ABSTRACT The paper describes problem of isolating, evaluating and eliminating interharmonics of current using the example of the operation of an asynchronous electric motor operating at a variable periodic load. The complexity of the problem lies in the fact that the value of the current changes depending on the load of the electric motor, which can change by a multiple of the frequency of the supply network, thereby introducing an interharmonic distortion of the current waveform. The main indicators of harmonic distortion of currents and voltages are the individual harmonic coefficient and total harmonic distortion, which must not exceed the IEC requirements, but at the same time it worsens the operation of the entire network due to interharmonics. The paper applies simulation modeling in the Matlab/Simulink mathematical package. The model consists of an asynchronous motor with a short-circuited rotor, a variable periodic load unit with a three-phase voltage source, and a current spectral analysis subsystem. The parameters of the main current harmonic were determined. An algorithm for the selection of interharmonics of current arising as a result of a variable periodic load is given. By representing the difference between the current curve and the fundamental harmonic as a series of Fourier harmonics, the frequencies, amplitudes and phases of the interharmonics were determined. To reduce the current interharmonics for devices operating with variable periodic load, it is proposed to use active harmonic filters of fixed filtration or with automatic adjustment of filtration parameters.

INDEX TERMS Interharmonics, variable periodic load, higher harmonics, Fourier.

I. INTRODUCTION

The problem of the quality of electrical energy in the power supply systems continues to be one of the most important, determining both the reliability and efficiency of power supply to consumers. One of its main components is the problem of the presence of higher and interharmonics in the network.

The relevance of the study lies in the fact that since 2016 the unified requirements of IACS UR E24 have come into force, according to which it is necessary to measure the voltage non-sinusoidal indicators during the vessel survey [1]. Therefore, it is essential to ensure the quality of electricity in autonomous electric power systems used on vessels.

The presence of harmonics is caused by the extensive use of non-linear devices, such as welding machines, electric machines and arc furnaces. Distortions in the shape of the curves of currents and voltages lead to an increase in losses, accelerated heating of equipment, loss of resource intensity, deterioration of insulation and the resulting reduction in the service life of electrical equipment and its premature failure. In order to maintain the quality of electricity and the operation of electrical equipment, it is necessary to
determine the parameters of interharmonics that arise during the operation of electrical equipment.

The main consumer of electricity on the vessel is electric drives, therefore, there is a need to investigate the interharmonic components of current and voltage and the operation of these devices. The objective is to estimate the harmonics of the stator current of an asynchronous electric motor operating on a variable periodic load.

The IEC 61000-4-7: 2009 [2] standard defines interharmonics as harmonics of the fundamental (power) frequency of a current that are not multiples of the fundamental frequency. In the amplitude-frequency spectrum, they are between the canonical, i.e. higher harmonics (HH), as well as between the constant component and the fundamental harmonic. Based on the generalization of the best practices of international organizations involved in the regulation and modeling of non-sinusoidal processes with frequencies that are not multiples of the base one, the paper [3] defines a range of problems in the section of power quality indicators, which include malfunction of devices and control systems. One of the sources of interharmonics according to [4] can be electric motors. Harmonics arise from gaps between the metal in the rotor and stator, especially when the magnetic circuit is saturated (so-called gap harmonics). Natural elements of asymmetry in the design of an electric drive (deviations from detailed drawing geometric harmonics). Natural elements of asymmetry in the design of an electric drive (deviations from detailed drawing geometric harmonics). Natural elements of asymmetry in the design of an electric drive (deviations from detailed drawing geometric harmonics). Natural elements of asymmetry in the design of an electric drive (deviations from detailed drawing geometric harmonics).

At present, the analysis of the principles of the mathematical description of interharmonic distortions is being carried out. The article [5] analyzes the properties of the Fourier series of several variables and shows the advantages of describing signals by several components, demonstrates the principle of projection of a multidimensional spectrum onto one variable. Also, the analysis of the network voltage disturbance for each load was carried out and a voltage model was obtained in the frequency domain of several variables. Based on the calculations performed, the shape of each perturbation for a batch of input parameters and the general shape of the network voltage and its spectrum are plotted. Thus, the nature of the formation of interharmonics as combination harmonics is shown.

The paper [6] discusses the modeling of diagnostics of malfunctions of an induction motor based on spectral analysis of the stator current signal using the fast Fourier transform. The current recognition system is based on the study of the frequency spectrum of the stator using the FFT current signal. A short circuit in the supply phase, an open stator winding, an unbalanced input voltage and an open phase of an induction motor were studied as faults. Current spectra are obtained for each fault. The paper [7] simulates the diagnostics of shaft vibrations due to misalignment or breakage of bearings of an asynchronous electric motor, based on the analysis of the steady-state current by the Fourier series expansion method. Simulation is carried out with parameters without displacement on the shaft and in case of faults to analyze the differences in the spectral components of the current and further apply the results in diagnostics. Moreover, interharmonics of current occur when an asynchronous electric motor operates at a variable periodic load, for example, in electric drives of reciprocating compressors, robots, conveyor production and other industrial applications.

The authors of the article [8] consider the issue of reducing the level of interharmonic distortions at enterprises using AC electric arc furnaces. The article proposes the use of a neural network to identify harmonics and make a decision to compensate them with an active filter.

II. DEVELOPMENT OF A MODEL OF AN ELECTROMECHANICAL SYSTEM IN MATLAB

To evaluate the values of current interharmonics arising in the stator of an AC drive, the authors will create a simulation model in the MATLAB / Simulink mathematical modeling package.

The simulation model consists of the following functional subsystems (Figure 1): asynchronous squirrel-cage motor Asynchronies Machine SI Units, Real Three-Phase Source with internal impedance, Variable Periodic Load unit, THD measurement units, stator current spectral analysis subsystem Harmonic Analyzer.

The Variable Periodic Load block changes at regular intervals from 1 to 100 Nm with a frequency of 47 Hz. Mechanisms with this type of load can be, for example, crushers, mining mills, continuous rolling mills, shears and saws for metal, blast furnace skip winches and piston compressors. [9,10]

![FIGURE 1. The system model in the Matlab/Simulink.](image)

The parameters of the asynchronous motor unit are shown in Table 1. The power ratings were chosen due to the high
prevalence of electric drives with variable shaft loads up to 10 kW. Three-phase power supply voltage is connected to a star with line voltage 380 V and a frequency of 60 Hz. Such voltage ratings are widely used on new vessels due to the geographic location of large-scale ship-building yards (South Korea, Japan, etc.) The moment of inertia of an electric motor is determined by design data according to the power of the electric drive

### TABLE I

| Symbol | Quantity |
|--------|----------|
| Name plate rating | 4 kW |
| Nominal voltage | 380 V |
| Rated frequency | 60 Hz |
| Rated speed | 1750 rpm |
| Current ratings | 8.7 A |
| Starting torque ratio | 1.8 |
| Overload capacitance | 2.8 |
| Moment of inertia | 0.05 kg m² |

### IV. ASSESSMENT OF THE HARMONIC DISTORTION

The main indicators of harmonic distortion are as follows:

1. Individual voltage harmonic distortion (or h-order harmonic distortion):

\[ U_h(\%) = \left( \frac{U_h}{U_1} \right) \times 100\% \]  

where \( U_h \) is amplitude value of interharmonic voltage of h – frequency, \( U_1 \) is amplitude value of the voltage for fundamental harmonics.

As for the current:

\[ I_h(\%) = \left( \frac{I_h}{I_1} \right) \times 100\% \]  

where \( I_h \) is amplitude value of interharmonic current of h – frequency, and \( I_1 \) is amplitude value of the current for fundamental harmonics, А.

According to IEC 61000-2-4:2002 [11], the measured value of THDi and the phenomena observed in the installation are as follows:

1. **THDi** value less than 10 % is considered normal. There is no danger of a malfunction.
2. **THDi** values from 10 to 50 % indicates significant harmonic disturbance. There is a danger of heating, which requires overrating the parameters of cables and sources.

3. **THDi** values more than 50 % suggests a very large harmonic disturbance. Operational failures are possible. Furthermore, IEC [9] provides for the levels of electromagnetic compatibility for interharmonic voltages. Individual interharmonic coefficient with multiplicity below 17 should not exceed 2.5%.

To estimate the current distortion by multiples of the harmonics, the model provides THD blocks that estimate the total harmonic distortion in voltage and current, respectively.

### V. SIMULATION RESULTS

To assess the elimination of interharmonics, we propose the following method based on the use of an active filter.

Current sensors collect information about the currents of all three lines (\( i_A, i_B, i_C \)) of the receiver operating with a periodic variable load and transmit the information to the control system, where analog signal is being converted to digital one and the signal is filtered from random interference. Based on the information received, the currents are decomposed into Fourier series with the fundamental harmonic (in this case, it is known and is 60 Hz) equal to the network frequency.

Then the carrier (first) harmonic current component is selected for each of the phases. Fundamental harmonic for phase A and substitute the amplitude \( I_{AFund} \) and phase \( \varphi_{AFund} \) into an equation of the form:

\[ i_{AFund} = I_{AFund} \sin(\omega t + \varphi_{AFund}), \]

The difference between real currents and carrier harmonics is determined:

\[ \Delta i_{AFund} = i_A - i_{AFund}. \]

The differences of all three phases are being compared. The difference between the current and the fundamental harmonic is represented by the subsystem shown in Fig. 3.

![FIGURE 3. Subsystem for analyzing harmonic current components.](image_url)
\[ \varepsilon \leq \left| I_{AF_{\text{fund}}} \sin(\omega t + \varphi_{AF_{\text{fund}}}) - I_{BF_{\text{mag}}} \sin(\omega t + \varphi_{BF_{\text{mag}}}) \right| - 120^\circ \]  
(11)

or in discrete form
\[ \varepsilon \leq abc \left( \Delta I_{AF_{\text{fund}}} (j) - \Delta I_{BF_{\text{mag}}} (j + n_{AB}) \right) \]  
(13)

where \( \Delta t \) is the step of discreteness in time; \( f_{\text{Fund}} \) is fundamental frequency; \( n_{AB} \) is the number of offsets to eliminate the phase difference between lines A and B.

- line C:
\[ \varepsilon \leq \left| I_{CF_{\text{mag}}} \sin(\omega t + \varphi_{CF_{\text{mag}}}) - I_{CM_{\text{mag}}} \sin(\omega t + \varphi_{CM_{\text{mag}}}) \right| - 240^\circ \]  
(14)

or in discrete form:
\[ \varepsilon \leq abc \left( \Delta I_{CF_{\text{mag}}} (j) - \Delta I_{CM_{\text{mag}}} (j + n_{AC}) \right) \]  
(15)

where \( \Delta t \) is the step of discreteness in time; \( f_{\text{Fund}} \) - fundamental frequency; \( n_{AC} \) is the number of offsets to eliminate the phase difference between lines A and B.

Then in order to simplify, we will carry out calculations only for line A.

In the steady-state mode of an electric motor operating with a variable periodic load, pulsations of torque and speed are observed (Figure 2). The amplitude of the moment pulsations is 10 Nm, the velocity ripples are 6 rad/s. The ripple frequency of both the rotation frequency and the torque coincides with the load change frequency, being equal to 47 Hz. The authors find the relative coefficient of velocity pulsations by the formula:
\[ \Delta \omega = \frac{\omega_{\text{max}} - \omega_{\text{min}}}{\omega_{\text{mean}}} \times 100 \% = 6.6 \% \]  
(5)

where \( \omega_{\text{max}} , \omega_{\text{max}} \) are maximum and minimal values of the speed with ripples, rad/s,
\[ \Delta \omega = \frac{\omega_{\text{max}} + \omega_{\text{min}}}{2} = 180 \text{rad} / s. \]  
(6)

Similarly, the relative torque ripple ratio is as follows:
\[ T_{\text{mean}} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}}} \times 100 \% = 18 \%, \]  
(7)

where \( T_{\text{max}}, T_{\text{max}} \) are the maximum and minimum values of speed with ripples, Nm
\[ T_{\text{mean}} = \frac{T_{\text{max}} + T_{\text{min}}}{2} = 55 \text{Nm}. \]  
(8)

The torque ripple rate is 18%, so the motor with the considered load has significant vibration. The problem of the vibration occurrence, ripples of speed and torque is considered in the paper [12], in which, by the example of the operation of an asynchronous electric drive on the load of a piston compressor, methods of speed and torque ripples attenuation are proposed.

With the existing torque ripples in the electric motor, proportional ripples of the stator electric current appear. The current can be represented as a harmonic Fourier series [13] and the total harmonic distortion of current and voltage may be found. They were 7.5%.

The obtained values do not exceed the IEC requirements. However, total harmonic distortion is calculated for harmonics that are multiples of the fundamental one. In order to make a complete assessment of the harmonic components, it is necessary to obtain a spectrum or isolate interharmonics.

Let us find the difference between the phase A of the stator of the electric motor and its selected fundamental harmonic. The results are shown in Figure 4 a.

\[ \Delta i_{\text{AFund}} \]  
(11)

\[ \Delta i_{\text{IH}_1} \]  
(12)

\[ \Delta i_{\text{IH}_2} \]  
(13)

FIGURE 2. Torque ripples on the shaft (1) and speed (2).

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(11)

\[ \Delta i_{\text{IH}_1} \]  
(12)

\[ \Delta i_{\text{IH}_2} \]  
(13)

FIGURE 4. Signal \( \Delta i_{\text{AFund}} \) (a) \( \Delta i_{\text{IH}_1} \) (b) and \( \Delta i_{\text{IH}_2} \) (c)
Figure 4 a shows that, in addition to the fundamental current harmonic, when the electric motor operates at a variable periodic load, other current ripples appear in the stator which are not multiples of the fundamental harmonic. Thus, the period of large oscillations is 0.083 s, the frequency is 12 Hz, the amplitude is 2 A, and the period of the smaller oscillations is 0.0093 s, the frequency is 108 Hz, the amplitude is 2.75 A. As we can see, all harmonics, with the exception of the fundamental (12 Hz) and the ninth (108 Hz), do not exceed 0.3 A (0.88% of the effective current value).

When the amplitude of the fundamental harmonic is 34 A, the individual interharmonic coefficient with frequencies of 12 and 108 Hz is
\[
 i_{\text{ih}12}(\%) = 5.6\% 
\]
and
\[
 i_{\text{ih}108}(\%) = 7.35\%.
\]
However, a person cannot manually determine the parameters of harmonics from a graph. Spectral analysis of disturbances introduced by a periodic variable load should be performed by the control system.

Taking the difference \(\Delta i_{\text{AFund}}\), a fast Fourier transform is performed. Spectral analysis is used to determine the frequency of the intergamonic \(\omega_{\text{IH}}\) with the highest amplitude.

\[
\omega_{\text{IH}} = \max(\hat{i}_{\text{AFund}}) 
\]
(16)

For the calculated intergamonic frequency \(\omega_{\text{IH}}\), the current difference \(\Delta i_{\text{AFund}}\) is decomposed into a trigonometric Fourier series with the separation of the \(I_{\text{IH}}\) amplitude and \(\phi_{\text{IH}}\) phase at the frequency \(\omega_{\text{IH}}\). The first intergamonics will take the following form:

\[
i_{\text{IH}} = I_{\text{IH}} \sin(\omega_{\text{IH}} t + \phi_{\text{IH}}). 
\]
(17)

The difference \(\Delta i_{\text{IH}}\) between \(\Delta i_{\text{AFund}}\) and \(i_{\text{IH}}\) is determined (fig. 4 b):

\[
\Delta i_{\text{IH}} = \Delta i_{\text{AFund}} - i_{\text{IH}}. 
\]
(18)

The active filter control system using PWM modulation generates an alternating current using a bridge autonomous voltage inverter and supplies it to the grid.

The total harmonic distortion (THDi) is calculated for the current \(i_A\) and if it is greater than the specified level, then for the \(\Delta i_{\text{IH}}\), a fast Fourier transform is performed and the interharmonic with the next highest amplitude is selected. Calculations according to formulas (16) - (18) are repeated until THDi enters the specified range. Figure 4c shows \(\Delta i_{\text{IH}12}\), from which it follows that a further search for interharmonics is futile. The same result is given by the fast Fourier transform (Fig. 5), where the third interharmonic is an order of magnitude less than the two previous ones.

The simulation modeling for different loads of an asynchronous motor (rectangular, triangular, sinusoidal, sawtooth) showed that removal of 2-3 interharmonics with the highest amplitude is enough, and removal of the following practically does not improve the quality of the current.

![Figure 5. Fast Fourier Transform for current of line A.](image)

To reduce interharmonics of current for devices operating with variable periodic load, it is advisable to use active harmonic filters with fixed filtering or with automatic tuning of filtering parameters.

Simulation modeling has been carried out using an active compensation-type harmonic filter. The general form of the model is shown in Figure 6. The interharmonic analyzer transmits data on harmonic distortion to the active filter inverter control module. The IGBT bridge generates an interharmonic signal in the antiphase and compensates for current distortions through the TV1-TV3 current transformers.

![Figure 6. The system model with active filter](image)

The simulation modeling results showed a significant effect of the active filter on the THDi level. Thus, the use of an active filter can reduce the distortion level by almost 2 times – from 7.5% to 4%.

The simulation modeling results of two models (with an active filter and without it) is shown in Table II:

| Symbol | Quantity |
|--------|----------|
|        |          |

**TABLE II**

**RESULTS OF MODELLING**

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Interharmonic compensation is performed by using active filters or by compensating for reactive power. The presented method differs from the classical one. Thus, according to the given method, it is mathematically possible to process periodic perturbations. Moreover, the filter can be adjusted in such a way that, after the initial adjustment, the system will operate with such quality indicators that cannot be achieved using a tracking system operating in real time, due to the system lag when processing and isolating an interharmonic signal in current or voltage. Thus, the active harmonic filter operates by perturbation, and the classical one – by deviation. Therefore, the proposed method for compensating for interharmonic components will be more accurate and it will have a faster response rate than the classical one. The efficiency of the proposed method is higher due to the fact that the calculations are made only once; the control system of the active harmonic filter is adjusted and operates without change until the non-periodic load is turned off or until it changes. It is much easier in terms of performance to control the constancy of a periodically varying load, than to perform new calculations in each discrete time interval in order to compensate for interharmonics. The computational complexity of the proposed method is equal to the computational complexity of classical methods only at the initial stage of adjustment, which takes no more than $5T$, where $T$ is the interharmonic period.

A distinctive feature of these devices from well-known devices is that, depending on the load, the current amplitude changes. Thus, it becomes impossible to apply a constant reference signal as in active harmonic filters. In this regard, it is advisable to use the above technique to determine the difference that must be introduced to compensate for interharmonics. The task of implementing an active filter for suppressing interharmonics of current, a signal equal to the difference between the current between the stator phase and load of 50 Nm was connected to the electric motor. The generator of such distortions is the UNI-T UTG2025A pulse generator. Figure 7 shows the amplitudes of interharmonics before and after switching on the device. It can be seen that the amplitudes have decreased by more than 3 times, which confirms the adequacy of the developed device and the algorithm for the analysis of interharmonics.

Moreover, as a result of, oscillograms of currents were obtained and processed, showing a decrease in the THDi level from 7.5 to 4%.

**VII. CONCLUSION**

The developed method for determining the interharmonic components of the current of an electric motor operating on a variable periodic load makes it possible to eliminate interharmonics and high harmonics. The prototype of the developed device is shown in Fig. 7. The control system of the device is designed using the Mathworks MATLAB laboratory. The peculiarities of the device are modular design and application of the developed method for determining interharmonics in the operation algorithm. The experiment was carried out in laboratory conditions and at the enterprise.

**FIGURE 7. – Prototype implementation of the developed device**

The tests of the device operating on the basis of the proposed method for determining the interharmonic components were carried out using additional equipment that creates a previously known distortion of the current in the network. The generator of such distortions is the UNI-T UTG2025A pulse generator. Figure 7 shows the amplitudes of interharmonics before and after switching on the device. It can be seen that the amplitudes have decreased by more than 3 times, which confirms the adequacy of the developed device and the algorithm for the analysis of interharmonics.

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**FIGURE 7. – Spectrum of interharmonic current distortion before and after activation of active filter**

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variable periodic load showed the presence of interharmonics with an individual coefficient exceeding the IEC requirements.

The presence of such harmonics in the current of an electric drive can lead to a deterioration in the parameters of the supply network, an increase in losses and a decrease in the service life of power lines and other electricity consumers. The obtained characteristics of interharmonics make it possible to assess the influence of the motor operation on the supply network and can be used to develop an active harmonic filter. Simulation modeling is presented and it shows that the given algorithm removes the main interharmonics, thereby increasing the quality of operation of devices with variable periodic load.

An experiment was carried out with the use of an external device for generating interference, which showed a high efficiency of compensation for interharmonic current components.

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