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Research Article

THE RESEARCH OF CURRENT DIFFERENCE MEASURE ERRORS OF NEW INDUCTION CONVERTER

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ABSTRACT

The article examines the large inductance difference passing through adjacent busbars and the new induction converter errors designed to measure the symmetry of three-phase currents using the parametric structure method. The additive components of the error are shown in the variable parametric structure diagram as a correction to the output size, and the multiplicative components - in the form of a transmission coefficient or correction to the parameter. It has been found that the input of errors in the form of corrections to the inter-chain transmission coefficients, magnitudes and parameters in the parametric structure scheme is the effect of interfering physical effects that link the different physical nature of the variable to the main parameter, magnitude and transmission coefficients. It was found that the regular component of the error of the variable studied does not exceed 0.68%, and its random component does not exceed 1.28%.

KEYWORDS

Induction converter, large alternating current difference, symmetrical three-phase current, parametric structure circuit, magnetomodulation mode, transformer mode, error, additive error, multiplicative error.

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INTRODUCTION

Currently, more than 30% of electricity generated in the country is distributed in low-voltage zero-wire networks [1]. Numerous studies on the operating modes of such networks show that the quality of electricity in them often does not meet the requirements of the standards.

One of the main factors in the deterioration of voltage regimes in electricity consumers and the increase in power losses in low-voltage networks is the occurrence of current symmetry in three-phase circuits. In such chains, automatic symmetry devices are widely used to restore the symmetric mode [2].

A single-phase gravity load in an electrified railway system is a source of symmetry for an external three-phase power supply system. Therefore, high-precision measurement of current symmetry in three-phase alternating current circuits is one of the important and topical issues.

Non-contact electromagnetic measuring converters (MC) are mainly used to measure the difference in currents flowing through the busbars [3, 4, 5]. However, the existing MCs do not meet the requirements for them in terms of functional capabilities.

At the Department of "Power Supply" of our university developed a new design of induction converter (IC), which measures the difference in current in the bus (Figure 1) [6]. The device detects the symmetry of three-phase currents or large alternating currents passing through three can change the difference in proportion to the alternating voltage. When an IC is designed to measure a large value of alternating current difference, its modulation coils are supplied from an industrial frequency alternating current source, resulting in an alternating magnetic flux of $Q_{\mu м}$ value in each modulation circuit. $Q_{\mu A}$, $Q_{\mu B}$, $Q_{\mu C}$ magnetic fluxes on non-adjacent rods of a three-contour magnetic conductor when alternating currents pass through busbars 1, 2, 3, and $\Delta Q_{\mu AB} = Q_{\mu A} - Q_{\mu B}$, $\Delta Q_{\mu BC} = Q_{\mu B} - Q_{\mu C}$, $\Delta Q_{\mu CA} = Q_{\mu C} - Q_{\mu A}$ currents on adjacent rods is formed. When the currents in the tires are equal to each other,$Q_{\mu A} = Q_{\mu B} = Q_{\mu C}$ the differences in the magnetic fluxes of the adjacent rods are zero, ie. $\Delta Q_{\mu AB} = 0$, $\Delta Q_{\mu BC} = 0$, $\Delta Q_{\mu CA} = 0$. As a result, the voltages generated by the modulated magnetic currents in the measuring coils on the non-adjacent rods are proportional to the magnitude of the current flowing through the corresponding bus, and the signals at the outputs of the measuring coils on the adjacent rods are zero.

If the magnitude of the currents in the tires differs from each other (or the current in one of them from the currents in the others), then at the outputs of the measuring coils on the corresponding adjacent rods are generated signals proportional to the difference in currents in two adjacent tires.

When the generated IC is installed in three-phase alternating current circuits, the measuring coils on the adjacent and non-adjacent rods are connected to each other in an open triangular manner, and the modulation coils are disconnected from the corresponding current source. When the three-phase circuit operates in symmetrical mode, the signals at the corresponding common outputs of the 16, 17, 18 and 19, 20, 21 coils connected in the open triangle method are zero. If a symmetrical mode occurs in a three-phase circuit, then the output signals are proportional to the symmetry of the three-phase currents at the corresponding common outputs of the IO bands and their values are equal to the effective values of the sum of the following complex voltages: $\dot{U}_{э.чик.1} = \dot{U}_{эA} + \dot{U}_{эB} + \dot{U}_{эC}$,ва $\dot{U}_{э.чик.2} = \dot{U}_{эAB} + \dot{U}_{эBC} + \dot{U}_{эCA}$. The signals induced in the measuring coils on non-adjacent rods are proportional to the alternating current in the corresponding busbar.

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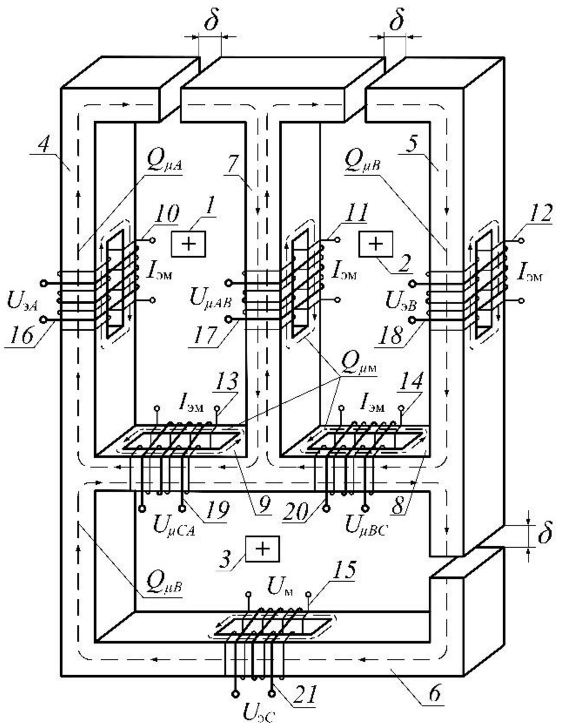

Figure 1. Construction of a new electromagnetic converter measuring the symmetry of three-phase currents: 1, 2,3 - current tires; 4, 5, 6 and 7, 8, 9 - non-adjacent and adjacent rods of a three-contour magnetic conductor, respectively; 10, 11, 12 and 13, 14, 15 - modulation coils on non-adjacent and adjacent rods; 16, 17, 18 and 19, 20, 21 - measuring rings on adjacent and non-adjacent rods, respectively; δ is the air gap in the non-adjacent rods

When the generated IC is installed in three-phase alternating current circuits, the measuring coils on the adjacent and non-adjacent rods are connected to each other in an open triangular manner, and the modulation coils are disconnected from the corresponding current source. When the three-phase circuit operates in symmetrical mode, the signals at the corresponding common outputs of the 16, 17, 18 and 19, 20, 21 coils connected in the open triangle method are zero. If a symmetrical mode occurs in a three-phase circuit, then the output signals are proportional to the symmetry of the three-phase currents at the corresponding common outputs of the IO bands and their values are equal to the effective values of the sum of the following complex voltages: $\dot{U}_{э.чик.1} = \dot{U}_{эA} + \dot{U}_{эB} + \dot{U}_{эC}$,ва $\dot{U}_{э.чик.2} = \dot{U}_{эAB} + \dot{U}_{эBC} + \dot{U}_{эCA}$. The signals induced in the measuring coils on non-adjacent rods are proportional to the alternating current in the corresponding busbar.

The advantage of the created IC over existing devices of this type is that, firstly, it can be used to measure the asymmetry of currents in three-phase AC circuits, as well as to measure the difference of alternating currents passing through two or three busbars, secondly, the device simultaneously can measure the current difference, thirdly, it can give information about the symmetry of the currents in the circuit from two outputs that are not galvanically connected to each other in a three-phase alternating current circuit, and fourthly, the measuring chains on non-adjacent rods (due to the presence of air gaps δ).

Before recommending the generated IC for widespread use, it is necessary to study its basic technical characteristics.

One of the main characteristics of MCs is its measurement error. This is because the accuracy class of MCs, including ICs, is precisely measured by the measurement error [7].

Elements of measurement error theory are often used to identify, analyze, and quantify the sources of IC errors [8]. However, there are some difficulties in identifying the sources of error and taking into account the interactions of the parameters of different chains

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of MC in the derivation of error equations, as well as in evaluating the results.

RESEARCH METHOD AND RESULTS

Therefore, it is more convenient to use the method of parametric structure schemes (PSS) based on the energy information model of different physical chains in the study of errors of measuring converter(MC or transducers) based on events and processes occurring in different physical chains, especially the principle of operation. [9].

In the PSS for the theoretical study of measurement errors of IC, additive errors consisting of regular and random components are in addition to the output size of each elementary link, and multiplicative errors consisting of regular and random components are added to each elemental link in the PSS (inter-chain physical effect (PhTE).) or chain parameter) is considered in addition to the transmission coefficient or parameter. The causes of errors in the PSS in the form of additions to the magnitudes, parameters and coefficients of interconnection of chains of different nature are directly related to the physical effects that link the sizes of chains of different physical nature to the parameters and coefficients of the chain.

The sequence for calculating IC measurement errors using the PSS method is as follows [9]: 1) the PSS is divided into elementary links configured for the static mode of the device; 2) the regular and random (mean square deviation) components of additive and multiplicative errors for each elementary link that reflects this or that physical effect are taken into account in the structural scheme; 3) the sources of errors and their values are determined and evaluated using PSS, taking into account the inter-chain sizes and inter-chain effects between the parameters in the structural scheme, as well as external quantities of different physical nature; 4) are regular and random organizers of additive and multiplicative errors for each elementary link (variable); 5) The error of the PSS elementary links is calculated using the equations of the theory of errors, taking into account the methods of their interconnection in the circuit.

It should be noted that the accuracy of the assessment of regular and random components of additive and multiplicative errors largely depends on the degree of detection of sources that cause the coefficients, parameters and magnitudes in the PSS to deviate from their true values.

1. Identify sources of IC error operating in magnetomodulatory mode (to measure the difference in alternating currents in tires). For this mode, its sources of error are shown in Figure 2 of the PSS.

The following PhTE and parameters were used in the above PSS: 1) PhTE, which converts electric current into magnetic voltage (ampere-winding effect): $U_{\mu xA} = K_{I_{эxA}U_{\mu xA}} I_{эxA}$, here is $I_{эxA}$, $U_{\mu xA}$ –respectively, the electric current passing through the bus A and the magnetic driving force (MDF) generated by it in the corresponding contour of the magnetic circuit around the bus (x) is included in the indices of magnitude and parameters of electrical and magnetic circuits corresponding to the difference between the measured currents and (or) currents [A]; $K_{I_{эxA}U_{\mu xA}} = w_{xA} = 1$ - A the number of windings on the tire, [-]; 2) internal PhTE, which correlates the reduced magnetic voltage ($U_{\mu xA\delta}$) in the air gap in a non-adjacent branch of a three-contour magnetic circuit with the magnetic flux ($Q_{\mu xA}$) in it through the magnetic capacitance parameter ($C_{\mu xA\delta}$): $Q_{\mu xA} = U_{\mu xA\delta} C_{\mu xA\delta}$; 3) internal PhTE: $U_{\mu xAп} = Q_{\mu xA} W_{\mu xAп}$; which correlates the reduced magnetic voltage ($U_{\mu xAп}$) in the magnetic conductor (steel) part of the non-adjacent branch of the magnetic chain with the magnetic flux ($Q_{\mu xA}$) in it through the magnetic hardness parameter ($W_{\mu xAп}$); 4) internal PhTE: $U_{\mu xAB} = Q_{\mu xAB} W_{\mu xAB}$, which correlates the reduced magnetic voltage ($U_{\mu xAB}$) with the magnetic flux ($Q_{\mu xAB}$) in the magnetic conductor (steel) part of the adjacent branch of the magnetic chain through the magnetic hardness parameter ($W_{\mu xAB}$); 5) PhTE (ampere-winding effect), which converts the electric current ($I_{эм}$)in the modulation

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circuit to magnetic voltage $U_{\mu м} = K_{I_{эм}U_{\mu м}} I_{эм}$, where $K_{I_{эм}U_{\mu м}} = w_{м}$ is the number of windings in the modulation circuit, [-];

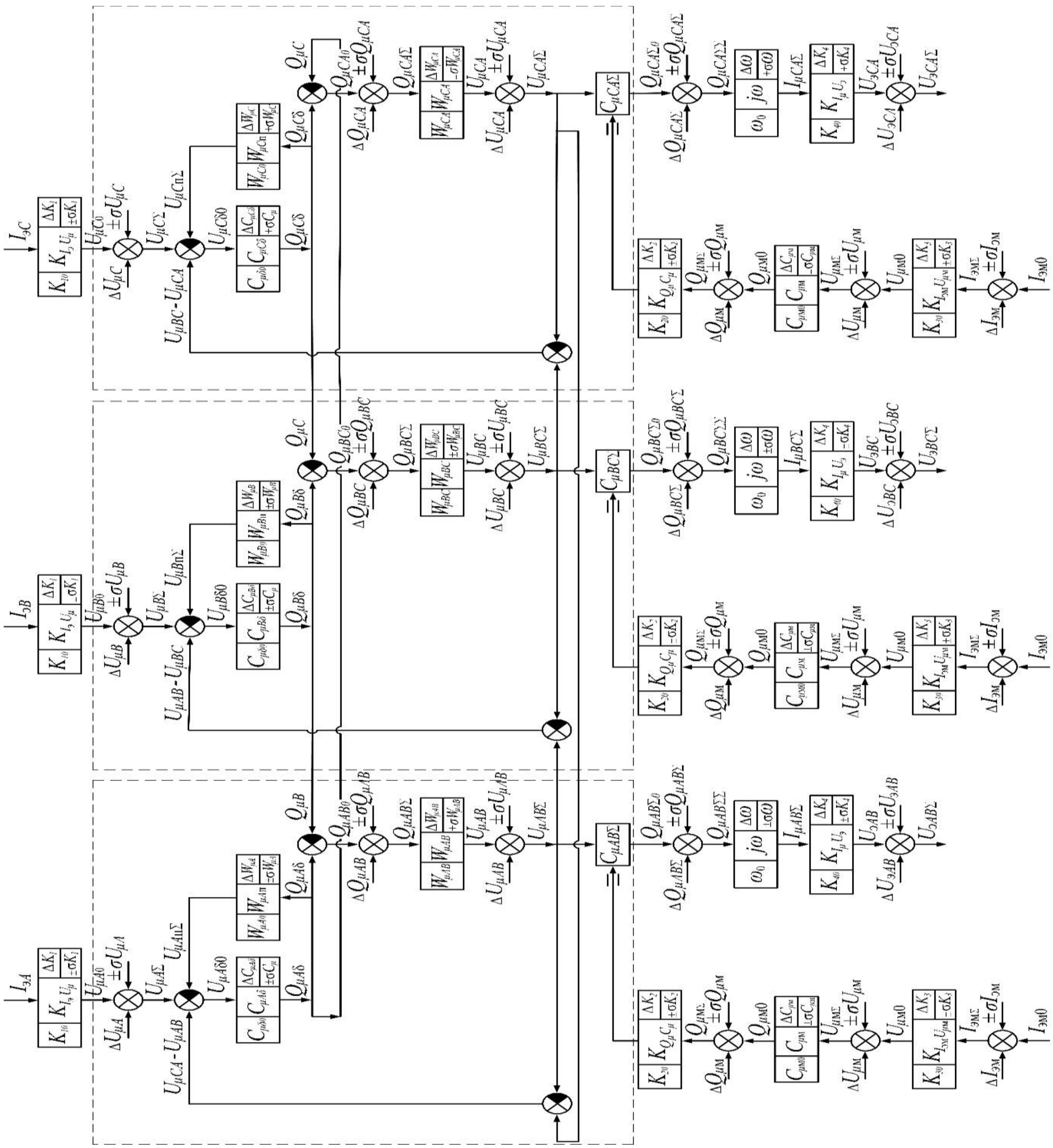

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Figure 2. PSS scheme of EMC, which measures the symmetry of three-phase currents, taking into account all sources of error internal PhTE, which interconnects the MYuK ($U_{\mu м}$)generated by the $I_{эм}$ current in the modulation magnetic circuit by the magnetic flux ($Q_{\mu м}$) in it through the magnetic capacitance parameter ($C_{\mu м}$), $Q_{\mu м} = U_{\mu м} C_{\mu м}$; where $C_{\mu м} = \mu\mu_0 \frac{S_\mu}{l_\mu}, [H]$; 6) magnetomodulation effect: $Q_{\mu AB\sum} = K_{Q_{\mu м} Q_{\mu м}} U_{\mu x AB} Q_{\mu м}$, where is $K_{Q_{\mu м} Q_{\mu м}} = \frac{1}{l_{\mu м}} \cdot \frac{d(\mu\mu_0)}{dB_м}$, $\left[\frac{H}{Wb}\right]$, and here $l_{\mu м}$, $B_м$ – the average length of the magnetic flux path along the modulation magnetic circuit and the magnetic induction in it, respectively, $[m]$; $[T]$; 7) magnetic flux ($Q_{\mu AB\sum}$) interacts with differential operation that ($I_{\mu AB\sum}$): $I_{\mu AB\sum} = \frac{d}{dt} Q_{\mu AB\sum}, [V]$; 8) electromagnetic induction ФТЭ: $U_{эAB} = K_{I_{\mu AB\sum} U_{эAB}} I_{\mu AB\sum}$, where is $K_{I_{\mu AB} U_{эAB}} = w_{ўл}$ – the inter-chain PhTE coefficient that converts the magnetic current ($I_{\mu AB\sum}$) into an electrical voltage - the number of windings of the output coil, $[-]$.

It should be noted that the tires and the modulation coil heat up as a result of the passage of appropriate currents. As a result, the active resistance of the modulation coil cable increases. However, since this coil is supplied from a current source, a change in the electrical resistance of the wire under the influence of temperature does not lead to a change in the source current. The current in the output coil is also close to zero because the corresponding element (load) of the measuring instrument or control system connected to the output coil has a large input resistance. Therefore, the change in resistance of these wires under the influence of temperature of the IC in the PSS was not taken into account [10].

Although the PSS IC structure shown in Figure 1 is structured taking into account all sources of errors affecting each elementary link in the structure diagram, the process of calculating the IO error based on it poses some difficulties. This is because for one column of the PSS (for example, to derive the equation of dependence of the measured current difference on the output voltage generated in the measuring strip on the rod between busbars A and B, taking into account all sources of error), the effect of magnetic chain sizes on the other column must be taken into account.

Therefore, in order to simplify the calculations a bit, using the equations generated in the study of static and dynamic characteristics of IC, we replace the part of the PSS in Figure 2 with a dashed line in each column with a single elemental link and examine each column separately (Figure 3). . In this case, for each segment of the PSS separated by dashed lines, for example, for the segment in column 1, we can write the following equation:

$$Q_{\mu AB\Sigma} = U_{\mu AB} C_{\mu AB\Sigma} = \frac{U_{\mu AB}}{W_{\mu 1} + 3W_{\mu 2}}, \qquad (1)$$

here is $C_{\mu AB\Sigma} = 1/(W_{\mu 1} + 3W_{\mu 2})$ – the resulting magnetic capacity of the chain in the path of the magnetic flux generated by the currents in the adjacent tires in the rod between them, [H];$W_{\mu 1} = W_{\mu\delta} + W_{\mu Aп}$; $W_{\mu\delta}$; $W_{\mu Aп}$ – the resultant, non-adjacent branch of the three-contour magnetic chain, respectively, δ air gap and the magnetic stiffness of the steel part (magnetic resistance by classical analogy), $[1/H]$; $W_{\mu 2} = W_{\mu AB} = W_{\mu BC} = W_{\mu CA}$ - the magnetic stiffness of the adjacent branches of a three-contour magnetic chain, $[1/H]$; $U_{\mu AB} = K_{I_э U_\mu}(I_{эA} - I_{эB})$ - A and B MYuK formed by the difference in currents in the busbars, $[A]$.

For each elementary link (transducer) in the PSS, we write the equation of static characteristic, taking into account the sources of error in it as follows:

$$U_{эAB} = (K_{40} + \Delta K_4 \pm \sigma K_4) I_{\mu AB\Sigma\Sigma}, \qquad (2)$$

It is $K_4 = K_{I_\mu U_э} = w_{ўл}$, $[-]$ – coefficient of inter-chain physical-technical effect (elemental link) that converts magnetic current I_μ to electric voltage; $K_{40}, \Delta K_4, \pm\sigma K_4$ - $K_{I_\mu U_э}$ the value of the coefficient in the ideal state (without errors), respectively, its gains from

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systematic and random sources of error (in the following elementary links, the corresponding coefficient "0" in the index, the ideal value of a parameter or quantity, preceded by "Δ" and "$\pm\sigma$" – regular and random components of the error, respectively; $w_{ўл}$ – the number of wrappings.

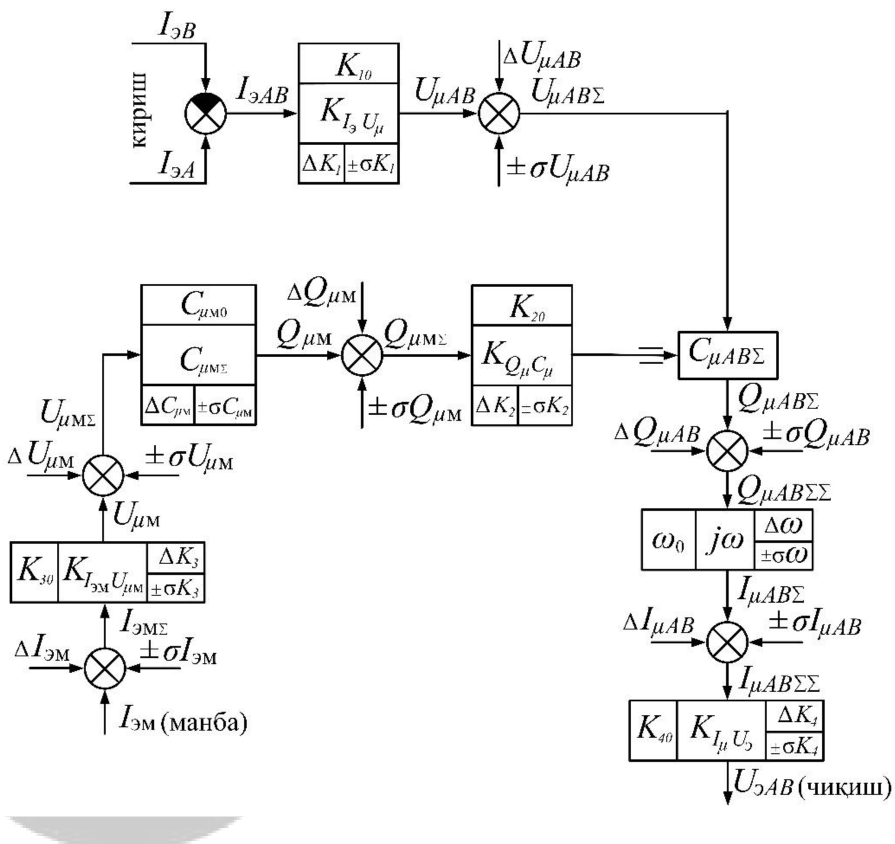

Figure 3. A simplified parametric structure diagram of the PSS 1 column shown in Figure 2

$$I_{\mu AB\Sigma\Sigma} = \Delta I_{\mu AB} \pm \sigma I_{\mu AB} + j(\omega_0 + \Delta\omega \pm \sigma\omega) Q_{\mu AB\Sigma\Sigma}, \quad (3)$$
$$Q_{\mu AB\Sigma\Sigma} = \Delta Q_{\mu AB\Sigma} \pm \sigma Q_{\mu AB\Sigma} + U_{\mu AB\Sigma} C_{\mu AB\Sigma}, \quad (4)$$
$$C_{\mu AB\Sigma} = (K_{20} + \Delta K_2 \pm \sigma K_2) Q_{\mu м\Sigma}, \quad (5)$$
$$Q_{\mu м\Sigma} = \Delta Q_{\mu м} \pm \sigma Q_{\mu м} + \left(C_{\mu м0} + \Delta C_{\mu м} \pm \sigma C_{\mu м}\right) U_{\mu м\Sigma}, \quad (6)$$
$$U_{\mu м\Sigma} = \Delta U_{\mu м} \pm \sigma U_{\mu м} + (K_{30} + \Delta K_3 \pm \sigma K_3) I_{эм\Sigma}, \quad (7)$$
$$I_{эм\Sigma} = I_{эм} + \Delta I_{эм} \pm \sigma I_{эм}, \quad (8)$$
$$U_{\mu AB\Sigma} = \Delta U_{\mu AB} \pm \sigma U_{\mu AB} + (K_{10} + \Delta K_1 \pm \sigma K_1) I_{эAB}, \quad (9)$$
$$I_{эAB} = I_{эA} - I_{эB}. \quad (10)$$

On the basis of PSS, change the magnitude of the IC output in the order of derivation of the equation of dependence on its input size [9], equation (3) and subsequent equations, respectively, and multiplication of two or more multiplications by a measuring device operating in magnetomodulation mode we obtain the following equation of the function formed by taking into account the sources of errors in it::

$$U_{эAB.\Sigma(мм)} = \Delta I_{\mu AB}K_{40} \pm \sigma I_{\mu AB}K_{40} + j\Delta Q_{\mu AB\Sigma}\omega_0 K_{40} \pm j\sigma Q_{\mu AB\Sigma}\omega_0 K_{40} +$$
$$+j\Delta U_{\mu AB}K_{30}I_{эм}C_{\mu м0}K_{20}\omega_0 K_{40} \pm j\sigma U_{\mu AB}K_{30}I_{эм}C_{\mu м0}K_{20}\omega_0 K_{40} +$$
$$+j\Delta K_1 I_{эAB}K_{30}I_{эм}C_{\mu м0}K_{20}\omega_0 K_{40} \pm j\sigma K_1 I_{эAB}K_{30}I_{эм}C_{\mu м0}K_{20}\omega_0 K_{40} +$$
$$+j\Delta Q_{\mu м}K_{20}K_{10}I_{эAB}\omega_0 K_{40} \pm j\sigma Q_{\mu м}K_{20}K_{10}I_{эAB}\omega_0 K_{40} +$$
$$+j\Delta U_{\mu м}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 K_{40} \pm j\sigma U_{\mu м}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 K_{40} +$$
$$+jK_{30}I_{эм}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 K_{40} + j\Delta K_3 I_{эм}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 K_{40} \pm$$
$$\pm j\sigma K_3 I_{эм}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 K_{40} + j\Delta I_{эм}K_{30}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 K_{40} \pm$$
$$\pm j\sigma I_{эм}K_{30}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 K_{40} + j\Delta C_{\mu м}K_{30}I_{эм}K_{20}K_{10}I_{эAB}\omega_0 K_{40} \pm$$
$$\pm j\sigma C_{\mu м}K_{30}I_{эм}K_{20}K_{10}I_{эAB}\omega_0 K_{40} + j\Delta K_2 K_{30}I_{эм}C_{\mu м0}K_{10}I_{эAB}\omega_0 K_{40} \pm$$
$$\pm j\sigma K_2 K_{30}I_{эм}C_{\mu м0}K_{10}I_{эAB}\omega_0 K_{40} + j\Delta\omega K_{30}I_{эм}C_{\mu м0}K_{20}K_{10}I_{эAB}K_{40} \pm$$
$$\pm j\sigma\omega K_{30}I_{эм}C_{\mu м0}K_{20}K_{10}I_{эAB}K_{40} + j\Delta K_4 K_{30}I_{эм}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 \pm$$
$$\pm j\sigma K_4 K_{30}I_{эм}C_{\mu м0}K_{20}K_{10}I_{эAB}\omega_0 \quad (13)$$

For the ideal case, that is, the analytical equation for the static characteristics of the device under study without a source of error is written as follows on the basis of PSS:

$$U_{эAB.0(мм)} = K_{10}K_{20}K_{30}K_{40}j\omega_0 C_{\mu м0}I_{эм}I_{эAB} \quad (14)$$

The accuracy class of a measuring transducer is mainly determined by its reported error. Therefore, we conduct an analysis of the IC error under investigation for its reported error. The given error is found on the basis of the following formula [11]:

$$\gamma_{кел.U_{эAB(мм)}} = \frac{U_{эAB.\Sigma(мм)} - U_{эAB.0(мм)}}{U_{эAB.0(мм)}} \cdot 100\ \% =$$
$$= [\frac{\Delta I_{\mu AB}}{I_{\mu AB}} \pm \frac{\sigma I_{\mu AB}}{I_{\mu AB}} + \frac{\Delta Q_{\mu AB\Sigma}}{Q_{\mu AB\Sigma}} \pm \frac{\sigma Q_{\mu AB\Sigma}}{Q_{\mu AB\Sigma}} + \frac{\Delta U_{\mu AB}}{U_{\mu AB}} \pm \frac{\sigma U_{\mu AB}}{U_{\mu AB}} + \frac{\Delta K_1}{K_1} \pm \frac{\sigma K_1}{K_1} +$$
$$+ \frac{\Delta Q_{\mu м}}{Q_{\mu м}} \pm \frac{\sigma Q_{\mu м}}{Q_{\mu м}} + \frac{\Delta U_{\mu м}}{U_{\mu м}} \pm \frac{\sigma U_{\mu м}}{U_{\mu м}} + \frac{\Delta K_3}{K_3} \pm \frac{\sigma K_3}{K_3} + \frac{\Delta I_{эм}}{I_{эм}} \pm \frac{\sigma I_{эм}}{I_{эм}} + \frac{\Delta C_{\mu м}}{C_{\mu м}} \pm$$
$$\pm \frac{\sigma C_{\mu м}}{C_{\mu м}} + \frac{\Delta K_2}{K_2} \pm \frac{\sigma K_2}{K_2} + \frac{\Delta\omega}{\omega} \pm \frac{\sigma\omega}{\omega} + \frac{\Delta K_4}{K_4} \pm \frac{\sigma K_4}{K_4}] \cdot 100\ \% =$$
$$= \left[\gamma^{мун.}_{кел.U_{эAB(мм)}}(\Delta U_х, \Delta U_\mu, \Delta I_э) + \gamma^{тас.}_{кел.U_{эAB(мм)}}(\pm\sigma U_х, \pm\sigma U_\mu, \pm\sigma I_э)\right] \cdot 100\ \%, \quad (16)$$

Where is $\gamma^{мун.}_{кел.U_{эAB(мм)}}(\Delta U_и, \Delta U_\mu, \Delta U_э)$ and $\gamma^{тас.}_{кел.U_{эAB(мм)}}(\pm\sigma U_и, \pm\sigma U_\mu, \pm\sigma U_э)$ - respectively regular and random components of the given error of the IC operating in the mode of magnetomodulation; (ΔU_μ ва $\pm\sigma U_\mu$), ($\Delta U_х$ ва $\pm\sigma U_х$) and ($\Delta I_э$ ва $\pm\sigma I_э$) – sources of additive and multiplicative errors in the studied IC due to deviations from the normal values of the source current parameters that provide the external alternating and constant magnetic fields, temperature and modulation chain, respectively.

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