Monitoring of asymmetric values and parameters of electric networks

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Abstract. This paper considers the digitalization of electrical networks, the organization of remote control of the values and parameters of electrical energy, the creation of digital elements, devices and complexes for monitoring and managing power quality indicators based on Cloud Computing technology, the conversion of primary currents into signals in the form of secondary voltages, and also discusses management issues symmetrical quantities and parameters of these converters. In addition, a model of a three-phase AC converter with specific loads and analytical expressions for determining the output voltage of a three-phase AC converter with a specific load based on the configuration of this model are presented, a cloud computing algorithm for studying a three-phase AC converter, the characteristics of electrical loads are given, the dynamic characteristics of electromagnetic three-phase load current converters, graphs of magnetic fluxes and a three-phase current converter of specific loads, stabilization mode in the conversion system of electromagnetic converters of three-phase current in 0.02-0.03 seconds after being connected to the network under a special load, an algorithm for constructing dynamic characteristics and generating analytical expressions. Based on this information, conclusions were drawn about the cost and parameters of three-phase current electromagnetic converters.

1 Introduction

In the world recently, in the context of the globalization of the economy, an important place is given to digitalization and automation of monitoring indicators and values of production processes, including in the field of electric energy consumption. Ensuring high accuracy and efficiency of monitoring the values and parameters of power supply, ensuring non-contact signal conversion of the values and parameters of the electrical network (EN) based on modern elements and devices of Cloud Computing technology are relevant and the main tasks of ensuring reliable operation of power supply systems.

An analysis of the research shows that at present certain successes have been achieved in the field of monitoring the magnitudes and phases of currents. The conducted studies show that the works of these scientists do not adequately consider mathematical and computer

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models of electromagnetic current converters in Cloud Computing, as well as the impact on the monitoring results of the asymmetry of three-phase currents in magnitude and phases, current harmonics, frequency swing, changes in ambient temperature.

2 Materials and methods

2.1 Values and parameters of power supply systems with specific loads

The electric current and voltage of three-phase electrical networks and the shape of their curve in accordance with the standard (GOST 13109-97 Electrical energy. Electromagnetic compatibility of technical means. Quality standards for electrical energy in general-purpose power supply systems) is characterized by the following indicators [1]:

- frequency deviation (Δf);
- steady-state voltage deviation (δU_y);
- voltage fluctuations, characterized by the magnitude of the voltage change (δU_t) and the dose of flicker (P_t);
- coefficient of the n-th harmonic component of the voltage $(K_{U(n)})$;
- coefficient of distortion of the sinusoidality of the voltage curve (K_U);
- coefficient of voltage asymmetry in reverse sequence (K_{2U});
- coefficient of voltage asymmetry in the zero sequence (K_{0U});
- voltage dip duration ($\Delta t_{\text{п}}$);
- voltage pulse (U_{pul});
- coefficient of temporary overvoltage $K_{\text{ove}U}$.

Balancing device parameters are determined on the basis of data from active and reactive power sources [2, 3].

In the EN node, in the presence of an asymmetric load, the reactive power should be taken equal to the reactive power generated by the balancing device [4, 1]: $Q_{\text{к.у}} = Q_{\text{с.у}}$ When connecting the reactive elements of the balancing device, it is necessary to ensure the allowable voltage unbalance factor [5]:

$$\varepsilon_{U\text{доп}} = (1+\delta U)\sqrt{\alpha^2+\beta^2}\,/\,S_{\text{к}} \tag{1}$$

The reactive power factor of the node of the balancing device of an unbalanced load is determined by the expression [5]:

$$tg\varphi_{\text{вх}} = (Q_{\text{с.у}} + Q_{\Sigma})/P_{\Sigma}. \tag{2}$$

Depending on the set value of the reactive power in the ES node, the permissible deviations of the positive sequence voltage and the voltage asymmetry factor are determined based on the reactive powers of the elements of the balancing device according to the expressions [2, 6]:

$$Q_{AB} = -\frac{1}{3}\left[\sqrt{3}C - D - Q_{\text{с.у}}(1 - A - \sqrt{3}B)\right]; \tag{3}$$

$$Q_{BC} = -\frac{1}{3}\left[2D - Q_{\text{с.у}}(1 + 2A)\right]; \tag{4}$$

$$Q_{CA} = \frac{1}{3}\left[\sqrt{3}C + D + Q_{\text{с.у}}(1 - A + \sqrt{3}B)\right] \tag{5}$$

where $A = \varepsilon_{U\text{доп}} \cos\psi_U / (1 + \delta U_{\text{доп}})$; $B = \varepsilon_{U\text{доп}} \sin\psi_U / (1 + \delta U_{\text{доп}})$;
$C = BS_{\text{к}} + S_{AB}\cos(60^0 - \varphi_{AB}) - P_{BC} + S_{CA}\cos(60^0 + \varphi_{CA})$;
$D = -AS_{\text{к}} + S_{AB}\sin(60^0 - \varphi_{AB}) + Q_{BC} - S_{CA}\cos(60^0 + \varphi_{CA})$ - coefficients;
$S_{AB}, S_{CA}, P_{BC}, Q_{BC}$ power modules of electrical loads.

The positive value of the reactive power of the electric network $Q_{\text{с.у}}$ corresponds to inductive power, and the negative value corresponds to capacitive power.

If there are generating sources of harmonics in the ES node, for the resulting circuit of the balancing device using the expressions given in table. 1, one should check whether current resonances do not occur at any frequencies for the selected parameters [7].

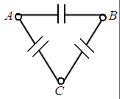
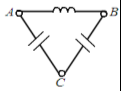
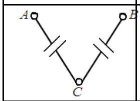
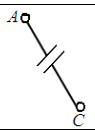
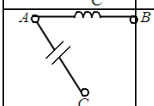
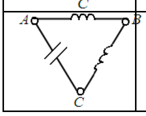
If resonance occurs, check the power sources to see if they are overloaded with harmonic currents. In case of unacceptable overload of the power source, a series connection of the reactor should be used or filter circuits should be created, i.e. install a filter balancing device (FBD) based on inductive and capacitive elements [2, 3, 5, 7].

Successful solution of the problem of asymmetry of currents and voltages of ES leads to a decrease in the cost of operation and losses of electricity during transportation [2, 3, 5, 7]. The features of the development of primary measuring converters are their wide use as converters of symmetrical components of three-phase currents of EN, which allow monitoring the quality of electric energy while simplifying the principle of construction [2, 3, 5, 7].

The number of output nodes of the primary measuring converters of currents of symmetrical components can be equal to two in the case of monitoring a single-phase electrical load, three - in the case of a three-phase load, three and four - in the case of two single-phase electrical loads of the EN [3, 6].

Since the input nodes of the converters are affected by magnetic fluxes created by the primary phase currents $I_{\text{эвх}A}$, $I_{\text{эвх}B}$, $I_{\text{эвх}C}$ or the difference of these phase currents $I_{\text{эвх}AB}$, $I_{\text{эвх}BC}$, $I_{\text{эвх}CA}$, they induce voltages U_{eA}, U_{eB}, U_{eC} in the output nodes of the converter (when the secondary windings are connected by a star) or their difference U_{eAB}, U_{eBC}, U_{eCA} (when connecting the secondary windings in a triangle), the amplitudes and phases of which exactly correspond to the values the primary phase currents. The principle of operation and design of sensors of parameters of the primary three-phase circuit is based on the use of this principle, the operation of which is used for Cloud Computing monitoring of specific electrical loads.

Table 1. Sources of harmonics for the resulting balancing device circuit using expressions.

Balancing device diagram	Ordinal number of the resonant harmonic
	$v_{1,2}=\sqrt{\dfrac{S_{к}\left[Q_{AB}+Q_{BC}+Q_{CA}\pm\sqrt{Q_{AB}^{2}+Q_{BC}^{2}+Q_{CA}^{2}-(Q_{AB}Q_{BC}+Q_{BC}Q_{CA}+Q_{CA}Q_{AB})}\right]}{3(Q_{AB}Q_{BC}+Q_{BC}Q_{CA}+Q_{CA}Q_{AB})}}$
	$v_{1,2}=\sqrt{\dfrac{(2S_{к}+3Q_{AB})(Q_{BC}+Q_{CA})\pm\sqrt{(2S_{к}+3Q_{AB})^{2}(Q_{BC}+Q_{CA})-12Q_{BC}Q_{CA}S_{к}(2Q_{AB}+S_{к})}}{6Q_{BC}Q_{CA}}}$
	$v_{1,2}=\sqrt{\dfrac{S_{к}(Q_{BC}+Q_{CA})\pm\sqrt{Q_{BC}^{2}+Q_{CA}^{2}-Q_{BC}Q_{CA}}}{3Q_{AB}Q_{CA}}}$
	$v_{1}=\sqrt{\dfrac{S_{к}}{2Q_{CA}}}$
	$v_{1}=\sqrt{\dfrac{S_{к}(S_{к}+2Q_{AB})}{Q_{CA}2S_{к}+3Q_{AB}}}$
	$v_{1}=\sqrt{\dfrac{S_{к}(S_{к}+2Q_{AB})+Q_{BC}(2S_{к}+3Q_{AB})}{Q_{CA}\left[2S_{к}+3(Q_{AB}+Q_{BC})\right]}}$

A general overview of the services of the Cloud Computing monitoring model provided by the Internet for the study of asymmetric and nonlinear quantities and parameters of the EN is shown in fig. 1. The study used the following Cloud Computing monitoring technologies [8]:

- Software (SaaC) - software.
- Platform (PaaC) - service platform.
- Infrastrucche (IaaC) - infrastructure platform.

In the form of an application on the site www.reactive-energy.uz, materials on the Cloud Computing monitoring model are presented in the form of algorithms and software that allow evaluating, among other things, the efficiency of reactive power sources [1].

The input (primary) values of primary converters of specific electrical loads are electric currents flowing through the electrical networks of the power supply system [4, 7, 9, 10]. In the general case, primary currents are functions of the parameters and magnitudes of electrical loads and time of arbitrary shape. To model and study primary current converters and study their main technical characteristics, it is necessary to choose accurate, but at the same time simple and convenient mathematical models, taking into account the specific operating conditions of current conversion [11].

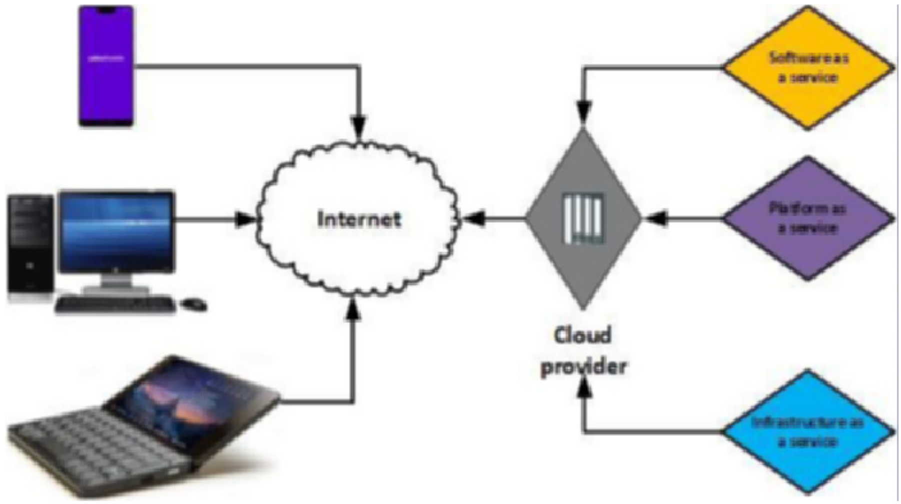


Fig.1. Cloud Computing Model of Technology for Monitoring Values and Parameters of EN.

The model of circuits for converting three-phase current with specific loads with lumped parameters, built using the previously accepted symbols and assumptions, is shown in fig.2.

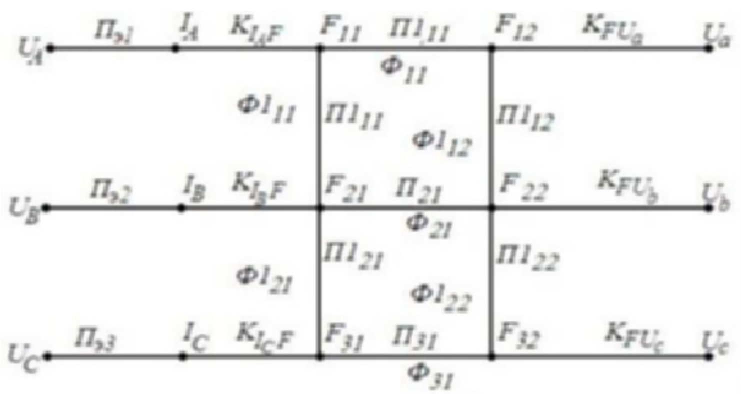


Fig.2. Three-phase current conversion circuit model with specific loads.

Based on the configuration of the model, analytical expressions can be formulated to determine the output voltages.

$$U_a = K_{F_aU_a} \cdot W_a(x,y,z,t)(K_{I_AF} \cdot \Pi_{эA}\dot{U}_A + K_{I_BF} \cdot \Pi_{эB}\dot{U}_B + K_{I_CF} \cdot \Pi_{эC}\dot{U}_C);$$
$$U_b = K_{F_bU_b} \cdot W_b(x,y,z,t)(K_{I_AF} \cdot \Pi_{эA}\dot{U}_A + K_{I_BF} \cdot \Pi_{эB}\dot{U}_B + K_{I_CF} \cdot \Pi_{эC}\dot{U}_C);$$
$$U_c = K_{F_cU_c} \cdot W_c(x,y,z,t)(K_{I_AF} \cdot \Pi_{эA}\dot{U}_A + K_{I_BF} \cdot \Pi_{эB}\dot{U}_B + K_{I_CF} \cdot \Pi_{эC}\dot{U}_C); \quad (1)$$

where is the $K_{F_aU_a} = 4{,}44 \cdot f \cdot W_2; K_{F_bU_b} = 4{,}44 \cdot f \cdot W_2; K_{F_cU_c} = 4{,}44 \cdot f \cdot W_2$ coefficient of intercircuit coupling between magnetic and electrical quantities, depending on the frequency f and number of turns of the sensitive element W_2 installed in the corresponding magnetic conversion circuit; $\dot{I}_A = \Pi_A \cdot \dot{U}_A; \dot{I}_B = \Pi_B \cdot \dot{U}_B$ and

$\dot{I}_C = \Pi_C \cdot \dot{U}_C$ - phase currents flowing through the electrical networks of a three-phase electrical network with a specific load; $\Pi_A; \Pi_B$ and Π_C - parameters of a three-phase electrical network; $K_{I_aF_a} = W_{\Pi A}; K_{I_bF_b} = W_{\Pi B}$ and $K_{I_cF_c} = W_{\Pi C}$ - the number of turns of the current conductors of a three-phase electrical network and its corresponding configuration; coefficients of intercircuit coupling between electrical and magnetic quantities; $W_a(x,y,z,t); W_b(x,y,z,t)$ and $W_c(x,y,z,t)$ - transfer functions of the transformation space, determined depending on the chosen transformation model (concentrated or distributed) to take into account the effect of the scattering of the transformed quantities, the heterogeneity of the sections, depending on the accuracy of the solution of the problem; *W, M, K* - the number of sections of the model shape, determined on the basis of the accuracy of solving problems by the finite element and difference method.

For the presented transformation model (fig. 2), the transfer functions $W_a(x,y,z,t); W_b(x,y,z,t)$ and $W_c(x,y,z,t)$ solution are proposed as follows:

$$\begin{aligned}
&\frac{F_{11}-F_{12}}{\Pi_{11}} + \frac{F_{11}-F_{12}}{\Pi 1_{11}} = K_{IF_A}\dot{I}_A \\
&\frac{F_{12}-F_{11}}{\Pi_{11}} + \frac{F_{12}-F_{22}}{\Pi 1_{12}} = -K_{FU_a}\dot{U}_a \\
&\frac{F_{21}-F_{11}}{\Pi 1_{11}} + \frac{F_{21}-F_{22}}{\Pi_{21}} = K_{IF_B}\dot{I}_B \\
&\frac{F_{22}-F_{21}}{\Pi_{21}} + \frac{F_{22}-F_{32}}{\Pi 1_{22}} = -K_{FU_b}\dot{U}_b \\
&\frac{F_{31}-F_{21}}{\Pi 1_{21}} + \frac{F_{31}-F_{32}}{\Pi_{31}} = K_{IF_C}\dot{I}_C \\
&\frac{F_{32}-F_{31}}{\Pi_{31}} + \frac{F_{32}-F_{22}}{\Pi 1_{22}} = -K_{FU_c}\dot{U}_c
\end{aligned} \tag{2}$$

or in matrix form

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} \end{bmatrix} \begin{bmatrix} F_{\mu 11} \\ F_{\mu 12} \\ F_{\mu 21} \\ F_{\mu 22} \\ F_{\mu 31} \\ F_{\mu 32} \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix}. \tag{3}$$

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3 Results and discussion

To study the dynamic characteristics of a three-phase current converter of specific loads, electric currents are presented on the basis of the corresponding magnetic fluxes Φ_A, Φ_B, Φ_C [3]:

$$d\Phi_A / dt + R_{\mathrm{I}} \cdot \Phi_A L_{\mathrm{I}} = (U_{mA} / W_1)\sin(\omega t + \psi_{\mathrm{I}}),$$

$$d\Phi_B / dt + R_{\mathrm{II}} \cdot \Phi_B L_{\mathrm{II}} = (U_{mB} / W_2)\sin(\omega t + \psi_{\mathrm{II}} + 120^0),$$

$$d\Phi_C / dt + R_{\mathrm{III}} \cdot \Phi_C L_{\mathrm{III}} = (U_{mC} / W_3)\sin(\omega t + \psi_{\mathrm{III}} - 120^0),$$

where: w_1, w_2, w_3 - the number of turns of the secondary measuring windings.

These equations are solved subject to the constancy of the parameters: electrical resistance $R_{\mathrm{I}}, R_{\mathrm{II}}, R_{\mathrm{III}}$ and inductance at $L_{\mathrm{I}}, L_{\mathrm{II}}, L_{\mathrm{III}}$ and $t = 0$ angular frequency $\omega = 2\pi f$.

Expressions for determining magnetic fluxes Φ_A, Φ_B и Φ_C can be represented as follows:

$$\Phi_{\mathrm{A}} = \Phi_{\text{макс A}}\left[\cos\psi_{\mathrm{I}} \cdot e^{-(R_{\mathrm{I}}t/L_{\mathrm{I}})} - \cos(\omega t + \psi_{\mathrm{I}})\right] \pm \Phi_{\text{ост A}} \cdot e^{-(R_{\mathrm{I}}t/L_{\mathrm{I}})}$$

$$\Phi_{\mathrm{B}} = \Phi_{\text{макс B}}\left[\cos\psi_{\mathrm{I}} \cdot e^{-(R_{\mathrm{II}}t/L_{\mathrm{II}})} - \cos(\omega t + \psi_{\mathrm{II}})\right] \pm \Phi_{\text{ост B}} \cdot e^{-(R_{\mathrm{II}}t/L_{\mathrm{II}})}$$

$$\Phi_{\mathrm{C}} = \Phi_{\text{макс C}}\left[\cos\psi_{\mathrm{I}} \cdot e^{(R_{\mathrm{III}}t/L_{\mathrm{III}})} - \cos(\omega t + \psi_{\mathrm{III}})\right] \pm \Phi_{\text{ост C}} \cdot e^{-(R_{\mathrm{III}}t/L_{\mathrm{III}})}$$

The reasoning carried out and the dependencies used can be formalized in the form of an algorithm (fig.3)

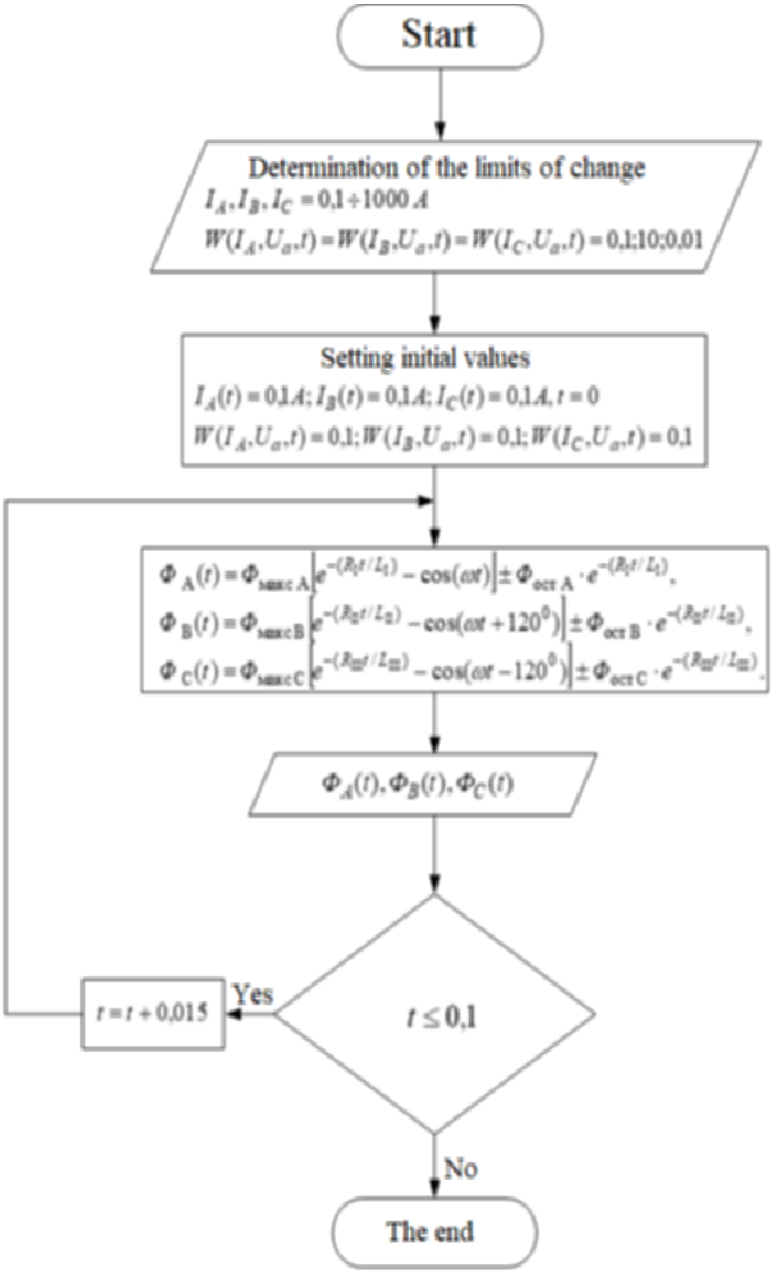

Fig.3. Algorithm for studying dynamic characteristics.

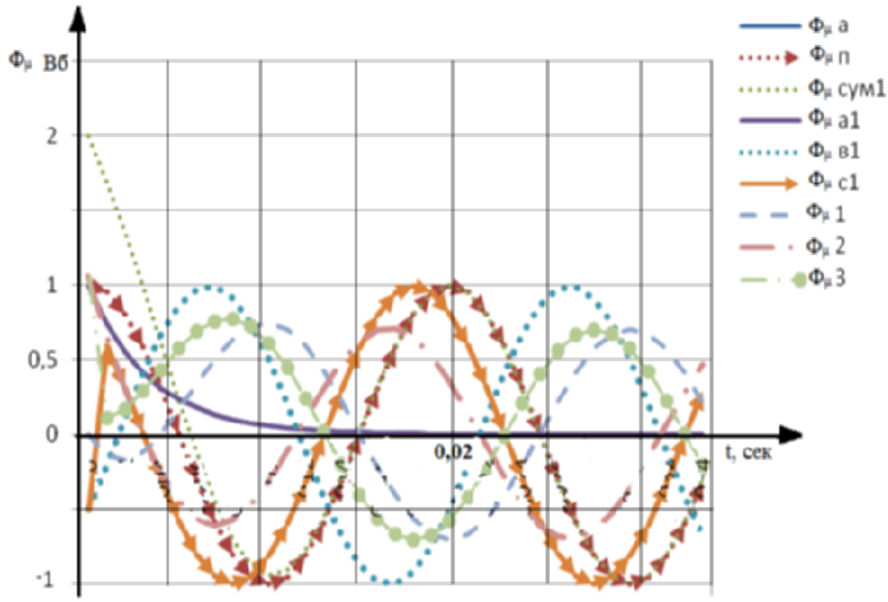

Fig.4. Magnetic Flux Graphs Φ_A, Φ_B и Φ_C three-phase current converter of specific loads.

Graphs of changes in magnetic fluxes (fig.4) and constructed using this algorithm (fig.3) allow us to conclude that the steady state in the system for converting three-phase current converters of specific loads is achieved in 0.02 - 0.04 s after the current converter is turned on to the supply network and currents pass through its primary windings laid out between the cores of the magnetic circuit.

4 Conclusions

A graph model and an algorithm have been developed that allow monitoring the characteristics of a three-phase current converter of specific electrical loads, and the results of the study showed that the duration of the transient process does not exceed two periods of the fundamental frequency.

A classification of the sources of the main and additional errors of the transducer is proposed, which makes it possible to carry out their objective analysis and develop measures to reduce them.

The influence of the secondary current of the converter and the ambient temperature on the accuracy of the conversion was theoretically and experimentally studied, and it was found that the secondary currents practically do not affect the accuracy of the three-phase current converter, and the effect of the ambient temperature leads to an increase in the error by 0.11%.

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