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ERROR DETERMINATION OF RANGE-VERIFIED FERROMAGNETIC CURRENT TRANSFORMERS

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Abstract. *Increasing the reliability of ferromagnetic current transducers, the range of which is adjusted. During the trial period, the defunct FMTO was not replaced by a new one. Total trial period T0=200·103s during this period, the isolation of the lungs, the failure of their input and output parts, and the FMTOS find and calculate the failure intensity, upper limit, double reliability marginal values of the 90% resource of the working state change. .A source of error that leads to a random change in the measured current value, that is, the study of the appearance of high harmonics in the measured current as a result of transient processes occurring in the energy system and short circuits as a result of the transition of magnetic materials(generators, power transformers, etc.) to the saturation part of the magnetization characteristic*

Keywords: *ferromagnetic current conductors, Exponential distribution law, values of lower and upper reliability limits, probability of operation without failure.*

It is known that measurement error is one of the most important characteristics of O'O, including FMTO. Because depending on this characteristic, the model and design of the FMTO is selected.

FMTO based on transformer and galvanomagnetic EPTs are compiled on the basis of information given in educational and scientific literature about sources of errors, according to which methodological, technological and operational sources of FMTO error are its main sources of error, and its internal, external and regime sources. refers to additional sources of errors [58, pp.43-46; 55-59; 87, p. 34-36].

To identify these sources of errors, their qualitative and quantitative assessment, in this article we use the method of parametric block diagrams (PSC), based on energy information models of circuits of various physical natures [55]. In the PSS it is clearly visible at what stage the electromagnetic processes occurring in the FMTO occur and what EP, parameters and quantities influence it, which greatly facilitates the identification of error components and the assessment of their numerical values [56].

To determine O'O errors and estimate their numerical values, the sequence for creating their PSS is compiled by the author of this technique, Prof. Zaripov M.F. and is described in detail in the scientific literature published by his students [9;55;56;95].

Therefore, we will limit ourselves to presenting the SEP of the new FMTO' [90] based on transformer and galvanomagnetic EPTs, built taking into account all sources of errors (Fig. 1). “0” in the index of each FTE coefficient (for example,), parameter (for example) and value (for example) in PSS indicate their ideal values, that is, without sources of errors, and the symbols “ ” and “ “In front of them, errors are respectively indicated” are values caused by systematic and random error sources [55].

To estimate the uncertainty of a new FMTO, we first determine the uncertainty of each unit specified in its PSS (in Figure 1, each unit is separated by a box with a ring line and labeled with its corresponding Roman numeral).

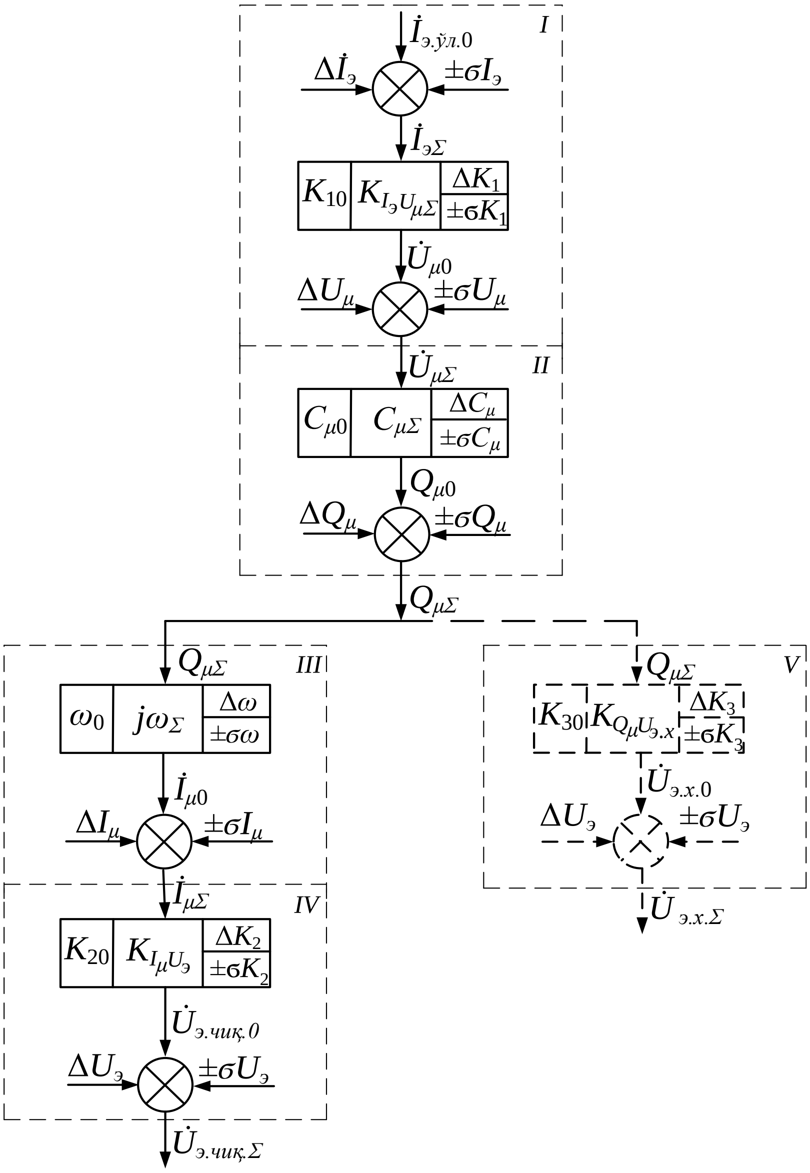


Figure 1. Parametric block diagram of a transformer and galvanomagnetic FMTO, taking into account all sources of errors

1. Ampere winding FTE, that is, an elementary link that converts the measured current ( ) into magnetic voltage ( ) generated around the bus (in the PSS this link is denoted by the Roman numeral I). For this elementary link we write the following equations:

$U_{\mu\Sigma} = U_{\mu 0} + \Delta U_{\mu} \pm \sigma U_{\mu},$ (1.1)	$U_{\mu 0} = K_{I_e U_{\mu\Sigma}} I_{e.o'l.\Sigma},$ (1.2)
$K_{I_e U_{\mu}\Sigma} = K_{10} + \Delta K_1 \pm \sigma K_1,$ (1.3)	$I_{e\Sigma} = I_{e.o'l.0} + \Delta I_e \pm \sigma I_e.$ (1.4)

Substituting (4.39), (4.40) and (4.41) into (4.38) respectively, we generate the following equation, disregarding the small values of the second-order sums in the resulting polynomial:

$$U_{\mu\Sigma} = K_{10} I_{e.o'l.0} + K_{10}\Delta I_e \pm K_{10}\sigma I_e + \Delta K_1 I_{e.o'l.0} \pm \sigma K_1 I_{e.o'l.0} + \Delta U_{\mu} \pm \sigma U_{\mu}. \quad (1.5)$$

This elemental link is ideal, i.e. without the influence of error sources, its static characteristic is equal to the following:

$$U_{\mu 0} = K_{10} I_{e.o'l.0}. \quad (1.6)$$

The absolute error of the link is calculated as follows [81, 57 b.]:

$$\gamma_{abs.} = U_{\mu\Sigma} - U_{\mu 0} = K_{10}\Delta I_e \pm K_{10}\sigma I_e +$$

$$+\Delta K_1 I_{e.o‘l.0} \pm \sigma K_1 I_{e.o‘l.0} + \Delta U_\mu \pm \sigma U_\mu. \qquad (1.7)$$

The relative error is found as follows [53, 35 b.]:

$$\gamma_{nis.} = \frac{\gamma_{abs.}}{U_{\mu 0}} \cdot 100\ \% = \left(\frac{\Delta I_e}{I_{e.o‘l.0}} \pm \frac{\sigma I_e}{I_{e.o‘l.0}} + \frac{\Delta K_1}{K_{10}} \pm \right.$$

$$\left. \pm \frac{\sigma K_1}{K_{10}} + \frac{\Delta U_\mu}{U_{\mu 0}} \pm \frac{\sigma U_\mu}{U_{\mu 0}} \right) \cdot 100\ \% =$$

$$= \gamma_{nis.}(\Delta I_e) \pm \gamma_{nis.}(\sigma I_e) + \gamma_{nis.}(\Delta K_1) \pm$$

$$\pm \gamma_{nis.}(\sigma K_1) + \gamma_{nis.}(\Delta U_\mu) \pm \gamma_{nis.}(\sigma U_\mu). \qquad (1.8)$$

As can be seen from the relevant part of the PSS and the equation (4.45) created on its basis, the error caused by the change in the measured current (mainly the appearance of high harmonics in the current) in the elementary link under consideration, ampere-o The error caused by the change of the ram FTE coefficient and the magnetic voltage created by this current around the measured current include sources of error caused by the effect of the external magnetic field and ferromagnetic mass [70213 p.].

The analysis of the above-mentioned sources of error shows that, because there is no known source of error that changes the value of the measured current. But the source of error that causes the measured current value to change randomly, that is, due to transient processes and short circuits in the power system, electromagnetic devices (generators, power transformers, etc.) as a result of its passage, higher harmonics appear in the measured current. Analysis shows that in most cases, only the third harmonic of the higher harmonic constituents significantly changes the current value and shape. Therefore, the random error caused by the appearance of higher harmonics is calculated as follows [67, p. 134]:

$$\gamma_{nis.}(\sigma I_e) = \frac{I_{e.o‘l.m3}}{I_{e.o‘l.m}} \cdot 100\ \%, \qquad (1.9)$$

Where $I_{e.o‘l.m}$, $I_{e.o‘l.m3}$ are the amplitude values of the first and third harmonics of the measured current. Usually, in the process of error calculation, the measured current shape is assumed to be sinusoidal [40]. Therefore, it is often accepted as, $\gamma_{nis.}(\sigma I_e) = 0$,

The ampere-winding FTE factor is equal to the number of turns of the busbar through which the current is being measured, i.e. $K_{I_e U_\mu} = w_{o‘l.}$ it is often (when made in the form of a busbar). $w_{o‘l.} = 1$ That's why and will be. $\gamma_{nis.}(\Delta K_1) = 0$ va $\gamma_{nis.}(\sigma K_1) = 0$.

In most cases $\gamma_{nis.}(\Delta U_\mu) \neq 0$ and $\gamma_{nis.}(\sigma U_\mu) \neq 0$ because, FMTO' is often affected by the external magnetic field (mainly magnetic fields of currents in adjacent tires) and ferromagnetic masses near the place where FMTO' is installed [70, 145- 147 p.]. It is appropriate to take into account the error caused by the influence of the external magnetic field when determining the sources of error of the next elementary link in the FMTO' PSS.

The error caused by the negative influence of the ferromagnetic mass near the FMTO's installation on the FMTO's operation is considered a regular error, because the location of the ferromagnetic mass, its distance from the FMTO, and the electromagnetic properties are always available. The error caused by the effect of the external ferromagnetic mass is calculated using the following formula [70, 212 p.]:

$$\gamma_{nis.(f.m.)}(\mathit{\Delta} U_\mu) = \frac{\delta_{ish}}{2C_\mu} \cdot C_{\mu s}, \qquad \mathit{(1.10)}$$

Here C_μ is the magnetic capacity along the path of the working magnetic flux,, $[H]$; $C_{\mu s}$ – Pogon value of the magnetic capacity of the air gap between the FMTO' and the external ferromagnetic mass, $[H/m]$; δ_{ish} working air gap, $[m]$. Studies have shown that for new FMTO installed in traction power supply systems $\gamma_{nis.f.m.}(\Delta U_{\mu}) < 0{,}02\ \%$, in particular traction substation.

2. The internal FTE of the magnetic circuit is a parameter of magnetic capacity, that is, an elementary link that converts magnetic voltage ( ) into magnetic current ( ). For this elemental link, we write equations similar to the ones written for the elemental link analyzed above, and after making the necessary substitutions, we create the following equation of the relative error: $\gamma_{nis.} = \frac{\gamma_{abs.}}{Q_{\mu 0}} \cdot 100\ \% = \left(\frac{\Delta C_{\mu}}{C_{\mu 0}} \pm \frac{\sigma C_{\mu}}{C_{\mu 0}} + \frac{\Delta Q_{\mu}}{Q_{\mu 0}} \pm \frac{\sigma Q_{\mu}}{Q_{\mu 0}} \right) \cdot 100\ \% =$

$$= \gamma_{nis.}(\Delta C_{\mu}) \pm \gamma_{nis.}(\sigma C_{\mu}) + \gamma_{nis.}(\Delta Q_{\mu}) \pm \gamma_{nis.}(\sigma Q_{\mu}), \qquad (2.1)$$

Here $C_{\mu} = \frac{C_{\mu\delta}}{1 + C_{\mu\delta} W_{\mu p}}$ the magnetic capacity of the FMTO' magnetic circuit (magnetic permeability according to the classical analogy), $[H]$; $C_{\mu\delta}$ – magnetic capacity of the KOPO working air gap,, $[H]$; $W_{\mu p}$ – KOPO magnetic hardness (magnetic resistance by classical analogy),$[1/H]$.

The first two terms on the right-hand side of equation (2.2) indicate the source of error caused by the increase of the magnetic capacitance of the magnetic circuit FMTO' due to the change in ambient temperature. In this case, the change of and under the influence of temperature is determined by the following formulas [53, p. 78-79]:

$$C_{\mu\delta} = C_{\mu\delta 0}(1 + \alpha_{l}\Delta\theta), \qquad (2.4) \qquad\qquad W_{\mu p} = W_{\mu p 0}\frac{(1 + \alpha_{\mu}\Delta\theta)}{(1 + \alpha_{l}\Delta\theta)}, \qquad (2.5)$$

where $\alpha_{\mu}, [K^{-1}]$ and $\alpha_{l}, [K^{-1}]$ – are the temperature coefficients for the magnetic hardness and expansion of POPO material, respectively; - the difference between the current and normal temperatures of the environment.

Due to the fact that the increase of MANY geometric dimensions in the FMTO magnetic circuit caused by temperature changes is very small, they can not be taken into account. The increase of the magnetic capacity of the considered elemental link caused by the change in ambient temperature refers to the random component of the error, which is determined as follows [53, 78-79 p.]:

$$\gamma_{abs.\Delta\theta}(\sigma C_{\mu}) = \frac{\partial C_{\mu}}{\partial W_{\mu p}} \cdot \frac{\partial W_{\mu p}}{\partial \Delta\theta} = -\frac{C_{\mu\delta}^{2} W_{\mu p 0}\alpha_{\mu}}{(1 + C_{\mu\delta} W_{\mu p})^{2}}. \qquad (2.6)$$

When the ambient temperature changes, the relative error caused by the change in the magnetic property (relative magnetic absorption) of the magnetic conductor material is calculated based on the following formula [53, 80b.]:

$$\gamma_{nis.}(\sigma C_{\mu}) = \frac{\Delta\theta}{C_{\mu\delta}} \cdot \frac{\partial C_{\mu}}{\partial W_{\mu p}} \cdot \frac{\partial W_{\mu p}}{\partial \Delta\theta} = \pm \frac{C_{\mu\delta} W_{\mu p 0}\alpha_{\mu}\Delta\theta}{(1 + C_{\mu\delta} W_{\mu p 0})^{2}}. \qquad (2.7)$$

For the construction of the new FMTO; $C_{\mu\delta} = 1{,}3 \cdot 10^{-7}\ H$; $W_{\mu p 0} = 1{,}1 \cdot 10^{6}\ 1/H$; $\alpha_{\mu} = 0{,}011\ K^{-1}$; $\Delta\theta = 40\ K$ it was $\gamma_{nis.}(\sigma C_{\mu}) \approx 0{,}047\ \%$.

The last two terms on the right-hand side of equation (2.8) determine the error sources arising from the negative effects of external magnetic fields affecting the FMTO' magnetic circuit [21, 96 p.]. These fields include the magnetic fields of the currents passing through the busbars of the three-phase line and the busbars of other three-phase lines [67, 111 p.].

When the current in one phase of a three-phase line is measured, the negative effect of the magnetic fields of the currents passing through the buses of the other two adjacent phases has been studied in detail theoretically and experimentally on the example of remote transformer current transformers, so we limit ourselves to presenting their results [21, 109- 111 p.; 67, pp. 134-137]. According to the results of these studies, in current transformers not surrounded by an $\gamma_{nis.}(\Delta Q_{\mu}) = 20{,}31$ %, the regular component $\gamma_{nis.}(\Delta Q_{\mu}) = 12{,}06$ %i. electromagnetic screen, the error caused by the magnetic field of the nearest neighboring phase reaches up to $\gamma_{nis.}(\Delta Q_{\mu}) = 2{,}18$ % and $\gamma_{nis.}(\Delta Q_{\mu}) = 1{,}36$ % when surrounded by an electromagnetic screen, these indicators are respectively [21, 109-111 b.]. In FMTOs surrounded by an electromagnetic shield, the currents passing through the bus bars of other three-phase lines, power transformers and other transformer-type devices located near the FMTO are small enough to ignore the regular errors that appear due to the influence of magnetic fields. [70, 221 p.].

The elementary links considered above are also common for transformer and galvanomagnetic FMTOs. In FMTO' PSS, the elementary links marked with Roman numerals III and IV are the relevant parts of FMTO' PSS operating in transformer mode, and the elementary link marked with Roman numeral V is a part of FMTO' PSS operating in galvanomagnetic mode. Below, we will first consider the sources of errors of the remaining elementary links in the new FMTO' PSS *operating in the transformer mode.*

The internal FTE of the magnetic circuit is an ideal differentiating elemental link that converts the magnetic flux ( ) into the magnetic current ( ). The relative error equation for this elemental link is as follows:

$$\gamma_{nis.} = \frac{\gamma_{abs.}}{\omega_0}\cdot 100\ \% = \left(\frac{\Delta\omega}{\omega_0} \pm \frac{\sigma\omega}{\omega_0} + \frac{\Delta I_{\mu}}{I_{\mu 0}} \pm \frac{\sigma I_{\mu}}{I_{\mu 0}}\right)\cdot 100\ \% =$$

$$= \gamma_{nis.}(\Delta\omega) \pm \gamma_{nis.}(\sigma\omega) + \gamma_{nis.}(\Delta I_{\mu}) \pm \gamma_{nis.}(\sigma I_{\mu}). \qquad (3.1)$$

The regular component of the relative error caused by the fluctuation of the measured current frequency in this elementary link is equal to zero, that is, because the change of the current frequency in the power system is a random event for FMTO. This random component of the relative error is defined as follows [64]:

$$\gamma_{nis.}(\sigma\omega) = \frac{\sigma\omega}{\omega_0}\cdot 100\ \%. \qquad (3.2)$$

According to GOST, the industrial frequency is allowed to change at most [64]. That's why. The third and fourth terms on the right-hand side of the relative error equation (3.3) for this elementary link were taken into account as sources of error caused by the influence of external magnetic fields when calculating the relative errors of the previous elementary link.

Electromagnetic induction FTE, that is, an elementary circuit that converts magnetic current (I_{μ}) into electric voltage ($U_{e.chiq.}$). The equation of the static characteristic generated for this link, taking into account the sources of error, has the following form:

$$\gamma_{nis.} = \frac{\gamma_{abs.}}{U_{e.chiq.0}}\cdot 100\ \% = \left(\frac{\Delta K_2}{K_{20}} \pm \frac{\sigma K_2}{K_{20}} + \frac{\Delta U_e}{U_{e.chiq.0}} \pm \frac{\sigma U_e}{U_{e.chiq.0}}\right)\cdot 100\ \% =$$

$$= \gamma_{nis.}(\Delta K_2) \pm \gamma_{nis.}(\sigma K_2) + \gamma_{nis.}(\Delta U_e) \pm \gamma_{nis.}(\sigma U_e). \qquad (4.1)$$

The first two terms on the right side of equation (4.2) are $\gamma_{nis.}(\Delta K_2) = 0$, and $\gamma_{nis.}(\sigma K_2) = 0$ because $K_2 = K_{I_{\mu}U_{e.chiq.}} = w_{o‘lch.} = const.$, .

The last two terms on the right-hand side of equation (4.3) estimate the errors caused by external magnetic fields induced in the measuring coil. They were also taken into account as sources of errors caused by the influence of external magnetic fields in the calculation of the relative errors of the previous elementary link. Therefore, it can be considered that .$\gamma_{nis.}(\Delta U_e) = 0$ and $\gamma_{nis.}(\sigma U_e) = 0$.

Thus, the regular and random components of the relative error of the new FMTO operating in the transformer mode will be equal to the following values:

$$\gamma_{nis.(tr)}\left(\Delta U_{e.chiq.}\right) = \gamma_{nis.(f.m.)}\left(\Delta U_{\mu}\right) + \gamma_{nis.}\left(\Delta Q_{\mu}\right) = 1{,}38\ \%. \qquad (4.4)$$

$$\gamma_{nis.(tr)}\left(\sigma U_{e.chiq.}\right) = \sqrt{\gamma^2_{nis.}\left(\sigma C_{\mu}\right) + \gamma^2_{nis.}(\sigma\omega)} \approx 0{,}4\ \%. \qquad (4.5)$$

A common error is:

$$\gamma_{nis.(tr)}\left(U_{e.chiq.}\right) = \gamma_{nis.(tr)}\left(\Delta U_{e.chiq.}\right) + \gamma_{nis.(tr)}\left(\sigma U_{e.chiq.}\right) \approx 1{,}42\ \%. \ (4.6)$$

Now let's consider the error sources of the elementary link (this link is marked with Roman numeral V in PSS) belonging to the galvanomagnetic mode in the new FMTO' PSS.

It is worth mentioning that although the galvanomagnetic effect is separated in the general PSS in the form of one elementary link, firstly, they are different in type (Hall effect, magnetoresistive effect, magnetotransistor effect, magnetodiode effect, etc.) [107] , and secondly, these effects include external effects and other factors that negatively affect their work [125, p. 45-77]. In this dissertation, we will limit ourselves to seeing the sources of errors that occur in the Hall element (XE), which is widely used not only in galvanomagnetic current transformers, but also in other electrical and non-electrical measuring devices.

In the classification of error sources presented in Figure 4.5, the sources of error that appear due to the external effects related to the XE and the negative effects of the geometric shape of the XE sample are noted. In order to study the sources of these errors in more detail, a complete classification of them was developed by analyzing the data presented in the existing educational and scientific literature (Figure 4.7).

The name of the Hall effect and FTEs adjacent to it, the PSS of the elementary link, the expression of the coefficient and its value and the range of change of the input quantity, which are necessary for calculating the error of measuring the ЭЕ ЕЯУК (I.4.1) - table).

An XE sample would not ideally be homogeneous. In such a sample under the influence of a magnetic field, a transverse component of the current appears, which negatively affects the measurement results [125, 49 p.].

The relative error due to the non-uniformity of the induction of the working magnetic field is approximately half of the degree of non-uniform distribution of the induction ( ) [62]. Therefore, we try to reduce the XE installed working interval as much as possible. It is achieved in most magnetic systems and does not exceed [70, 126 p.].

The geometry of Hall junctions also causes errors in the measurement of Hall EC [132]. When the length and thickness of the XE sample is , the relative error is [125, 78 p.]. Reduction of this error is carried out by choosing the optimal option of the contact forms presented in clause 1.2 of paragraph 2.2 of the dissertation.

When the XE sample is "grinded", it becomes elbow-shaped, which causes residual stress to appear in the sample [107]. This element of error is reduced using technological methods.

The error that occurs when the ambient temperature changes is reduced to using thermocompensation methods [107]. Figure 4.8 shows the PSS created taking into account the interaction of workers and foreign FTEs in XE. The relative errors due to foreign FTEs participating in each branch of this PSS are found as follows:

$$\gamma_{nis.}(U_{e2}) = \frac{U_{e2}}{U_{e0}} = \frac{K_2 Q_{\mu o'r.}}{U_{e0}} \cdot 100\ \% = 0{,}34\ \%, \qquad (4.7)$$

$$\gamma_{nis.}(U_{e36}) = \frac{U_{e36}}{U_{e0}} = \frac{K_3K_6Q_{\mu o'r.}}{U_{e0}} \cdot 100\ \% = 0{,}11\ \%, \qquad (4.8)$$

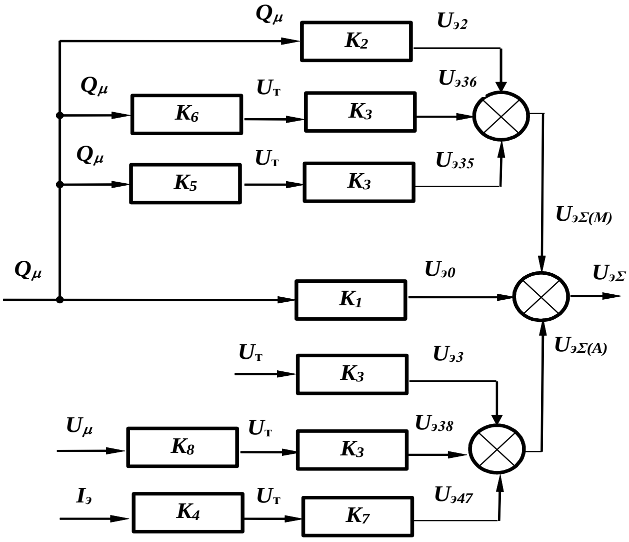
$$\gamma_{nis.}(U_{e35}) = \frac{U_{e35}}{U_{e0}} = \frac{K_3K_5Q_{\mu o'r.}}{U_{e0}} \cdot 100\ \% = 1{,}1 \cdot 10^{-2}\ \%, \qquad (4.9)$$

$$\gamma_{nis.}(U_{e3}) = \frac{U_{e3}}{U_{e0}} = \frac{K_3U_t}{U_{e0}} \cdot 100\ \% = 1{,}19\ \%, \qquad (4.10)$$

$$\gamma_{nis.}(U_{e38}) = \frac{U_{e38}}{U_{e0}} = \frac{K_3K_8U_\mu}{U_{e0}} \cdot 100\ \% = 8{,}1 \cdot 10^{-2}\ \%, \qquad (4.11)$$

$$\gamma_{nis.}(U_{e47}) = \frac{U_{e47}}{U_{e0}} = \frac{K_4K_7I_e}{U_{e0}} \cdot 100\ \% = 1{,}7 \cdot 10^{-3}\ \%, \qquad (4.12)$$

Here $Q_{\mu o'r.} = 0{,}5 \cdot (10^{-6} + 0{,}01) = 5 \cdot 10^{-3}$ Wb; $U_{e0} = K_1Q_{\mu o'r.} = 35\ V$.



Picture 2. The PSS is created taking into account the interaction of the employee and foreign FTEs in XE $\gamma_{nis.}(U_{e3})$, $\gamma_{nis.}(U_{e38})$ and $\gamma_{nis.}(U_{e47})$ are additive components of the error, and their sum is found:

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