Errors of sensors for conversion of multi-phase currents into voltage in power supply systems

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Abstract. The paper presents the structure of the sensor for converting multi-phase primary currents into secondary voltages of reactive power of power supply networks, the algorithm for modeling processes in the sensor that sends a signal to the primary current monitoring and control devices provides a highly formalized graph model based on an analytical expression, static characteristics and sensor errors studied on the basis of its analytic expression. **Keywords:** Polyphase, power, primary currents, sensor, control, signal, static characteristic, graph model.

1 Introduction

New designs, principles of operation and algorithms, software for primary sensors that determine the accuracy, speed, reliability, magnitude and parameters of reactive power (RP) and energy management, which are difficult to produce in power supply based on power supply systems (PSS), software and special attention is given to the development of technological tools. In developed countries, including the United States, Germany, France, Sweden, Italy, Japan, China, Korea and Russia, one of the important tasks is to develop models of primary sensors of reactive magnitude and parameters of power supply systems, study the design principles and apply them in practice.

To study the processes of converting the reactive power of a multi-phase primary current into a secondary voltage in power supply systems at the present time. Extensive research is being carried out to develop the principles of their design and operation, to find solutions to the problems of efficient, high-quality and reliable power supply based on multi-phase sensors of primary current to secondary voltage, used in the management of power quality indicators.

The analysis showed that the complex application of modern methods and technologies in the study of sensor models for the conversion of multiphase primary currents into secondary voltages of reactive power of power supply systems, modeling, algorithms and research of control and monitoring devices and their processes, identification, issues of structural and parametric research of control and management devices , the development and

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implementation of new principles for the design of sensors for monitoring and controlling reactive power and devices that determine the quality of electricity have not been sufficiently studied.

PSS of reactive power sources A polyphase primary current sensor, like other primary measuring instruments, is characterized by errors: in a real sensor, the value of primary currents differs from the value generated by the conversion into secondary values. The magnetic susceptibility of alternating current, geometric dimensions, the influence of external magnetic fields and other factors that are characteristics of alternating currents of alternating current, one way or another cause the process of signal conversion in the sensor to differ from reality. These conditions determine the signal conversion errors in the sensor [1].

When analyzing sources of errors that negatively affect the process of signal conversion, it is necessary to separate them into primary and secondary sources of errors based on the function of determining the accuracy of the sensor. It is known that the main sources of errors are identified under normal conditions of use of primary measuring-variable sensors [2-5].

The main and additional error sources of a polyphase primary current sensor are divided into regular and random errors. The dependence of the process of change on the regulation range of the regulated primary multiphase currents, the non-linearity of the characteristics of the magnetic resistance of steel, the uncertainty of the characteristics of the magnetic permeability of the magnetic circuit and rods are sources of design errors of the multiphase primary current sensor. These errors can be completely eliminated or minimized in various ways [3].

2 Materials and methods

Signaling conversion process. The study of the dynamic characteristics of sensors for converting reactive power sources of PSS of primary currents into secondary voltages must be determined, $I_э$ - sensor with primary currents, $U_{эч}$ - generation of output voltages, Φ_μ - magnetic sensitive elements, $S_{CЭ}$ - cross-sectional area, $w_{сэ}$ - number of turns of the sensing element, depend whether the geometric dimensions of the section $l_{x.o}$ where the sensitive elements are located in the magnetic replaceable part, from the allowable ranges of change and variable geometric dimensions of the magnetic circuit [1-3].

The shapes of the magnetic conversion sections - the magnetic cores of the sensor of multi-phase primary currents - $I_{A\gamma}, I_{B\gamma}, I_{C\gamma}, I_{A\Delta}, I_{B\Delta}, I_{C\Delta}$- from the reactive power source of PSS, are shown in Fig. 1

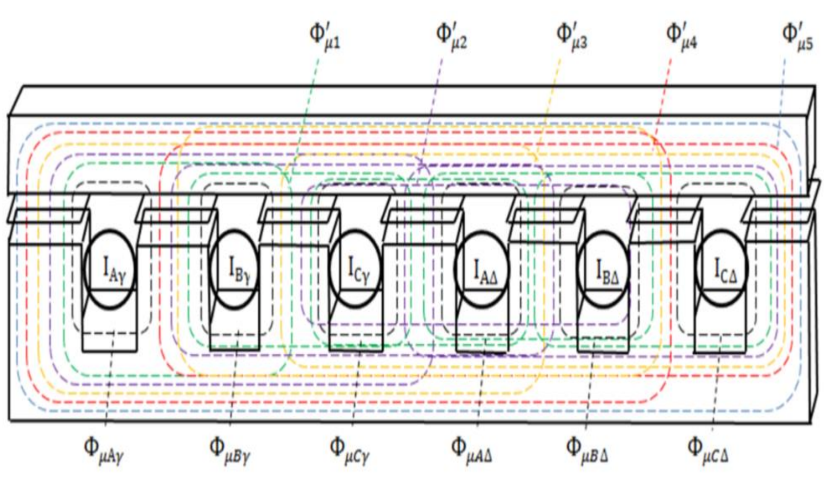

Fig. 1. Forms of magnetic conversion sections - magnetic circuits of the sensor of multiphase primary currents.

Primary currents of PSS reactive power sources - the first $I_{A\gamma}$, the second $I_{B\gamma}$, the third $I_{C\gamma}$, the fourth $I_{A\Delta}$, the fifth $I_{B\Delta}$, or the sixth $I_{C\Delta}$ when flowing through the excitation coils in the common magnetic circuit and parallel cores, magnetic fluxes $\Phi_{\mu A\gamma}$, $\Phi_{\mu B\gamma}$, $\Phi_{\mu C\gamma}$, $\Phi_{\mu A\Delta}$, $\Phi_{\mu B\Delta}$and $\Phi_{\mu C\Delta}$which also flow through the air gap between the cores.

Magnetic currents $\Phi_{\mu A\gamma}$, $\Phi_{\mu B\gamma}$, $\Phi_{\mu C\gamma}$, $\Phi_{\mu A\Delta}$, $\Phi_{\mu B\Delta}$and $\Phi_{\mu C\Delta}$ of the switching sensor, outputting a signal in the form of a secondary voltage for monitoring and controlling the primary currents of reactive power sources of PSS, reactive power sources, star-connected single-phase $I_{A\gamma}$, two-phase $I_{A\gamma}$, $I_{B\gamma}$ or $I_{B\gamma}$, $I_{C\gamma}$and three-phase $I_{A\gamma}$, $I_{B\gamma}$, $I_{C\gamma}$and triangle-connected single-phase $I_{A\Delta}$, two-phase $I_{A\Delta}$, $I_{B\Delta}$or $I_{B\Delta}$, $I_{C\Delta}$and three-phase $U_{a\gamma}$, $U_{в\gamma}$, $U_{c\gamma}$, $U_{a\Delta}$, $U_{в\Delta}$, and $U_{c\Delta}$- output voltages in values corresponding to the currents of reactive power sources at the outputs of the sensitive element (simple or flat measuring tape, hermetically sealed, etc.) by creating currents $I_{A\Delta}$, $I_{B\Delta}$, $I_{C\Delta}$ forms signals in the form.

Research model. On Fig. 2 shows a graph model corresponding to the structure of the magnetic part of the switching sensor, which outputs a signal in the form of a secondary voltage for monitoring and controlling the primary currents of the PSS reactive power sources and the processes occurring in them, magnetic switching part [6,8].

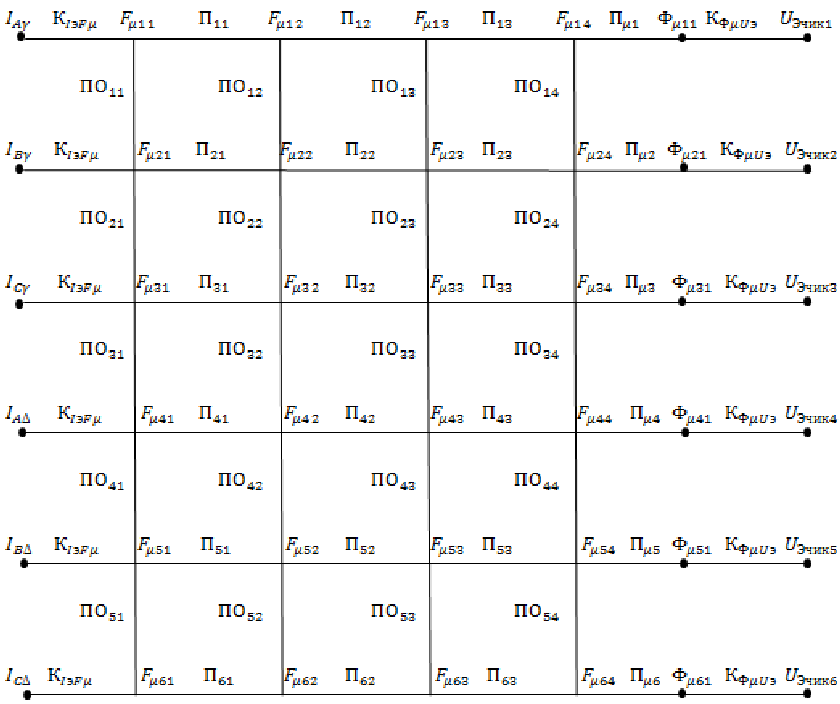

Fig. 2. The process of converting multi-phase primary currents into secondary voltage and a model of the sensor conversion structure.

In the graph model corresponding to the structure of the magnetic part of the sensor and reflecting the processes occurring in the part of the magnetic transformation, one can take $K_{\Phi\mu Uэ} = w_{2ч}$ - Φ_{μ}- the coefficient of the relationship between magnetic fluxes and Uech - output voltages. values up to $w_{2ч}$=1÷20 turns as needed [4-6].

Analytic expressions of static descriptions. When analyzing the static characteristics of sensors that convert the current value into an output signal in the form of voltage $U_{эч}$, output voltages in the form of multiphase signals $I_э$ into primary input currents, the cross-sectional surfaces of sensitive elements - $S_{CЭ}$, the number of turns of sensitive elements (simple or flat measuring coils) - $w_{CЭ}$ is necessary determine whether the geometric dimensions of the air gap between the magnetic rod depend, i.e. sensitive element, on the range of change $l_{x.o}$and the parameters of the magnetic circuit [8-10].

Statistical, dynamic and metrological characteristics of PSS reactive power sources based on conversion processes occurring in the structure of the sensor of multiphase primary currents into a secondary signal in the form of voltage are studied on the basis of a graph model with distributed parameters (Fig. 2) and the following analytical expression:

$$\begin{cases} U_{a\gamma} = K_{\Phi\mu U э}\Pi_{\mu 1}(W(F_{\mu 11}, F_{\mu 14})K_{IэF\,\mu}I_{A\gamma} + W(F_{\mu 21}, F_{\mu 14})K_{IэF\,\mu}I_{B\gamma} + \\ \quad +W(F_{\mu 31}, F_{\mu 14})K_{IэF\,\mu}I_{C\gamma} + W(F_{\mu 41}, F_{\mu 14})K_{IэF\,\mu}I_{A\Delta} + \\ \quad +W(F_{\mu 51}, F_{\mu 14})K_{IэF\,\mu}I_{B\Delta} + W(F_{\mu 61}, F_{\mu 14})K_{IэF\,\mu}I_{C\Delta}); \\ U_{b\gamma} = K_{\Phi\mu U э}\Pi_{\mu 2}(W(F_{\mu 21}, F_{\mu 24})K_{IэF\,\mu}I_{B\gamma} + W(F_{\mu 11}, F_{\mu 24})K_{IэF\,\mu}I_{A\gamma} + \\ \quad +W(F_{\mu 31}, F_{\mu 24})K_{IэF\,\mu}I_{C\gamma} + W(F_{\mu 41}, F_{\mu 24})K_{IэF\,\mu}I_{A\Delta} + \\ \quad +W(F_{\mu 51}, F_{\mu 24})K_{IэF\,\mu}I_{B\Delta} + W(F_{\mu 61}, F_{\mu 24})K_{IэF\,\mu}I_{C\Delta}); \\ U_{c\gamma} = K_{\Phi\mu U э}\Pi_{\mu 2}(W(F_{\mu 31}, F_{\mu 34})K_{IэF\,\mu}I_{C\gamma} + W(F_{\mu 11}, F_{\mu 34})K_{IэF\,\mu}I_{A\gamma} + \\ \quad +W(F_{\mu 21}, F_{\mu 34})K_{IэF\,\mu}I_{B\gamma} + W(F_{\mu 41}, F_{\mu 34})K_{IэF\,\mu}I_{A\Delta} + \\ \quad +W(F_{\mu 51}, F_{\mu 34})K_{IэF\,\mu}I_{B\Delta} + W(F_{\mu 61}, F_{\mu 34})K_{IэF\,\mu}I_{C\Delta}); \\ U_{a\Delta} = K_{\Phi\mu U э}\Pi_{\mu 2}(W(F_{\mu 41}, F_{\mu 44})K_{IэF\,\mu}I_{A\Delta} + W(F_{\mu 11}, F_{\mu 44})K_{IэF\,\mu}I_{A\gamma} + \\ \quad +W(F_{\mu 21}, F_{\mu 44})K_{IэF\,\mu}I_{B\gamma} + W(F_{\mu 31}, F_{\mu 44})K_{IэF\,\mu}I_{C\gamma} + \\ \quad +W(F_{\mu 51}, F_{\mu 44})K_{IэF\,\mu}I_{B\Delta} + W(F_{\mu 61}, F_{\mu 44})K_{IэF\,\mu}I_{C\Delta}); \\ U_{b\Delta} = K_{\Phi\mu U э}\Pi_{\mu 5}(W(F_{\mu 51}, F_{\mu 54})K_{IэF\,\mu}I_{B\Delta} + W(F_{\mu 11}, F_{\mu 54})K_{IэF\,\mu}I_{A\gamma} + \\ \quad +W(F_{\mu 21}, F_{\mu 54})K_{IэF\,\mu}I_{B\gamma} + W(F_{\mu 31}, F_{\mu 54})K_{IэF\,\mu}I_{C\gamma} + \\ \quad +W(F_{\mu 41}, F_{\mu 54})K_{IэF\,\mu}I_{A\Delta} + W(F_{\mu 61}, F_{\mu 54})K_{IэF\,\mu}I_{C\Delta}); \\ U_{c\Delta} = K_{\Phi\mu U э}\Pi_{\mu 5}(W(F_{\mu 61}, F_{\mu 64})K_{IэF\,\mu}I_{C\Delta} + W(F_{\mu 11}, F_{\mu 64})K_{IэF\,\mu}I_{A\gamma} + \\ \quad +W(F_{\mu 21}, F_{\mu 64})K_{IэF\,\mu}I_{B\gamma} + W(F_{\mu 31}, F_{\mu 64})K_{IэF\,\mu}I_{C\gamma} + \\ \quad +W(F_{\mu 41}, F_{\mu 64})K_{IэF\,\mu}I_{A\Delta} + W(F_{\mu 51}, F_{\mu 64})K_{IэF\,\mu}I_{B\Delta}); \end{cases} \tag{1}$$

Where$K_{\Phi\mu U э} = \omega_{2ч}$is the co-factor of the intercircuit connection between the mutually influencing magnetic fluxes $-\ \Phi_{\mu}$and the output voltage $U_{Эч}$;

$\Pi_{\mu j} = \frac{\mu_0 F_j}{\delta_{\mu j}}$ (j=$\overline{1.6}$) - magnetic parameter of the changing part of the sensor, which forms the output voltage $U_{Эч}$ (μ_0- magnetic absorption of air gaps with a sensitive element);

$\mu_0 = 1.25 * 10^{-6}Г/м)$;

Takes values up to $\omega_{2ч}$=1÷20 turns based on the requirement of output voltage modeling at nominal values of primary currents (20 V);

F- cross-sectional area of air gaps where sensitive elements are installed, for example: ab=0.01*0.01 $м^2$;

δ_{μ}- heights of air gaps with sensitive elements (м);

$W(F_{\mu ij}, F_{\mu in})$- is determined based on the decision of the signal function of the magnetic switching element;

$K_{IэF\,\mu}\ - \omega_{jk} - I_э\ -PSSF_{\mu}$- interchain coefficient between, usually $\omega_{jk} = 1$;

$I_{A\gamma}, I_{B\gamma}, I_{C\gamma}, I_{A\Delta}, I_{B\Delta}, I_{C\Delta}$ – multiphase primary reactive currents fed by reactive power sources connected to networks according to the schemes γ "va Δ" [7].

In particular, the magnitude of the output voltages $U_{a\gamma}, U_{b\gamma}, U_{c\gamma}, U_{a\Delta}, U_{b\Delta}, U_{c\Delta}$ depends mainly on the currents $I_{A\gamma}, I_{B\gamma}, I_{C\gamma}, I_{A\Delta}, I_{B\Delta}, I_{C\Delta}$ which are obtained from the network phases of their respective reactive powers:

$$\begin{cases} U_{a\gamma} = K_{\Phi\mu U Э}\Pi_{\mu 1}(W\big(F_{\mu 11}, F_{\mu 14}\big)K_{IЭF\ \mu}I_{A\gamma}; \\ U_{b\gamma} = K_{\Phi\mu U Э}\Pi_{\mu 2}(W\big(F_{\mu 21}, F_{\mu 24}\big)K_{IЭF\ \mu}I_{B\gamma}; \\ U_{c\gamma} = K_{\Phi\mu U Э}\Pi_{\mu 3}(W\big(F_{\mu 31}, F_{\mu 34}\big)K_{IЭF\ \mu}I_{C\gamma}; \\ U_{a\Delta} = K_{\Phi\mu U Э}\Pi_{\mu 4}(W\big(F_{\mu 41}, F_{\mu 44}\big)K_{IЭF\ \mu}I_{A\Delta}; \\ U_{b\Delta} = K_{\Phi\mu U Э}\Pi_{\mu 5}(W\big(F_{\mu 51}, F_{\mu 54}\big)K_{IЭF\ \mu}I_{B\Delta}; \\ U_{c\Delta} = K_{\Phi\mu U Э}\Pi_{\mu 6}(W\big(F_{\mu 61}, F_{\mu 64}\big)K_{IЭF\ \mu}I_{C\Delta}. \end{cases} \tag{2}$$

Based on the above formulas (1 and 2), the dependence between the single-phase current of the source RP of the PSS network and the output voltage of the sensor is shown in Fig.3 as a static description.

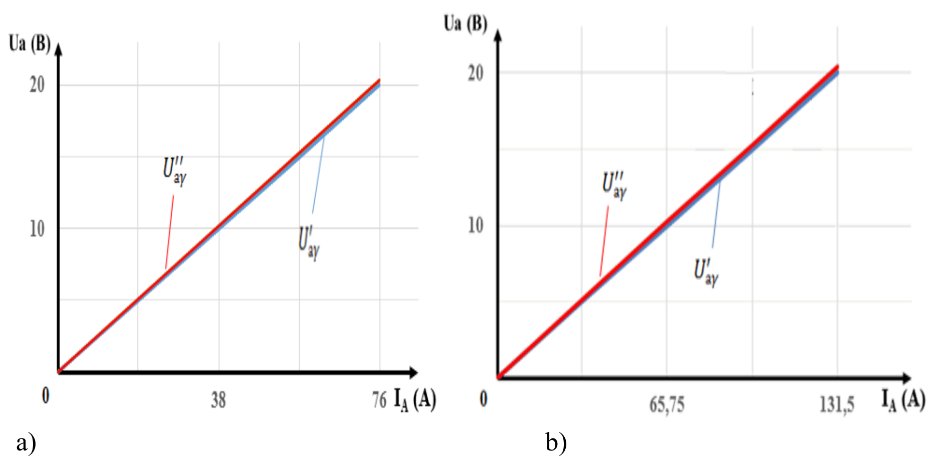

Fig. 3. Static characteristics of the connections between single-phase primary currents of the reactive currents of the PSS network and the output voltage of the sensor a) The source of reactive power is connected by a star. b) Delta connected reactive power source.

Where $U'_{a\gamma}$- description of the change in the output voltage, obtained on the basis of the assembled parametric model (based on the system of equations 1 $I_{A\gamma}$, $I_{A\Delta}$ - change in the output voltage corresponding to the currents, i.e. the reactive power source is connected in a star and a delta), $U''_{a\gamma}$- description of the change in the output voltage based on a distributed parametric model (static characteristics of the change in the output voltage, corresponding to the currents $I_{A\gamma}$, $I_{A\Delta}$based on a system of equations).

On the basis of the static characteristics presented in figures (3a) and (3b), the metrological characteristics of the multi-phase sensor for converting the primary current into the secondary voltage of the PSS RP were studied: the accuracy of the change, the linearity of the output characteristic, and the uniformity of the sensor. sensitivity over the entire range.

3 Results and discussion

To the sources of errors in the input-switching part of the multi-phase primary current sensor of reactive power sources PSS, I_{Ek} - multi-phase primary currents under the influence of temperature, humidity, external magnetic fields and other factors, ω - electric current frequency, W [I_E, F_μ] connections of various nature, coefficients, as well as the physical properties of the materials of the conductors and the excitation coil.

To estimate the cumulative error of the polyphase sensor of the primary current of the PSS reactive power source, change the $I_Э$ of the primary currents to m.f.s. which is the value of the magnetic conversion factor F_μ, i.e. $I_Э \rightarrow F_\mu$conversion errors, i.e. $\delta_1 = 0.1$ - (deviation of electrical and magnetic values from the initial nominal value by ± 0.1% of the limit values [5].

F_μ - m.f.s. in scattered fragments of parameter changes Φμ - conversion particles generate magnetic fluxes - i.e., $F_\mu \rightarrow \Phi_\mu$ - conversion errors, i.e. $\delta_2 = 0.1$ - (in this part of the change, the deviation of magnetic values from the nominal value by ±0.1% based on the distribution of parameters) change in the magnetic fluxes of particles of change Φ_μ per $U_{эч}$ - output voltage, i.e. $F_\mu \rightarrow U_{эч}$, - are determined based on small errors, i.e. $\delta_3 = 0.1$ and $\delta_4 = 0.1$ [10].

$$\delta_\Sigma = \sqrt{\delta_1^{\ 2} + \delta_2^2 + \delta_3^2 + \delta_4^2} = \sqrt{0.1^2 + 0.1^2 + 0.1^2 + 0.1^2} = 0.2. \quad (3)$$

All components of the errors of multiphase primary current sensors PSS are divided into types

of additive and multiplicative errors, and the probability of occurrence is found by their standard deviation according to the distribution law.

The entropy deviation of the error of the sensor of multi-phase current of reactive power sources of PSS is determined on the basis of the following formula [10].

$$\Delta = K_э \delta_\Sigma = 2.07 \text{ x } 0.2 = 0.41. \quad (4)$$

As a result of calculations and experiments, the entropy error of the electromagnetic sensor is Δ = 0.41 i.e., ± 0.41%, and the normalized value of the sensor accuracy can be selected from the numbers specified in the standard. The standard accuracy class of the polyphase primary current sensor of this series of reactive power sources is 0.5 i.e., ±0.5% [10].

In connection with the widespread introduction of microprocessor devices and electronic meters in the control and management of PSS reactive power, it is important to supply sensors and electronic data processing devices with normalized voltage (20 V) and current (0.1 A) and ensure their accuracy.

Analytical expressions (1) and (2) of the change in the signal for a single-phase current in the graph model of the sensor and the data of Figures 3a and 3b are recommended to be used to analyze and evaluate the errors of the reactive energy sources of the multi-phase primary current conversion sensor PSS.

According to the values $I_{A\gamma}, U'_{a\gamma}, U''_{a\gamma}$, based on Figure 3a, the indicators of errors in changing the sensor of multi-phase currents of reactive power sources of PSS, corresponding to the points of static characteristics, are:

$$I_{A\gamma} = 38\ \text{A}; \qquad U'_{a\gamma} = 10\ \text{B}; \qquad U''_{a\gamma} = 10.18\ \text{B};$$

$$\Delta = \frac{(U''_{a\gamma} - U'_{a\gamma})}{U'_{a\gamma}} * 100\% = \frac{(10.18 - 10)}{10} * 100\% = 1.8\%\,. \tag{4}$$

$$I_{A\gamma} = 76\ \text{A}; \qquad U'_{a\gamma} = 20\ \text{B}; \qquad U''_{a\gamma} = 20.37\ \text{B};$$

$$\Delta = \frac{(U''_{a\gamma} - U'_{a\gamma})}{U'_{a\gamma}} * 100\% = \frac{(20.37 - 20)}{20} * 100\% = 1.81\%\,. \tag{5}$$

Based on the calculated data, it can be concluded that the distributed parametric graph model of the multiphase primary reactive power current sensor of the solar power plant, the analytical expression formed on its basis and the graphic descriptions obtained from them are adequate, according to the results of the study of the sensor structure, it was possible to increase by 1.8%.

For the case when the capacitors of SPP reactive power sources are connected in a triangular shape, the conversion error indicators corresponding to the points of static characteristics were calculated based on the sizes $I_{A\Delta}$,$U'_{a\Delta}$,$U''_{a\Delta}$:

$$I_{A\Delta} = 65.75\ \text{A}; \qquad U'_{a\Delta} = 10\ \text{B}; \qquad U''_{a\Delta} = 10.184\ \text{B};$$

$$\Delta = \frac{(U''_{a\Delta} - U'_{a\Delta})}{U'_{a\Delta}} * 100\% = \frac{(10.184 - 10)}{10} * 100\% = 1.8\ \%\,; \tag{6}$$

$$I_{A\Delta} = 131.5\ \text{A}; \qquad U'_{a\Delta} = 20\ \text{B}; \qquad U''_{a\Delta} = 20.369\ \text{B};$$

$$\Delta = \frac{(U''_{a\Delta} - U'_{a\Delta})}{U'_{a\Delta}} * 100\% = \frac{(20.369 - 20)}{20} * 100\% = 1.8\ \%\,; \tag{7}$$

The results obtained here also show that the distributed parametric graph model of the multiphase primary current sensor generated by the PSS reactive power sources and the analytical expression based on it are adequate to the actual linear output characteristics of the sensor, which makes it possible to improve the accuracy of the sensor by 1.8%.

The input circuit of the multi-phase primary current sensor of the PSS reactive power sources is presented in the graph model $I_{Э1}$, U_{μ} (Fig. 2.2), in which $I_Э$ (I_A, I_B, I_A) multi-phase currents F_{μ} are converted into magnetic driving forces. The given share of signal change K [$I_Э$, F_{μ}] is reflected by the coefficient of contact between the electric and magnetic circuits [10]. In modifications F_{μ} and Φ, magnetic driving forces F_{μ} are converted into magnetic fluxes F_{μ} in modifications, its transfer function of modifications W_{μ} and $П_{\mu}$ reflects the parameters of the structure of the magnetic modification.

4 Conclusion

1. Analysis of the processes of signal conversion and sensitive elements in electromagnetic sensors for controlling multi-phase current and controlling reactive power sources of PSS is defined to meet the basic requirements, such as converting multi-phase primary currents into secondary voltages and speeds.
2. It has been established that the conversion of multi-phase primary currents of reactive power sources into secondary voltage is the entropy error of the electromagnetic sensor was

Δ = 0.41, i.e., ± 0.41%, which provides the standard accuracy class for these types of sensor, which is less than 0.5.

3. Models of sensors for multiphase primary currents generated by reactive power sources have been developed with the possibility of connecting according to the “star - Y” and “triangle - Δ” schemes, which make it possible to control the generated reactive power, compare the characteristics of the input current from the output voltage, a linear output signal, which increases the accuracy of the sensor by 1.8%.

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