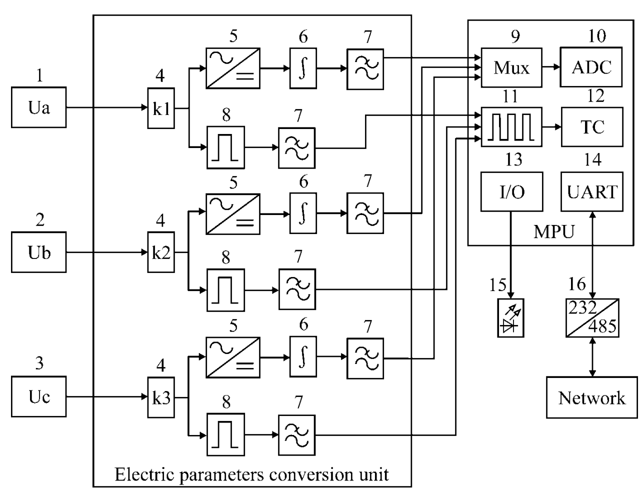

Fig. 4. Block diagram of the unbalance factor measuring and monitoring system

The lack of the necessary software encourages the development of intelligent programs with the desired properties, based on the ideas about the problem. However, there is no uniform understanding of the requirements and properties of such systems, in particular, the ways of their implementation. To develop software for microcontrollers, the automata-based approach is widely used [13].

The device is based on the microcontroller whose software algorithm can be represented in the form of digital automation $A_5=\{Q, X, D, f\}$, where $Q=\{q1–q4\}$ – a set of the automation states: $q1$ – digitization of the effective values of phase voltages; $q2$ – measurement of interphase angles; $q2.1$ – voltage frequency measurement U_A; $q2.2$ – measurement of the angle between the voltage vectors UA and UB; $q2.3$ – measurement of the angle between the stress vectors U_A and U_C; $q3$ –calculation of unbalance factors; $q4$ – accumulation of data – inquiry components; $q5$ – inquiry interpretation; $q6$ – inquiry answer transmission; $X=\{x1–x12\}$ – a set of input factors: $x1$ – system timer interrupt; $x2$ – interrupt upon ADC completion; $x3$ – all voltage values are digitized; $x4$, $x5$, $x6$ – interrupts of voltage null detectors U_A, U_B and U_C, respectively; $x7$ – values of frequency and interphase angles are measured; $x8$ – data byte receipt interrupt; $x9$ – timer interrupt; $x10$ – correct inquiry is received; $x11$ – data byte transmission interrupt; $x12$ – inquiry answer is transmitted; $D=\{d1 – d7\}$ – a set of operations performed during the transitions: $d1$ – "system" timer start; $d2$ – ADC channel switching; $d3$, $d4$, $d5$ – start of interrupts of voltage null detectors U_A, U_B and U_C, respectively; $d6$ – timer start to measure the time interval between the received bytes; $d7$ – start of byte-by-byte data transmission; f – next-state function (represented as a graph in Fig. 5).

Based on the block diagram of the unbalance factor measuring and monitoring system, the schematic diagram of the device was developed. For software implementation of the automation transition graph, automata-based programming together with the object-oriented approach was used. Automata-based programming allows solving complex cyclic tasks using minimum time and calculating resources for debugging and unit testing.

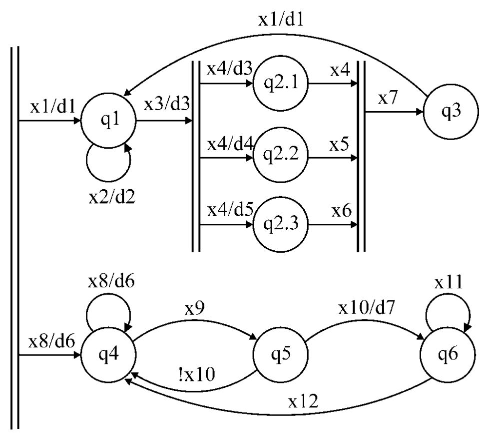

Fig. 5. Automation transition graph, describing the operation of the power quality monitoring system

5. Result of the development of hardware and software for the unbalance factor monitoring

Determination of the voltage unbalance factor in the ship power system is implemented using the device and software (Fig. 6), which perform the functions of measurement, processing and storage of the corresponding parameter in the file, as well as indication of the result. In the measuring system, determination of the unbalance factor of positive, negative and zero sequence voltages is implemented.

The total load of the SPS depends on the simultaneous operation of a large number of power consumers in the operating conditions with different load patterns. In the daily curve of the voltage unbalance factor of the SPS, there are peaks due to application and shedding of loads in operating conditions of the power plant, the identification of which is necessary to prevent unfavorable operating conditions of ship systems and mechanisms. Fig. 7 shows the daily curve of the voltage unbalance factor of the ship power plant, obtained experimentally using the developed system (operation of the voltage unbalance monitoring system in the statics).

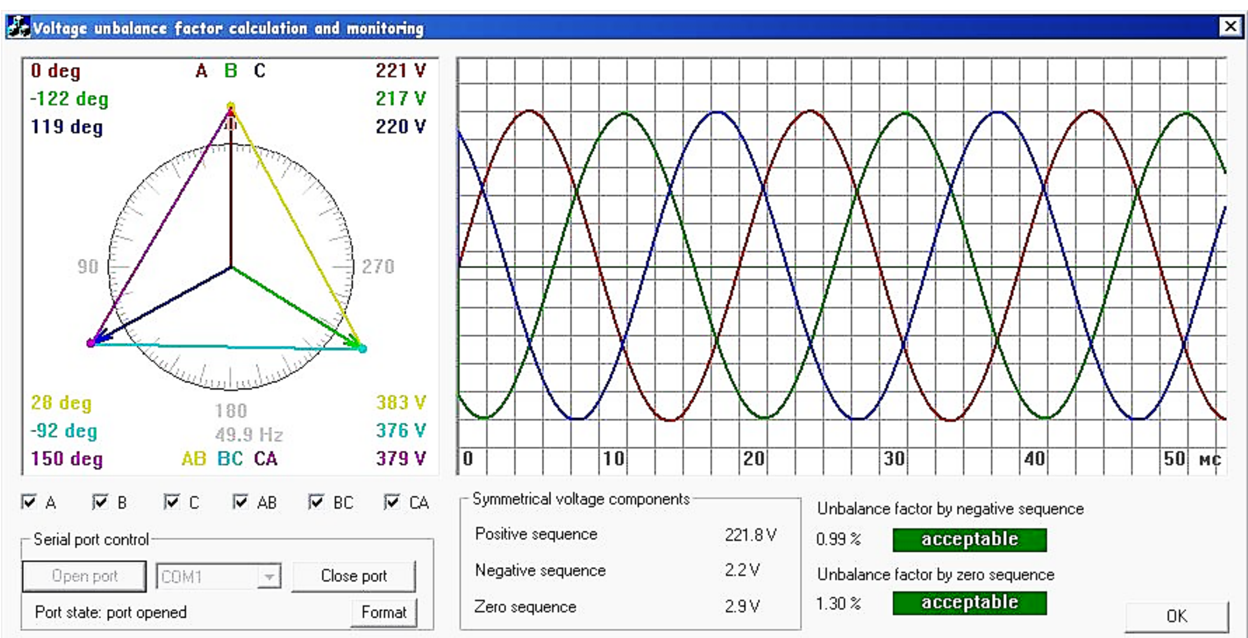

Fig. 6. Program dialog box in the absence of voltage unbalance

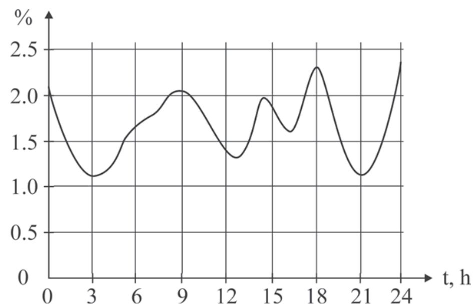

Fig. 7. Daily curve of the voltage unbalance factor of the ship power plant

During the measurement, the values of the quality indicators are averaged (the averaging interval is 3 seconds, the number of measurements for averaging is 9). Since the averaging is used in the measurement, the curve has no sharp changes in the unbalance factor due to the load switching. From the curve in Fig. 7, it can be concluded that the power quality in the considered SPS does not meet the requirements of GOST 13109-97 in terms of unbalance factors. The total time they exceed the normal allowable values (2 %) is more than 1 hour 12 minutes per day. However, there are no measurements corresponding to exceeding the maximum allowable values (4 %). The data obtained confirm the need to take measures for load balancing in the SPS, since currently such means are not used on the considered vessel. Also, the curve does not show changes in the unbalance factor at the moment of load switching. This is due to the transience of the transition processes, which last a few seconds. To analyze the operation of the unbalance factor monitoring system in the dynamic operating conditions of the power plant, an observation interval of 60 seconds was chosen. Fig. 8 shows the results of the monitoring system operation in dynamics.

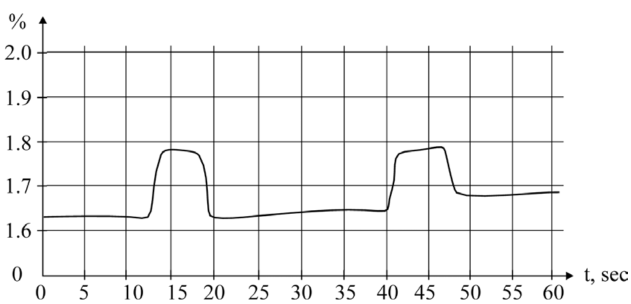

Fig. 8. Curve of the unbalance factor when starting induction motors

At timepoints t=13 s and t=40 s, direct-on-line starting of induction motors with a power of 30 kW was performed. At the same time, the total capacity of the ship power plant was 300 kW.

6. Discussion of the results of designing the unbalance factor measuring and monitoring system

Statistical processing of the measurement results showed that the deviation of the negative sequence unbalance has small values, that is, the unbalance is stable. In many cases, the stability of the unbalance module and argument was observed for many hours. With a high degree of certainty, it can be argued that for a particular ship network mode, both the unbalance module and argument obey the normal probability distribution law. The reason for this is the stability of the network load in each mode. The unbalance factor obtained using the developed monitoring system is consistent with the results presented in [1]. The frequency of load switching of the MSB is close to the time constants of diesel-generator sets. In the presence of oscillatory properties of the generating sets, switching of loads facilitates the "swing" of the latter and causes fluctuations in voltages and active power between the generator sets, which in turn lead to frequency fluctuations. At the same time, the use of the optimized digital filter to calculate the RMS voltage eliminated the influence of line frequency fluctuations on the measured values of the unbalance factor.

The developed system can be integrated into the automated control system of the ship power plant and used for the timely detection of voltage unbalance in order to protect the equipment. The developed hardware and software can also be used to improve the control over reactive power distribution between parallel-operating generators. In [10], for reactive power control, measurement of voltage and current of only one of the phases is used, and the assumption is made about the load balance. Introduction of an additional unbalance feedback loop will allow eliminating the unbalance of the three-phase network, and, if necessary, generating a control signal for protection systems to prevent violation of the normal operation of power consumers.

The developed digital automation can be implemented in the microcontroller of the induction motor control system and complements the author's research, the results of which have been presented in [11]. The optimized model of the induction motor control system contains the microcontroller, which receives all the necessary signals to calculate the unbalance factor. This allows adjusting the control signal to the rectifier and increasing the quality of power supplied to the frequency drive inverter.

The response time of the proposed RMS voltage calculation algorithm is T_s (sampling period). At the same time, an increase in the sampling rate in the optimized filter structures does not lead to an increase in the number of arithmetic operations of addition and multiplication, which is an advantage of the proposed system in comparison with similar ones. This allows monitoring of instantaneous changes in the unbalance factor of the three-phase voltage. If the length of the delay line of the digital filter does not coincide with the number of samples per period of periodic signals, the calculated effective values will change over time, i.e. will be modulated. The use of the microcontroller and software implementation of calculation algorithms allow eliminating this phenomenon by adjusting the length of the digital filter delay line depending on the line frequency. This makes the developed system adaptable, unlike other similar ones.

Using the developed hardware and software, the problems of standardization and practical monitoring of the quality of three-phase voltage at the stages of acceptance and operation of ship power systems are solved. Also, the developed system can be used in voltage control systems of power plants, as well as in various monitoring and protection systems developed by the author and considered in [12, 13].

7. Conclusions

1. Based on the analysis of the analytical expressions for calculating the unbalance factor, in which the effective

values of phase voltages are used, utilization of the hardware necessary to obtain the required signals is minimized. This also ensured high speed of the developed system, as it is equipped with three null detectors, signals from which are sent to the microprocessor for processing and determining phase shifts. Noise immunity of the system is improved due to the independence of the measured phase shift angles between line voltages of the mains voltage waveform. The use of the developed system to determine the unbalance factor allows taking timely measures to eliminate the voltage unbalance and reduce losses in networks by 15–20 %.

2. The optimized structure of the digital signal processing subsystem to calculate the RMS voltage is developed. The proposed structure of the digital filter is characterized by the independence of the number of calculations to obtain an output reading of the input signal sampling rate. The response time of the developed system does not exceed the value of the analog signal sampling period T_s (500 μs at a sampling rate of 2 kHz). This allows using it in high-speed automatic voltage quality control systems in the ship and general industrial networks.

3. The designed block diagram of the microprocessor unbalance factor measuring system is optimized in terms of hardware utilization, since all calculations are performed at the software level, using also digital signal processing algorithms. Exclusion of a number of complex units allowed reducing the cost of the developed system by 20 %.

4. Using the transition graph to describe the system operation algorithm allowed representing it in the form of digital automation with a finite number of states and performing an isomorphic transition to a software implementation of the algorithm. The graphic interface of the developed software is characterized by usability and clarity of the unbalance factor calculation results. The use of the automata-based approach allowed us to formally approach the software development process and use the methods of abstract synthesis of digital automata. This has reduced the time of development and testing of software by 30 %, which is important in a highly competitive environment.

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