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# ERROR OF ELECTROMAGNETIC CONVERTERS WITH EXPANDED FUNCTIONAL CAPABILITIES IN THE CONTROL OF REACTIVE POWER CURRENTS

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## Abstract

Extensive scientific research and investigations are being carried out to improve devices aimed at generating reactive power in power supply systems, measuring and remotely monitoring reactive power currents flowing through networks, improving the quality and efficiency of electrical energy through these measures, and ensuring the stable and uninterrupted operation of electrical networks. In this direction, it is necessary to ensure the reliable operating condition of power supply system networks, determine the quantity and quality of three-phase reactive power currents of the generated electrical energy, and develop elements, models, research algorithms, and software for primary current electromagnetic converter devices of reactive power sources.

At present, extensive scientific research is being conducted on the investigation of primary converter devices for measurement and control systems of three-phase reactive power currents in electrical network systems, the development of their structural and application principles, and the effective, high-quality, and reliable solution of energy supply problems based on primary current converter devices intended for measuring and remotely monitoring the quality and efficiency indicators of electrical energy.



The analysis showed that the issues of comprehensive application of modern digital techniques and technologies in converting three-phase primary reactive power currents of hybrid energy source electrical networks into secondary signals, as well as modeling, algorithmization, and investigation of measurement and remote monitoring devices and their processes, have not been sufficiently studied. At the same time, the issues of determining the capability of hybrid energy source electrical networks to transmit reactive power currents, conducting structural and parametric studies of current measurement and remote monitoring devices, and developing and implementing modern structural principles of converters and devices for reactive power currents that determine electrical energy quality, have not been adequately investigated.

## **MATERIALS AND METHODS**

Reactive power quantities act as a deterministic factor for electrical power supply system networks (EPSSN), serving to optimize the quality of electrical energy, the stability of the transmission process, and the overall economic efficiency of the system by increasing the efficiency coefficient of electrical networks. Currently, the growth of reactive power consumption significantly exceeds the growth of active power consumption, and in some enterprises the reactive load reaches 130% relative to the active load [1]. The transmission of reactive power over long distances reduces the technical and economic efficiency of the power supply system, leading to additional energy losses and overloads [2].

In EPSSNs, active power is mainly generated by centralized power supply (CPS) generators and hybrid energy sources (HES), while reactive power is produced by capacitor banks, station generators, synchronous compensators, and synchronous drives, which are considered reactive power sources, and is transmitted through power transmission lines. Based on the results of investigating a current converter device that converts three-phase reactive currents into voltage-form signals for remote measurement and monitoring of reactive power in EPSSNs, experimental studies were carried out using a measuring sensitive element according to the following scheme to obtain a standardized 5 V output voltage [3].

Based on the results of research on devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-



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neutral electrical power supply system networks, the joint dynamic characteristics of the voltage variation over time at the sensitive element located between the main stationary and movable magnetic cores of the electromagnetic current converter device were analyzed. In the process of converting three-phase reactive currents into secondary voltage-form signals, active, inductive, capacitive loads, and asynchronous motors were connected in order to control the magnetic flux generated by the primary reactive currents depending on the magnitude of the total output current [8].

From theoretical and practical experimental studies, it can be concluded that, in remote measurement and monitoring of reactive power in EPSSNs, in order to obtain a standardized 5 V voltage according to the requirements imposed on measuring sensitive elements, the system ensures this by controlling the magnetic flux generated by reactive currents depending on the sensitivity of changes in the primary currents of reactive power sources and the magnitude of the total output current.

The technical characteristics of single-phase and three-phase reactive electromagnetic current converter devices for EPSSNs include the following parameters: the connection group of the current converter device used for converting primary currents into secondary output voltage signals, cross-sectional area, the material of manufacture (copper or aluminum), linearity of the static characteristic, transition of the dynamic characteristic to a steady-state mode within a short time interval, and metrological characteristics. In accordance with the requirements of remote measurement and monitoring devices, the most important indicators are high accuracy class, compact structure, and economic affordability [4].

The errors of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks were investigated in the form of absolute, relative, and reduced errors [3, 5, 6].

In linearizing the static characteristic of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral networks of the electrical power supply system, when only the first component of the error  $U_k = \pm \Delta U_0$  exists, which does not depend on the value of



the measured quantity (additive error component), the relative error is determined as:  $\Delta_0 = \pm \frac{\Delta U_0}{U_k}$  Only the second component of the error is dependent on the measured quantity and is considered a multiplicative error component. In this case, the current value of the absolute error is expressed as:  $\Delta_a = \Delta_{nx}$  and the value of the relative error is:  $\Delta_a = \Delta_x$  where  $\Delta_n = \text{IoT}$  is the relative sensitivity variation error of the IoT-based isolated-neutral three-phase current converter device [2, 9].

To initially determine the measurement error of data obtained from devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks, the normalized value of the error was used. The normalized error value refers to the error assigned to a given measuring device. The errors of individually considered measuring devices are not identical, and the distributions of systematic and random errors may vary. However, in general, the total error of the measuring device should not exceed the normalized value. Information regarding the error limits and influencing coefficients of each measuring device is provided in the technical documentation of the measuring instrument.

The accuracy class of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks is a generalized characteristic of the converter device that reflects its degree of accuracy. It is determined based on the limits of the main and additional errors, as well as other characteristics affecting the accuracy of the measuring instrument [3, 9, 11].

According to the standard, the following accuracy classes are used in devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks:

$$\delta_{a.k} \in \{0,02; 0,05; 0,1; 0,2; 0,5; 1; 1,5; 2,5; 4\}$$

In most cases, the accuracy classes of the device are indicated on the scale of the instrument and represent the error generated by the device, which is expressed by the following relationship.

$$\delta_{a.k} = \beta_{k.x.max} \geq \beta_k; \quad \delta_{a.k} = \beta_{k.x.max} \geq \beta_k = \Delta/a_{x.max} \quad (1)$$



The accuracy classes of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks are indicated on the scale of the instrument and represent the error generated by the device, which is expressed by the following relationship.

$$\delta_{a.k} = \beta_{k.x.max} \geq \beta_k; \quad \delta_{a.k} = \beta_{k.x.max} \geq \beta_k = \Delta/a_{x.max} \quad (2)$$

If the accuracy class indicated on the scale of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks is enclosed within a circle, the sensitivity error is equal to  $\pm \dots \%$ .

If the accuracy class of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks is non-linear, then the accuracy class number indicates the corresponding error value [10].

The sensitivity of the device for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks is determined by the ratio of the secondary signal to the primary current:

$$S = \frac{dU}{dI} \quad (3)$$

The measurement error of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks is expressed in the form of relative error, reduced error, or absolute error [4, 7].

The measurement range of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks mainly applies to multi-range devices.

The static characteristics of devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks produce a nonlinearity error, the maximum value of which corresponds to the nonlinearity value determined by the following formula [4, 5, 9].



$$U_{noch} = 0,5 \frac{U_{ch\ noch} - U_{ch\ chiz}}{U_{ch\ max} - U_{ch\ min}} \quad (4)$$

where:  $U_{ch\ noch}$  and  $U_{ch\ chiz}$  – are the practically measured and theoretically calculated values of the output voltage in the nonlinear and linear states, respectively.

To reduce the nonlinearity of the output signal voltage  $k$  in devices for measuring and remotely monitoring reactive power currents in three-phase grounded-neutral and isolated-neutral electrical power supply networks, the following main approaches can be applied:

- Operation in a steady-state mode (T-constant mode);
- Limitation of the measurement range;
- Adjustment of the initial phase of the measurement range;
- Reduction of the influence of electromagnetic fields.

## RESULTS AND DISCUSSION

Among the sources of errors in the input conversion stages of three-phase current devices of reactive power sources in electrical power supply system networks (EPSSN), various factors can be included—such as temperature, humidity, external magnetic fields, and other environmental influences. These factors affect the three-phase currents  $I$ , the electric current frequency  $f$ , and the coupling coefficients  $W [I, f_\mu]$  of conversion stages of different physical nature. In addition, the physical properties of current conductors and excitation winding materials also have a significant influence on the overall measurement accuracy.

To evaluate the total (accumulated) error of the three-phase current device of reactive power sources in EPSSNs, the transformation of primary currents  $I$  into magnetomotive force values  $F_\mu$  in the magnetic conversion stage, i.e., the  $I \rightarrow F_\mu$  transformation errors are considered, namely:  $\delta_1 = 0,15$  - which represents the deviation of electrical and magnetic quantities in this conversion stage from their primary nominal values within a limit of  $\pm 0.15\%$  [3, 8].

$F_\mu$  - in distributed-parameter conversion elements of magnetomotive forces (MMF).  $\Phi_\mu$  - the conversion elements generate magnetic fluxes—that is, they produce  $F_\mu \rightarrow \Phi_\mu$  - the transformation errors, namely  $\delta_2 = 0,1$  - represents the normalized deviation of  $\pm 0.1\%$  from the nominal value due to parameter



dispersion of magnetic quantities in this conversion stage, as well as the transformation errors of MMF conversion elements. The transformation from magnetic flux  $\Phi_\mu$  to output electrical voltage  $U_{\text{chiq}}$  – i.e.,  $\Phi_\mu \rightarrow U_{\text{chiq}}$ , - introduces additional conversion errors, namely  $\delta_3=0,1$  and  $\delta_4=0,1$  which are determined based on these small contributions [2, 9].

The root mean square (RMS) error of the total conversion of three-phase reactive power currents into voltage by converters is determined using the following expression:

$$\delta_\Sigma = \pm\sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2} = \pm\sqrt{0,15^2 + 0,1^2 + 0,1^2 + 0,1^2} = \pm 0,22, \quad (5)$$

where:  $\delta_1$ - is the root mean square error of the primary winding of the converter device;

$\delta_2$ - is the root mean square error of the magnetic conversion system and magnetic core of the converter device;

$\delta_3$ - is the root mean square error of the flat (or simple) measuring windings of the converter device;

$\delta_4$ - is the root mean square error of the signal transmission cable in the sensitive element.

For a three-phase reactive power current converter device with flat (or simple) measuring windings, the entropy deviation value for converting the primary current into voltage is calculated using the following expression:

$$\Delta = k_e \delta_\Sigma, \quad (6)$$

where:  $\delta_\Sigma$ - is the total root mean square error (combined error deviation), i.e., the sum of error deviations;

$k_e$  is the entropy coefficient (for the normal distribution law  $k_e = 2.07$ ) [3].

$$\Delta = k_e \delta_\Sigma = 2,07 * 0,22 = 0,474$$

According to the calculation results, the entropy error of the electromagnetic converter for three-phase primary reactive power currents with flat (simple) measuring windings, converting current into voltage, is:  $\Delta = 0.474$ .

The normalized value of the converter device accuracy can be selected from data defined in standard regulations. According to the results of practical studies, this error is  $\Delta = 0.5$ , i.e.,  $\pm 0.5\%$  [8].



In the electrical power supply system networks (EPSSN), due to repeated use of electronic computing devices for measuring and remotely monitoring reactive power currents, ensuring the supply of standardized voltage (5 V) and current (0.1 A) to converter devices and electronic data processing units, as well as maintaining their accuracy, remains a highly relevant issue [4, 6, 8].

Based on the values of  $I_A$ ,  $U_a^1$ ,  $U_a^2$  the indicators of the conversion accuracy of the current transformer device corresponding to the points of the static characteristics of the three-phase reactive power current conversion system in electrical power supply system networks (EPSSN), including both three-phase and neutral-wire current transformer configurations, are determined as follows:

$$I_A = 131.5 \text{ A}; \quad U_a^1 = 5 \text{ B}; \quad U_a^2 = 4,92 \text{ B};$$
$$\Delta_{2.5} = \frac{(U_a^1 - U_a^2)}{U_a^1} * 100\% = \frac{(5 - 4,92)}{5} * 100\% = 1,6 \%. \quad (7)$$

$$I_A = 65.7 \text{ A}; U_a^1 = 2,5 \text{ B}; U_a^2 = 2,461 \text{ B};$$
$$\Delta_5 = \frac{(U_a^1 - U_a^2)}{U_a^1} * 100\% = \frac{(2,5 - 2,461)}{2,5} * 100\% = 1,56\%. \quad (8)$$

Based on the calculated data, it can be concluded that the analytical expressions formed on the basis of a distributed-parameter graph model of three-phase and neutral-wire primary current systems of EPSSN reactive power networks with current transformer devices, as well as the obtained graphical characteristics, are adequate to the results of structural investigations of the device. Moreover, by ensuring the linearity of the output characteristic, it was possible to improve the conversion accuracy by 1.6%.

## CONCLUSION

1. The entropy error of electromagnetic converter devices for converting three-phase reactive power currents into voltage-form signals was calculated to be  $\pm 0.474\%$ , thereby ensuring that the normalized value of the device accuracy class meets the standard normal accuracy class of 0.5 or less.
2. The distributed-parameter graph model of three-phase primary reactive power current devices of EPSSN reactive power sources, along with the mathematical models formed on its basis, were proven to be adequate to the real linear output



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characteristics of the devices. It was shown that the conversion accuracy of the device for transforming primary currents in three-phase and neutral-wire networks was improved by 1.6% compared to the aggregated parameter graph model and by 11.2% compared to the classical current transformer.

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