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Evaluation and Procedure for Estimation of Interharmonics on the Example of Non-Sinusoidal Current of an Induction Motor With Variable Periodic Load

BORIS A. AVDEEV[1], ALEKSEI V. VYNGRA[1], (Graduate Student Member, IEEE), SERGEI G. CHERNYI[1,2,3], (Member, IEEE), ANTON A. ZHILENKOV[2], AND SERGEY S. SOKOLOV[3]

[1]Department of Ship Electrical Equipment and Production Automation, Kerch State Maritime Technological University, 298309 Kerch, Russia
[2]Department of Cyber-Physical Systems, Saint Petersburg State Marine Technical University, 198303 Saint-Petersburg, Russia
[3]Complex Information Security Department, Admiral Makarov State University of Maritime and Inland Shipping, 198035 Saint-Petersburg, Russia

Corresponding author: Sergei G. Chernyi (sergiiblack@gmail.com)

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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. Experimental studies of the active filter with the proposed operation algorithm have been carried out. The results of the experiment justified the expediency of using this for suppressing interharomics in electric drive circuits.

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 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

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interharmonic components of current and voltage and the operation of these devices.

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 dimensions, misalignment, for example) can also cause interharmonics.

The objective is to estimate the harmonics of the stator current of an asynchronous electric motor operating on a variable periodic load.

The scientific contribution of this work is to improve the quality of ship mechanisms by compensating for interharmonics using the developed algorithms and devices.

The relevance motivaton 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.

II. RELATED WORK

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.

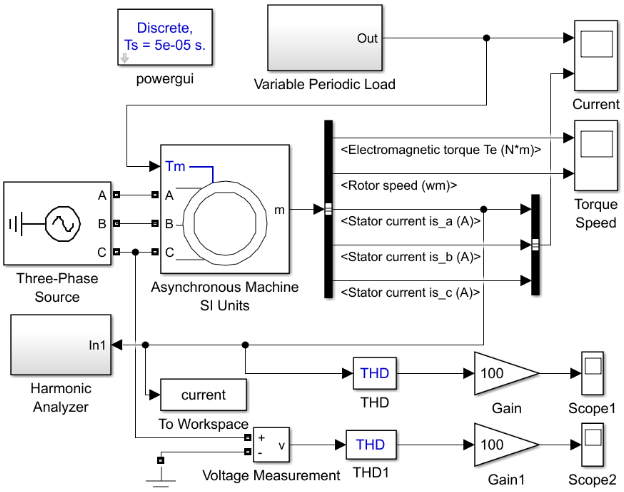

FIGURE 1. The system model in the Matlab/Simulink.

III. THE SIMULINK MODEL

A. 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

TABLE 1. Parameters of the asynchronous motor.

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·m^2

saws for metal, blast furnace skip winches and piston compressors [9], [10].

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.

B. ASSESSMENT OF THE HARMONIC DISTORTION

The main indicators of harmonic distortion are as follows:

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

$$U_h(\%) = \frac{U_h}{U_1} \cdot 100\% \tag{1}$$

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:

$$I_h(\%) = \frac{I_h}{I_1} \cdot 100\% \tag{2}$$

where I_h is an amplitude value of interharmonic current of h – frequency, and I_1 is amplitude value of the current for fundamental harmonics, A. And as for the current:

$$THDi = \frac{\sqrt{\sum_{2}^{\infty} I_h^2}}{I_1} = \sqrt{\left(\frac{I_{rms}}{I_1}\right)^2 - 1}, \tag{3}$$

where I_{rms} is the current root-mean square, A.
where I_h is is amplitude value of interharmonic current of h – frequency, and I_1 is amplitude value of the current for fundamental harmonics, A.

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 overstating 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.

C. DEVELOPMENT OF THE ALGORITHM

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 φ_{AFund} into an equation of the form:

$$i_{AFund} = I_{AFund}\sin(\omega t + \varphi_{AFund}), \tag{4}$$

The difference between real currents and carrier harmonics is determined.

$$\Delta i_{AFund} = i_A - i_{AFund}. \tag{5}$$

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. 2.

If the values of Δi_{AFund}, Δi_{BFund} and Δi_{CFund} differ from each other by the permissible error, then the calculations are carried out for one phase, and the rest are shifted by $-120°$ and $+\ 120°$ for the phases of lines B and C, respectively. Condition for calculating only one phase is the following:

- lime B

$$\varepsilon \le \big|I_{AFund}\sin(\omega t + \varphi_{AFund}) - I_{BMag}\sin(\omega t + \varphi_{BFund} - 120°)\big| \tag{6}$$

or in discrete form

$$\begin{aligned} \varepsilon &\le abc\,(\Delta i_{AFund}(j) - \Delta i_{AFund}(j + n_{AB})) \\ n_{AB} &= 1/\,(3 f_{Fund}\Delta t) \end{aligned} \tag{7}$$

where Δt is the step of discreteness in time; fFund is fundamental frequency; n_{AB} is the number of offsets to eliminate the phase difference between lines A and B:

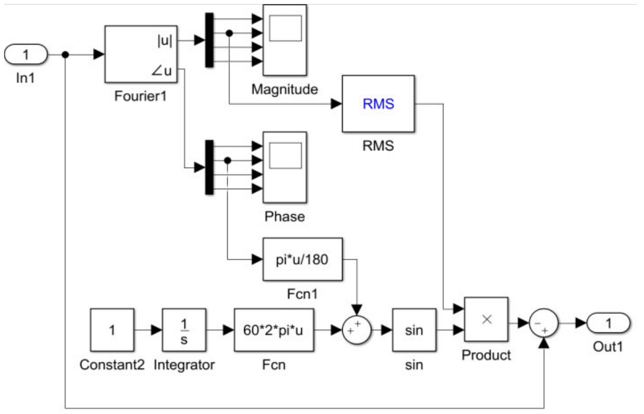

FIGURE 2. Subsystem for analyzing harmonic current components.

- line C:

$$\varepsilon \le |I_{AFund}\sin(\omega t + \varphi_{AFund}) - I_{CMag}\sin(\omega t + \varphi_{CFund} - 240^\circ)| \quad (8)$$

or

- in discrete form:

$$\varepsilon \le abc\,(\Delta i_{AFund}(j) - \Delta i_{AFund}(j + n_{AC}))$$
$$n_{AB} = 2/\,(3f_{Fund}\,\Delta t) \quad (9)$$

where Δt is the step of discreteness in time; fFund - fundamental frequency; n_{AB} 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.

D. SIMULATION RESULTS

In the steady-state mode of an electric motor operating with a variable periodic load, pulsations of torque and speed are observed (Figure 3). 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:

$$\Delta\omega = \frac{\omega_{\max} - \omega_{\min}}{\omega_{mean}} 100\% = 6.6\% \quad (10)$$

where w_{max}, w_{max} are maximum and minimal values of the speed with ripples, rad/s,

$$\Delta\omega = \frac{\omega_{\max} + \omega_{\min}}{2} = 180 rad/s. \quad (11)$$

Similarly, the relative torque ripple ratio is as follows:

$$T_{mean} = \frac{T_{\max} - T_{\min}}{T_{\max}} 100\% = 18\%, \quad (12)$$

where T_{max}, T_{max} are the maximum and minimum values of speed with ripples, Nm

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} = 55 Nm. \quad (13)$$

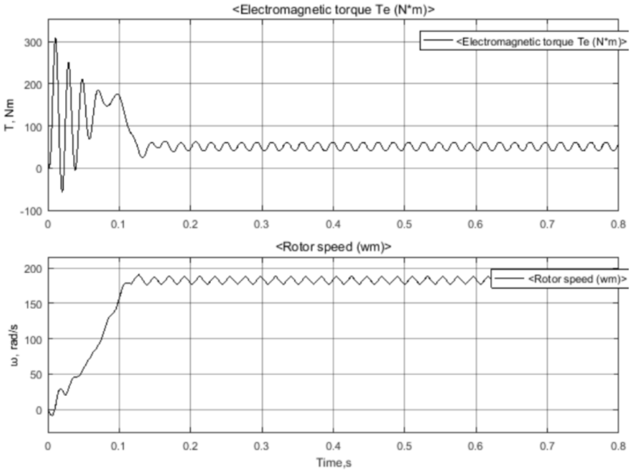

FIGURE 3. Torque ripples on the shaft (1) and speed (2).

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.

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_{h12} (%) = 5.6% and i_{h108} (%) = 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.

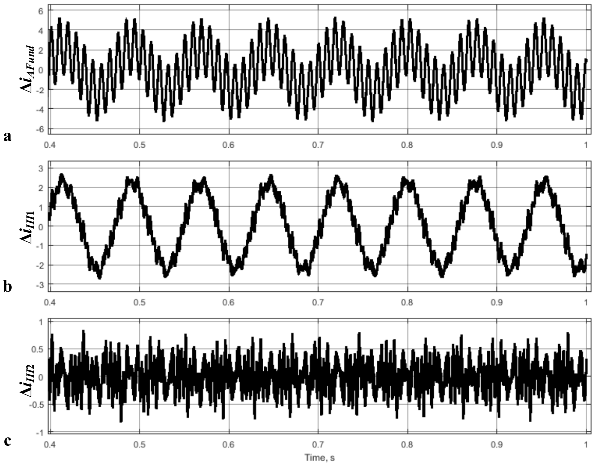

FIGURE 4. Signal Δi_{AFund} (a) Δi_{IH1} (b) and Δi_{IH2} (c).

Taking the difference Δi_{AFund}, a fast Fourier transform is performed. Spectral analysis is used to determine the frequency of the intergamonic ω_{IH1} with the highest amplitude.

$$\omega_{IH1} = \max(\Delta\hat{i}_{AFund}) \tag{14}$$

For the calculated intergamonic frequency ω_{IH1}, the current difference Δi_{AFund} is decomposed into a trigonometric Fourier series with the separation of the I_{IH1} amplitude and φ_{IH1} phase at the frequency ω_{IH1}. The first intergamonics will take the following form:

$$i_{IH1} = I_{IH1}\sin(\omega_{IH1}t + \varphi_{IH1}). \tag{15}$$

The difference Δi_{IH1} between Δi_{AFund} and i_{IH1} is determined (fig. 4 b):

$$\Delta i_{IH1} = \Delta i_{AFund} - i_{IH1}. \tag{16}$$

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 Δi_{IH1}, a fast Fourier transform is performed and the interharmonic with the next highest amplitude is selected. Calculations according to formulas (14) - (16) are repeated until THDi enters the specified range. Figure 4c shows Δi_{IH12}, 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.

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.

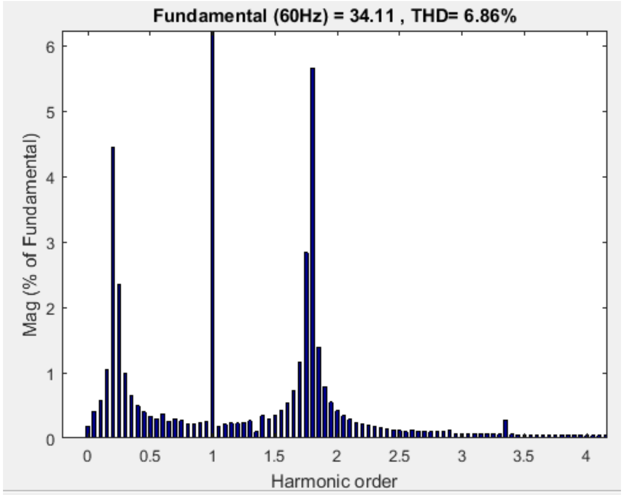

FIGURE 5. Fast Fourier transform for current of line A.

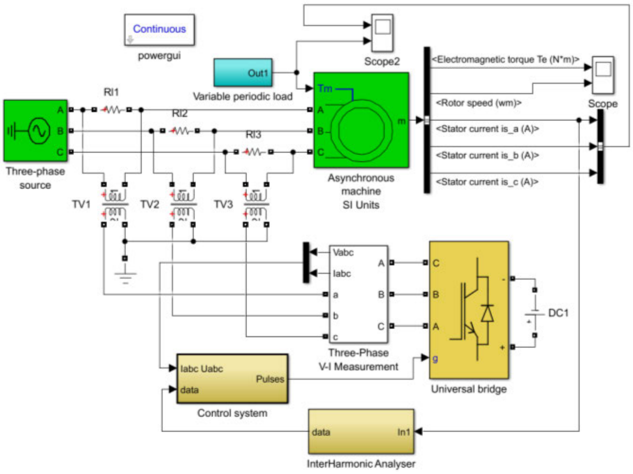

FIGURE 6. The system model with active filter.

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.

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 2:

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

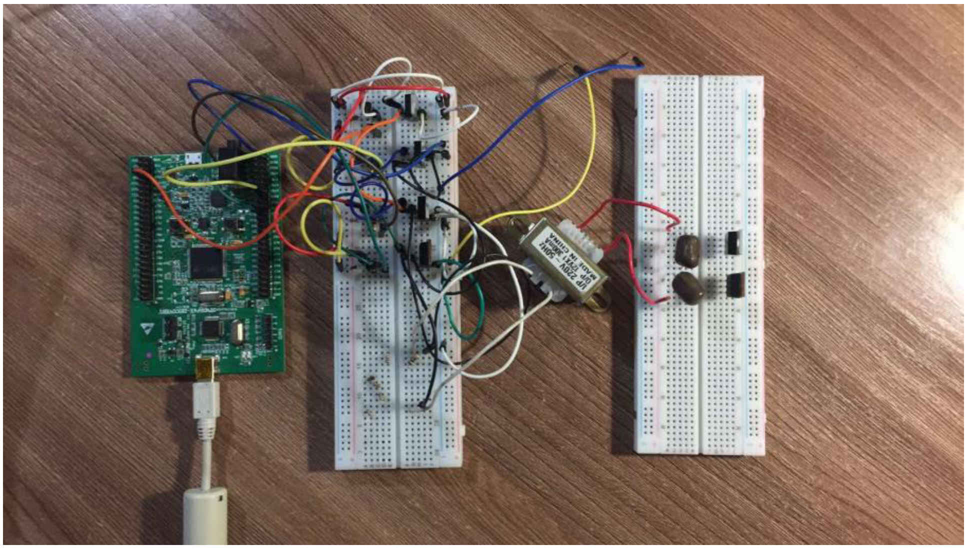

FIGURE 7. Prototype implementation of the developed device.

TABLE 2. Results of modelling.

Symbol	Quantity
THDi	7.5%
Torque ripple	18%
Speed ripple	6.6%
With active filter	
THDi	4 %
Torque ripple	14%
Speed ripple	5.8%

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 sum of two sinusoidal voltages using a voltage inverter based on IGBT transistors, is feasible.

To check the correct operation of the model, a constant load of 50 Nm was connected to the electric motor. The difference between the current between the stator phase and its fundamental harmonic does not exceed 0.21 A, which is 0.76% of the fundamental harmonic value. Based on this, we can conclude that the developed model is correct and can be used to reduce the influence of interharmonics.

As a result of the research carried out, a computer program was registered, designed to find the interharmonic components of the current, according to the data obtained from the oscilloscope [15].

IV. EXPERIMENT

As a result of the research, a device for a single-phase active harmonic filter was developed. The device 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 Mathwoks 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.

A. EXPERIMENT UNDER LABORATORY CONDITIONS

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.

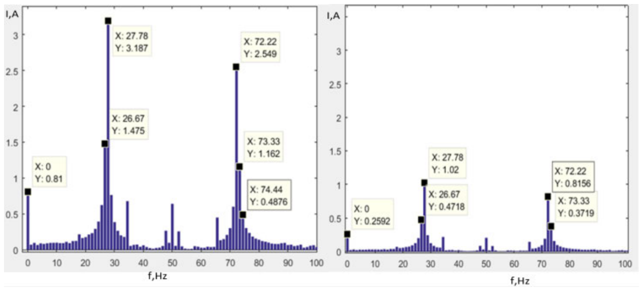

FIGURE 8. **Spectrum of interharmonic current distortion before and after activation of active filter.**

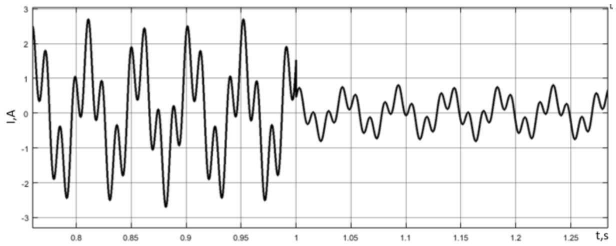

FIGURE 9. **The process of reducing the selected interharmonics by active filter.**

Figure 8 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.

B. PRODUCTION EXPERIMENT

The production test algorithm is as follows. After installing an active filter in series in the compressor supply circuit, the compressor is started. The THD coefficient and the amplitudes of the interharomnik current are monitored with the help of measuring equipment. The percentage of suppression of the amplitude of the interharmonics of the current is set through a personal computer connected to the active filter via USB. The filter control system, which operates according to the algorithm described in Section 4, determines the amplitudes and phases of the interharmonics of the current and gives a ready signal. Next, the power supply of the active filter is connected and the process of filtering the stator current of the electric motor begins. Figure 9 shows the highlighted interharmonics which are suppressed by the active filter during device operation.

Also, as a result of the tests, oscillograms of currents were obtained and processed, showing a decrease in the *THDi* level from 11 to 5%.

V. 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 reveal the influence of a variable periodic load on the electric drive system. The essence of the technique is to eliminate the fundamental harmonic and analyze the remaining ripple current. Analysis of the harmonic components of the stator current of an asynchronous electric motor operating at a 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. The use of an active filter in the model made it possible to reduce the *THDi* level by 4.5%, and to reduce the amplitudes of interharmonics by almost 2 times.

An experiment was carried out with the use of an external device for generating interference, which showed a high efficiency of compensation for interharomnic current components. The laboratory experiment showed results consistent with the simulation results. The effectiveness of compensation in industrial conditions is confirmed by a decrease in *THDi* of the compressor electric drive by more than 2 times.

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BORIS A. AVDEEV received the graduate degree in electromechanical automation systems and electric drives from FSBEI HE Kerch State Maritime Technological University, in 2011. He is currently an Associate Professor with the Department of Ship Electrical Equipment and Production Automation and a Candidate of Technical Sciences with the Kerch State Maritime Technological University. He defended his Ph.D. thesis on the topic "Improving the efficiency of engine oil purification in marine diesel engines using magnetic hydrocyclones," in 2015.

ALEKSEI V. VYNGRA (Graduate Student Member, IEEE) received the degree in operation of ship electrical and automation equipment from FSBEI HE Kerch State Maritime Technological University (KGMTU), in 2016, where he is currently pursuing the master's degree with the Department of Electrical Equipment for Ships and Production Automation.

SERGEI G. CHERNYI (Member, IEEE) received the B.S. degree in computer engineering from Kherson National Technical University, Kherson, Ukraine, in 2005, where he is currently pursuing the Ph.D. degree in IT technology. From 2009 to 2017, he was a Ph.D. scholar at Kerch State Maritime University, Russia. He is currently working at the Complex Information Security Department, Admiral Makarov State University of Maritime and Inland Shipping, Saint-Petersburg, Russia. His research interests include development of modeling and fault tolerant control. He is a member of the editorial boards of Springer, MDPI, and EAI journals.

ANTON A. ZHILENKOV received the Ph.D. degree. He is currently an Associate Professor and the Head of the Department of Cyber-Physical Systems, Faculty of Digital Industrial Technologies, Saint Petersburg State Marine Technical University. He is the author of more than 100 articles.

SERGEY S. SOKOLOV received the Ph.D. degree in technical science. He is currently the Head of the Complex Information Security Department, Admiral Makarov State University of Maritime and Inland Shipping, Saint-Petersburg, Russia. He is the author of more than 180 articles. He has educational and scientific–pedagogical experience.

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