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MODELING OF ELECTROMAGNETIC DEVICES FOR MEASURING ASYMMETRIC REACTIVE POWER CURRENT PROCESSES IN A HYBRID POWER SUPPLY SYSTEM NETWORK

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Abstract:
This article presents the modeling of reactive power currents in hybrid energy source electrical supply systems using primary asymmetric processes, employing collected and distributed parameter graph models as well as analytical expressions to ensure high accuracy for electromagnetic devices.

Keywords: Reactive power, graph model, modeling, electromagnetic device, electrical supply, analytical expression.

1. INTRODUCTION:

Worldwide, significant attention is being given to the advancement of electromagnetic conversion devices, components, and systems, as well as structures that ensure standardized maintenance and precisely defined quality of reactive energy and power in three-phase current networks within power supply systems using hybrid energy sources.

In developed countries, a key issue is the development of primary electromagnetic converter structures that provide high-accuracy measurement and remote monitoring of three-phase reactive power currents in electrical networks with hybrid energy sources. Of particular importance is the creation, investigation, and practical implementation of new types of these converter devices and the principles behind their design [1].

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Currently, extensive scientific research is being conducted on primary conversion devices for measuring and remotely monitoring three-phase reactive power currents in networks with hybrid energy sources. These studies aim to advance the principles of design and application of such devices, as well as to address energy supply challenges through the use of primary conversion equipment for measuring and remotely monitoring reactive power quality indicators in electricity, in pursuit of effective, high-quality, and reliable solutions.

An analysis has shown that the comprehensive application of modern digital technologies for converting primary reactive currents of three-phase electrical networks with hybrid energy sources into secondary signals, as well as the modeling, algorithmization, and analysis of processes in remote measurement and control devices, has not been sufficiently explored. Moreover, issues such as the feasibility of current transmission in electrical networks with hybrid energy sources, structural and parametric studies of current measurement and remote control devices (which represent key electrical quantities), and the development of modern principles for constructing devices that convert three-phase reactive power currents and their implementation in practice, remain insufficiently investigated [2].

2. MATERIALS AND METHODS:

Principles for Constructing Reactive Current Converter Devices for Three-Phase Networks with Isolated Neutrals. The device provides closed magnetic flux loops generated by three-phase reactive power currents. It features extended functional capabilities for adjusting the magnitude and characteristics of unbalanced three-phase currents and is equipped with a magnetic core that includes an adjustable air gap. The construction principles of three-phase reactive power current converters are shown in Figure 1.

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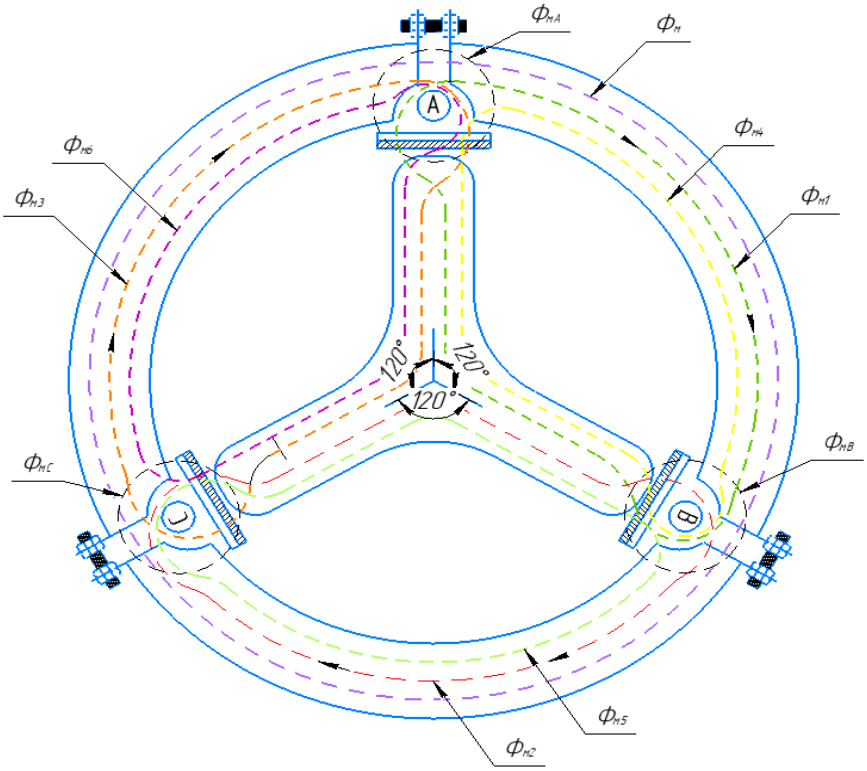

Figure 1. Principles of constructing three-phase reactive power current converters with isolated neutral

Here: ΦμA, ΦμB, ΦμC – the main magnetic fluxes generated by the currents of phases A, B and C of the electrical network, which pass through the corresponding sensing elements; Φμ1, Φμ2, Φμ3, Φμ4, Φμ5, Φμ6 – magnetic fluxes generated by the currents between phases, which are not primary for the sensing elements; δ – the air gap through which the magnetic fluxes pass in the magnetic core.

Research Model. In converting the three-phase primary currents flowing from electrical power supply networks (EPSNs) into secondary voltage or signal form, a signal conversion principle is applied. In particular, when using three simple measuring windings or flat measuring windings in Electromagnetic Devices for Measuring Asymmetric Reactive Power Currents (EDMARPC), the primary currents, the conversion circuit or structure, its geometric shape and dimensions, as well as the applied signal conversion principle based on physical and technical effects, are studied according to the following algorithms [3,4]:

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a) A graph model has been developed for generating the secondary voltage of a single-phase, single-sensing-element device with lumped parameters in a three-phase reactive power current electrical network with an isolated neutral connected to a reactive power source of the electrical power supply network (EPSN) (see Figure 1).

b)

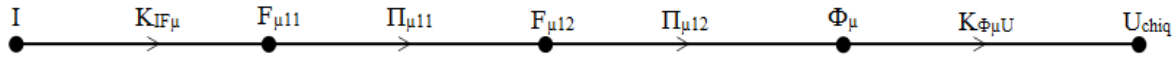

Figure 2. Lumped-parameter graph model for generating the secondary voltage of a three-phase current converter device with isolated neutral

An analytical expression (2) is formulated based on the lumped-parameter graph model for generating the output voltage of a single-phase, single-sensing-element Electromagnetic Device for Measuring Asymmetric Reactive Power Currents (EDMARPC) in an electrical network with an isolated neutral connected to a reactive power source of the electrical power supply network (EPSN) [2, 5-9]:

$$U_{chiq} = W_{IU_{chiq}}(IU_{chiq})I = К_{IF_\mu}П_\mu К_{Ф_\mu U_{chiq}} I = (4.44fw_2w_1/R_\mu)I \quad (1)$$

Here: Transfer function of converting the primary current I into the secondary voltage U_{out} through the conversion element $W_{IU_{chiq}}(IU_{chiq}) = К_{IF_\mu}П_\mu К_{Ф_\mu U_{chiq}}$;

Inter-circuit conversion coefficient from primary current to magnetic flux $К_{IF_\mu}$;

Inter-circuit conversion coefficient from magnetic flux to voltage $К_{Ф_\mu U_{chiq}}$;

I – primary current of the electrical network;

f – frequency of the electrical network current;

w_2,w_1 – number of turns of the primary and secondary windings of the electromagnetic device for measuring asymmetric reactive power currents (EDMARPC);

$П_\mu = R_\mu - \frac{\rho L}{F}$ – resistance of the signal conversion element (magnetic resistance);

ρ – relative resistivity of the magnetic core material;

L – length of the magnetic flux path;

F – geometric cross-sectional area of the magnetic core.

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c) A graph model of the secondary voltage of the EDMARPC with three sensitive elements of a distributed-parameter three-phase reactive power current electric network with an isolated neutral connected to a reactive power source of EPSN has been formed (Figure 3).

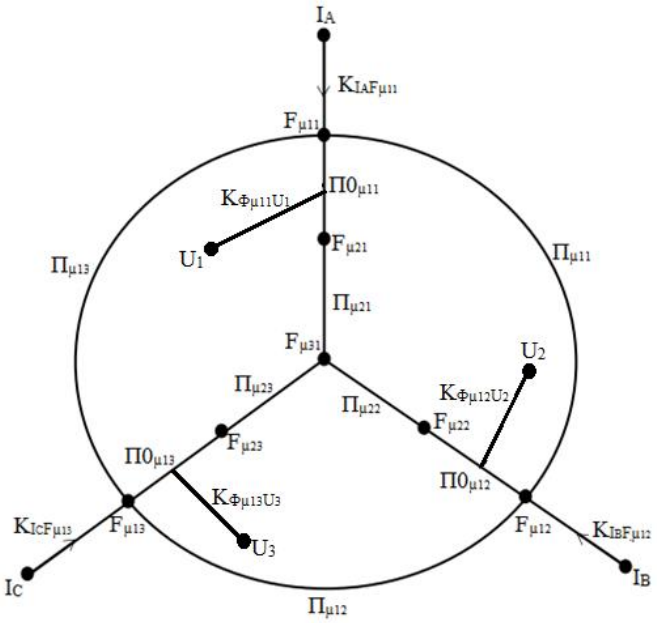

Figure 3. Graph model of the secondary voltage formation of a neutral-isolated three-phase current converter device with distributed parameters.

Based on the graph model of the distributed-parameter three-phase EDMARPC with three sensitive elements, the analytical expression for generating the electromotive forces (EMFs) through the currents takes the following form (2) [8, 9]:

$$\begin{cases} \frac{F_{\mu11}-F_{\mu12}}{\Pi_{\mu11}}+\frac{F_{\mu11}-F_{\mu21}}{\Pi 0_{\mu11}}+\frac{F_{\mu11}-F_{\mu13}}{\Pi_{\mu13}}=K_{I_AF_{\mu11}}I_A; \\ \frac{F_{\mu21}-F_{\mu11}}{\Pi 0_{\mu11}}+\frac{F_{\mu21}-F_{\mu31}}{\Pi_{\mu21}}=0; \\ \frac{F_{\mu12}-F_{\mu11}}{\Pi_{\mu11}}+\frac{F_{\mu12}-F_{\mu22}}{\Pi 0_{\mu12}}+\frac{F_{\mu12}-F_{\mu13}}{\Pi_{\mu12}}=K_{I_BF_{\mu12}}I_B \\ \frac{F_{\mu22}-F_{\mu12}}{\Pi O_{\mu12}}+\frac{F_{\mu22}-F_{\mu31}}{\Pi_{\mu22}}=0; \\ \frac{F_{\mu13}-F_{\mu12}}{\Pi_{\mu12}}+\frac{F_{\mu13}-F_{\mu22}}{\Pi 0_{\mu13}}+\frac{F_{\mu13}-F_{\mu11}}{\Pi_{\mu13}}=K_{I_CF_{\mu13}}I_C \\ \frac{F_{\mu23}-F_{\mu13}}{\Pi 0_{\mu13}}+\frac{F_{\mu28}-F_{\mu13}}{\Pi_{\mu23}}=0; \\ \frac{F_{\mu31}-F_{\mu21}}{\Pi_{\mu21}}+\frac{F_{\mu31}-F_{\mu22}}{\Pi_{\mu22}}+\frac{F_{\mu31}-F_{\mu23}}{\Pi_{\mu23}}=0. \end{cases} \quad (2)$$

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The coefficients (w_a, w_b, w_c) depend on the number of turns of the sensitive elements' windings — $K_{I_A F_{\mu 11}}$, $K_{I_B F_{\mu 12}}$, $K_{I_C F_{\mu 13}}$; the primary currents — I_A, I_B, I_C; the magnetic parameters of the magnetic core (rod) and air gap resistances — Π_{ij}, $\Pi O_{\mu ij}$; the electromotive forces (EMFs) in the device's magnetic core (rod) — $F_{\mu i,j}$.

From the resulting system of seven equations with unknowns, the distribution of the unknown EMFs in the magnetic conversion section is determined according to the magnetic parameters, and the values of the EMFs define the quantities of the transfer functions.

The analytical expressions of the relationships in the conversion process between the primary electric currents — I_A, I_B, I_C, the EMFs — $F_{\mu 11}$, $F_{\mu 12}$, $F_{\mu 13}$ the magnetic fluxes — $\Phi_{\mu 11}$, $\Phi_{\mu 12}$, $\Phi_{\mu 13}$ and the secondary output voltages — U_1, U_2, U_3 are formulated in forms (3), (4), and (5).

$$U_1 = K_{\Phi_{\mu 11} U_1} \Phi_{\mu 11}; \quad (3)$$

$$\Phi_{\mu 11} = \frac{F_{\mu 11} - F_{\mu 21}}{\Pi O_{\mu 11}};$$

$$F_{\mu_{11}} = K_{I_A F_{\mu 11}} I_A.$$

$$U_2 = K_{\Phi_{\mu 12} U_2} \Phi_{\mu 12}; \quad (4)$$

$$\Phi_{\mu 12} = \frac{F_{\mu 12} - F_{\mu 22}}{\Pi O_{\mu 12}};$$

$$F_{\mu 12} = K_{I_B F_{\mu 12}} I_B.$$

$$U_3 = K_{\Phi_{\mu 13} U_3} \Phi_{\mu 13}; \quad (5)$$

$$\Phi_{\mu 13} = \frac{F_{\mu 13} - F_{\mu 23}}{\Pi O_{\mu 13}};$$

$$F_{\mu 13} = K_{I_C F_{\mu 13}} I_C.$$

Using the above expressions, the secondary voltages can be obtained through the electromotive forces (EMFs) generated by the magnetic fluxes as shown in (6), (7), and (8).

$$U_1 = K_{\Phi_{\mu 11} U1} \left(\frac{K_{I_A F \mu 11}}{\Pi O_{\mu 11}} I_A - \frac{F_{\mu 21}}{\Pi O_{\mu 11}} \right); \quad (6)$$

$$U_2 = K_{\Phi_{\mu 12} U_2} \left(\frac{K_{I_A F \mu 12}}{\Pi O_{\mu 12}} I_B - \frac{F_{\mu 22}}{\Pi O_{\mu 12}} \right); \quad (7)$$

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$$U_3 = K_{\Phi_{\mu 13}U_3}\left(\frac{K_{I_C F\mu 13}}{\Pi O_{\mu 13}} I_C - \frac{F_{\mu 23}}{\Pi O_{\mu 13}}\right); \qquad (8)$$

$K_{\Phi_{\mu 11}Ua}$, $K_{\Phi_{\mu 12}U_b}$, $K_{\Phi_{\mu 13}U_c}$, — The mutual coupling coefficient between the secondary output voltages and the magnetic fluxes [2-7].

d) A graph model for generating the secondary voltage of a volumetric distributed-parameter three-phase device with three sensitive elements connected to a reactive power source in a HPS-based neutral-isolated three-phase electric network has been developed (Figure 4).

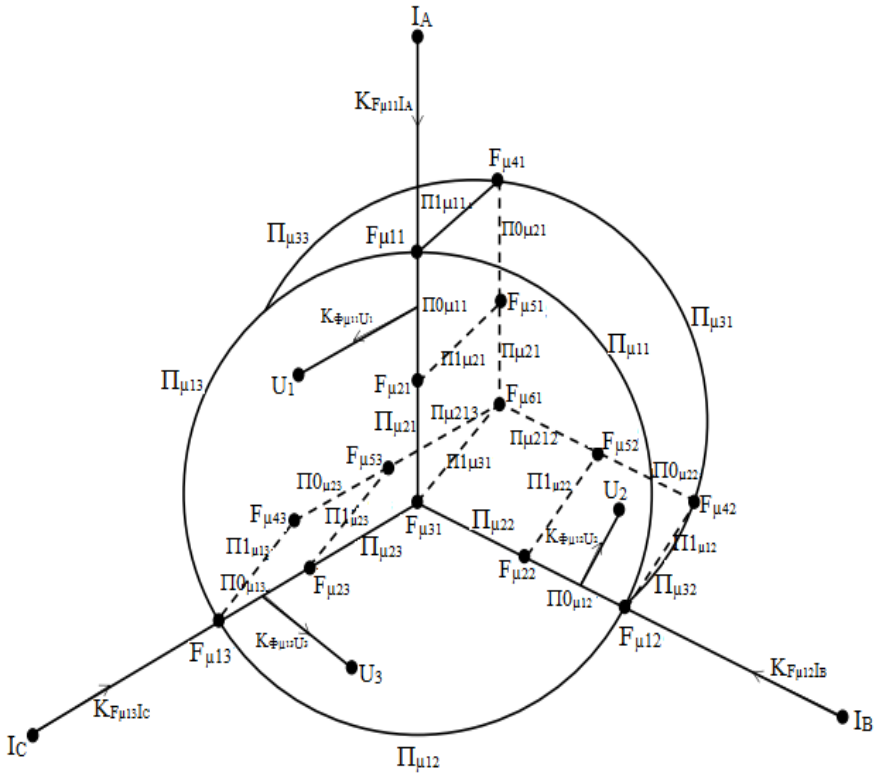

Figure 4. Volumetric distributed-parameter graph model for generating the secondary voltage of a neutral-isolated three-phase current converter device.

Based on the graph model of the volumetric distributed-parameter three-phase EDMARPC with three sensitive elements, the analytical expression for generating the electromotive forces (EMFs) through the currents takes the form of equation (9) [6]:

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$$\begin{cases} \frac{F_{\mu 11}-F_{\mu 12}}{\Pi_{\mu 11}}+\frac{F_{\mu 11}-F_{\mu 121}}{\Pi 0_{\mu 11}}+\frac{F_{\mu 11}-F_{\mu 13}}{\Pi_{\mu 13}}+\frac{F_{\mu 11}-F_{\mu 41}}{\Pi 1_{\mu 11}}=K_{I_A F_{\mu 111}} I_A; \\ \frac{F_{\mu 21}-F_{\mu 11}}{\Pi 0_{\mu 11}}+\frac{F_{\mu 21}-F_{\mu 31}}{\Pi_{\mu 21}}+\frac{F_{\mu 21}-F_{\mu 51}}{\Pi 1_{\mu 21}}=0; \\ \frac{F_{\mu 12}-F_{\mu 11}}{\Pi_{\mu 11}}+\frac{F_{\mu 12}-F_{\mu 22}}{\Pi 0_{\mu 12}}+\frac{F_{\mu 12}-F_{\mu 13}}{\Pi_{\mu 12}}+\frac{F_{\mu 12}-F_{\mu 42}}{\Pi 1_{\mu 12}}=K_{I_B F_{\mu 12}} I_B; \\ \frac{F_{\mu 22}-F_{\mu 12}}{\Pi O_{\mu 12}}+\frac{F_{\mu 22}-F_{\mu 31}}{\Pi_{\mu 22}}+\frac{F_{\mu 22}-F_{\mu 52}}{\Pi 1_{\mu 22}}=0; \\ \frac{F_{\mu 13}-F_{\mu 12}}{\Pi_{\mu 12}}+\frac{F_{\mu 13}-F_{\mu 22}}{\Pi 0_{\mu 13}}+\frac{F_{\mu 13}-F_{\mu 11}}{\Pi_{\mu 13}}+\frac{F_{\mu 13}-F_{\mu 43}}{\Pi 1_{\mu 13}}=K_{I_C F_{\mu 13}} I_C; \\ \frac{F_{\mu 23}-F_{\mu 13}}{\Pi 0_{\mu 13}}+\frac{F_{\mu 28}-F_{\mu 13}}{\Pi_{\mu 23}}+\frac{F_{\mu 23}-F_{\mu 53}}{\Pi 1_{\mu 23}}=0; \\ \frac{F_{\mu 31}-F_{\mu 21}}{\Pi_{\mu 21}}+\frac{F_{\mu 31}-F_{\mu 22}}{\Pi_{\mu 22}}+\frac{F_{\mu 31}-F_{\mu 23}}{\Pi_{\mu 23}}+\frac{F_{\mu 31}-F_{\mu 61}}{\Pi 1_{\mu 31}}=0. \end{cases} \quad (9)$$

The analytical expressions of the relationships in the conversion process between the primary electric currents — I_A, I_B, I_C, the electromotive forces (EMFs) — $F_{\mu 11}$, $F_{\mu 12}$, $F_{\mu 13}$ the magnetic fluxes — $\Phi_{\mu 11}$, $\Phi_{\mu 12}$, $\Phi_{\mu 13}$ and the secondary output voltages — U_1, U_2, U_3 are formulated in forms (10), (11), and (12).

$$U_1 = K_{\Phi_{\mu 11} U_1} \Phi_{\mu 11}; \quad (10)$$

$$\Phi_{\mu 11} = \frac{F_{\mu 11}-F_{\mu 21}}{\Pi O_{\mu 11}}+\frac{F_{\mu 11}-F_{\mu 41}}{\Pi 1_{\mu 11}};$$

$$F_{\mu_{11}} = K_{I_A F_{\mu 11}} I_A.$$

$$U_2 = K_{\Phi_{\mu 12} U_2} \Phi_{\mu 12}; \quad (11)$$

$$\Phi_{\mu 12} = \frac{F_{\mu 12}-F_{\mu 22}}{\Pi O_{\mu 12}}+\frac{F_{\mu 12}-F_{\mu 42}}{\Pi 1_{\mu 12}};$$

$$F_{\mu 12} = K_{I_B F_{\mu 12}} I_B.$$

$$U_3 = K_{\Phi_{\mu 13} U_3} \Phi_{\mu 13}; \quad (12)$$

$$\Phi_{\mu 13} = \frac{F_{\mu 13}-F_{\mu 23}}{\Pi O_{\mu 13}}+\frac{F_{\mu 13}-F_{\mu 43}}{\Pi 1_{\mu 13}};$$

$$F_{\mu 13} = K_{I_C F_{\mu 13}} I_C.$$

Using the above expressions, the secondary voltages can be obtained through the electromotive forces (EMFs) generated by the magnetic fluxes as shown in (13), (14), and (15).

$$U_1 = K_{\Phi_{\mu 11} U1} \left(\frac{K_{I_A F \mu 11}}{\Pi O_{\mu 11}} I_A - \frac{F_{\mu 21}}{\Pi O_{\mu 11}} - \frac{F_{\mu 41}}{\Pi 1_{\mu 11}} \right); \quad (13)$$

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$$U_2 = K_{\Phi_{\mu 12}U_2}\left(\frac{K_{I_A}F_{\mu 12}}{ПО_{\mu 12}}I_B - \frac{F_{\mu 22}}{ПО_{\mu 12}} - \frac{F_{\mu 42}}{П1_{\mu 12}}\right); \quad (14)$$

$$U_3 = K_{\Phi_{\mu 13}U_3}\left(\frac{K_{I_C}F_{\mu 13}}{ПО_{\mu 13}}I_C - \frac{F_{\mu 23}}{ПО_{\mu 13}} - \frac{F_{\mu 43}}{П1_{\mu 13}}\right); \quad (15)$$

3. RESULTS AND DISCUSSION:

In the presented model, the primary variables are taken as I_A, I_B, I_C - primary currents (within the range of 1-131.5 amperes). W_A, W_B, W_C — number of turns of the input windings (1-3 turns), W_1, W_2, W_3 - number of turns of the output windings of the sensitive elements (1-9 turns).

Research was conducted based on the model by varying the winding range, and the theoretical and practical results were relatively compared with the output signals of classical current transformers (Figure 5).

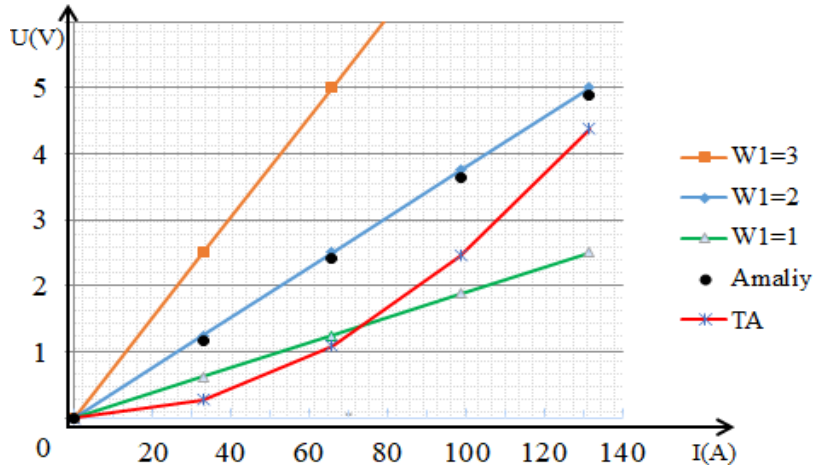

Figure 5. Relative static characteristic expressing the dependence of the secondary output signal of neutral-isolated three-phase current conductors on the reactive power primary currents I = 131.5 A in the electric network.

Here, **W1** — the dependence characteristic of the output voltage on the variation of current strength obtained from the lumped parameter model based on the change in the number of secondary windings turns (according to equation's 13, 14, 15 the variation of the output voltage corresponding to the current I_A). **TA** — the practical characteristic of classical current transformers.

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The table of output voltage variation depending on the number of turns of the sensitive element windings when the input current is I = 131.5 A is as follows (Table 1):

Table 1 Variation of the output voltage depending on the number of turns of the sensitive element windings when the input current is I = 131.5 A.

Primary Currents – I [A]	Secondary Voltage Signals – U [V] (Theoretical)	Secondary Voltage Signals – U [V] (Practical)	Secondary Voltage Signals – U [V] (Classical Current Transformers)	Number of Sensitive Element Turns – W2
32,87	1,25	1,162	0,27	3
65,75	2,5	2,441	1,09	5
98,62	3,75	3,641	2,46	7
131,5	5	4,88	4,37	9

The comparison results show that the adequacy between the theoretical and practical measurement results of the output signal of the GEM-based reactive power current converter device in the electric network is **2.4%** for the neutral-isolated three-phase device. Moreover, compared to the practical results of classical current transformers, the neutral-isolated three-phase device shows an improvement of **10.4%**.

$$\delta_{NUF} = \frac{U_{nazariy} - U_{amaliy}}{U_{nazariy}} 100\% = \frac{5 - 4{,}88}{5} 100\% = 2{,}4\ \%,$$

$$\delta_{NUF} = \frac{U_{amaliy} - U_{TA\ amaliy}}{U_{amaliy}} 100\% = \frac{4.88 - 4{,}37}{4.88} 100\% = 10{,}4\ \%.$$

4. CONCLUSION:

1. In electromagnetic current-to-voltage converters, the method for calculating the values of the output voltages U_1, U_2, and U_3 generated in the sensitive elements - based on the criterion of uniform and orthogonal distribution of the magnetic flux crossing the surface of the converter's sensitive elements, as well as the values of the magnetomotive force and magnetic flux in the converter sections - has been developed using distributed parameter graph models.

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2. The distributed parameter graph model of GEM-based three-phase reactive power current devices and their corresponding mathematical models have been proven to be adequate in representing the real linear output characteristics of the devices. For the neutral-isolated three-phase network, the conversion accuracy of the developed device was improved by **2.4%** compared to the lumped parameter model and by **10.4%** compared to the classical current transformer.

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