Research of error electromagnetic current-to-voltage converters with flat measuring windings in the recesses of the magnetic circuit

Ilkhomjon Siddikov[1], *Halimjon* Khujamatov[2], *Azizbek* Temirov[3*], and *Nozima* Atadjanova[2]

[1]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers National Research University, Tashkent, Uzbekistan
[2]Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Tashkent, Uzbekistan
[3]Namangan State University, Namangan, Uzbekistan

Abstract. There are many signal converters of the magnitude and parameters of direct and alternating current, but it is necessary to briefly review them to choose the optimal type of current converters for monitoring and control systems of energy sources in distributed telecommunication systems. advantages and disadvantages and evaluation of their development prospects and application in the hybrid system mentioned above. control of power supply sources. The most widely used electromechanical current converters in various flow monitoring and control systems have a simple and technological design, but they have a moving measurement part, which reduces their reliability and limits the scope of application.

1 Introduction

High accuracy, uniformity, provision of standardized data, and reliable operation of current transformers, which are widely used in the management of continuous processes of production, transmission, distribution, and consumption of electric energy, are important. Development of a comprehensive approach to ensuring energy and resource efficiency in the management of electrical energy sources, expanding the capabilities of electrical devices depending on their tasks, simplifying the structure of control elements and devices based on a unified form, and reducing weight dimensions. Theoretical and practical problems of energy system management of electrical quantities based on the development of cost-effective devices and technologies, provision of non-contact measurement processes, and use of high-precision current transformers are still being studied and the necessary solutions are being sought. Providing a universal block-module principle of designing current transformers, which includes convenient, versatile, and minimal structural elements based on the use of modern technologies, a current that provides flexibility in creating information, energy, metrology indicators, and regulatory structure modules transformers. includes standardization and standardization-based elements and devices [1]. At present, the widespread use of single-phase and three-phase electromagnetic transformers in the power

*Corresponding author: aaotemirov@gmail.com

system is somewhat limited, because the spectrum of electrical quantities has not been changed. Conventional research methods of magnetic switching circuits and systems cannot provide the specified switching accuracy, because they do not take into account the three-phase current asymmetry. Construction of electromagnetic current to voltage converters of hybrid power supply sources and elements used in it, types of three-phase general magnetic core sensors. The designs of the sensors differ significantly from each other, and it is necessary to conduct analyses on the designs of several types of sensors to determine the differences. In the form. 1. A flat magnet is placed in the recesses of the circuit with a measured winding [2,3].

In Fig.1. A diagram of the design of an electromagnetic current-voltage converter with a flat measuring winding in the recesses of a flat magnetic circuit is presented.

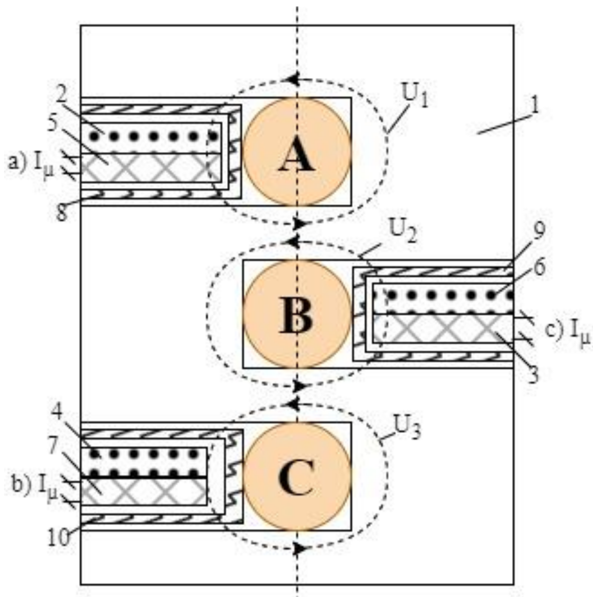

Fig. 1. Design diagram of a three-phase current electromagnetic transducer with flat measuring windings in pits: 1 – *magnetic circuit;* 2, 3, 4 – *depressions;* 5, 6, 7 – *flat measuring windings; A, B, C – phase conduc*tors; *U_1, U_2, U_3* – magnetic fluxes crossing flat measuring windings 5, 6, and 7.

To analyze and evaluate the errors of electromagnetic current-to-voltage converters with flat measuring windings (ECVC with FMW), we use the information graph error model presented [4] in Fig. 2. for ECVC with FMW for one current phase.

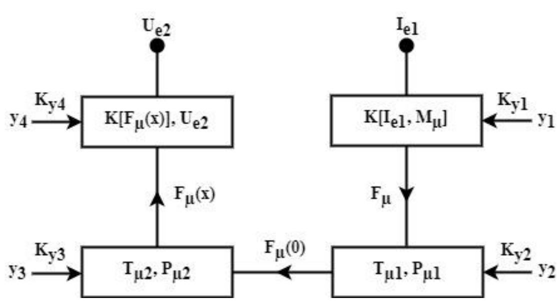

Fig. 2. Information graph model of ECVC with FMW.

The input circuit of the converter is represented by the subgraph I_{e1}, U_{μ} in which the phase current I_{e1} (I_A) is converted into magnetomotive force U_{μ}, which is reflected by the inter-circuit coupling coefficient $K[I_{e1}, U_{\mu}]$. In the circuit U_{μ}, $\Phi(0)$, the magnetomotive force U_{μ} is converted into magnetic flux $\Phi_{\mu}(0)$, for which the circuit function $T_{\mu 1}$, $\Pi_{\mu 1}$ reflects the structure of the circuit. In magnetic core 1, the magnetic flux $F_{\mu}(0)$ generally propagates along the coordinate x, along the magnetic core from x=0 to x, and has the value $F_{\mu}(x)$. In the chain, $F_{\mu}(x)$, U_{E2}, a transformation of $F_{\mu}(x)$ into U_{E2} occurs, which is reflected by the interchain coupling coefficient $K[F\mu(x), U_{e2}]$.

Independent influencing variables y_1, y_2, y_3, y_4 are introduced into the information graph model, which takes into account the ambiguity of transformations: I_{e1}, U_{μ}; U_{μ}, $F_{\mu}(0)$; $F_{\mu}(0)$, $F_{\mu}(x)$; $F_{\mu}(x)$, U_{e2}. The connections of the influencing factors y_1, y_2, y_3, *and* y_4 with the corresponding conversion circuits are displayed by the coefficients K_{y1}, K_{y2}, K_{y3}, *and* K_{y4}.

2 Materials and methods

To analyze and evaluate the errors of ECVC with FMW, it is very effective to use the provisions of the information theory of measuring devices [5,6] in combination with the information graph model shown in Fig. 2.

According to the information theory of measuring devices, the error of ECVC with FMW is one scientifically determined by the value of the entropy error Δ_e, and the entropy coefficients K_e depends on the type of probability density distribution law of errors of individual elements [7]. The root mean square error of ECVC with FMW $\sigma_{\sum}$ is determined from the expression:

$$\sigma_{\sum} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} \qquad (1)$$

Where: $\sigma_1^2, \sigma_2^2, \sigma_n^2$ – root-mean-square errors of individual elements.

With known K_e and σ_e, the value of ΔE is determined from the expression:

$$\Delta_e = K_e \cdot \sigma_{\sum} \qquad (2)$$

According to the information graph model, the components of the total error are errors in the circuits: I_{e1}, U_{μ}; U_{μ}, $F_{\mu}(0)$; $F_{\mu}(0)$, $F_{\mu}(x)$; $F_{\mu}(x)$, U_{e2}.

In the input circuit of the ECVC with FMW, the sources of errors are fluctuations in current IE1, frequency ω_{e1}, changes in the inter-circuit coupling coefficient $K[I_{e1}, U_{\mu}]$ from various factors: temperature, humidity, external magnetic fields and masses, and other factors, as well as changes in the physical properties of conductor materials and field windings.

In the section of the magnetic circuit $F_{\mu}(0)$, $F_{\mu}(x)$ there are errors from the influence of temperature, external magnetic fields, and the mutual influence of neighboring magnetic fluxes in the section of the circuit $F_{\mu}(x)$, U_{e2} there are errors from the influence of external and secondary magnetic fluxes, temperature, humidity.

The main errors of ECVC with FMW can be divided into three groups:

- methodological;
- instrumental;
- operational.

Additional errors of ECVC with FMW can be divided into three groups:

- internal;
- external;
- regime.

Methodological sources of error in ECVC with FMW arise

due to the incompleteness of taking into account all the legalities of their work when calculating static and dynamic characteristics. The degree of nonlinearity of the static characteristic of converters introduces an error in cases where the converters have a nonlinear static characteristic, but are used in monitoring and control systems as converters with a linear characteristic.

To determine the degree of nonlinearity of ECVC with FMW, the formula is used.

$$\varepsilon = 0.5\frac{U_{entry} - U_{exit}}{U_{entry\max} - U_{exit\min}}100\% \tag{3}$$

In ECVC with FMW, while ensuring uniformity and constancy of the magnetic flux crossing the FMW in the air gap of the pit

$$F_{\mu g} = const \tag{4}$$

the static characteristic has high linearity.

In the general case, the degree of nonlinearity of the static characteristics of EMPT with FEC depends on the inter-circuit coefficients, the range of the primary current, and the optimal location and area of the FMW [8].

The nonlinearity of the static characteristics of the ECVC with FMW also depends on the presence of higher harmonic components in the output signal, which arise due to the nonlinearity of the magnetic characteristics of the magnetic core materials [9,10].

Instrumental errors of ECVC with FMW are caused by deviations in the transverse and longitudinal dimensions of the magnetic cores and their pits during inaccurate manufacturing and processing, which leads to an error in reproducing the specified values of the distributed parameters: specific per unit length of the magnetic resistance of the magnetic core r_μ and the magnetic conductivity of the air gap of the pits g_μ.

In ECVC with FMW, there is an error in the inaccuracy of the distribution of electrical resistivity and conductivity of flat measuring windings installed in the recesses of the magnetic circuit.

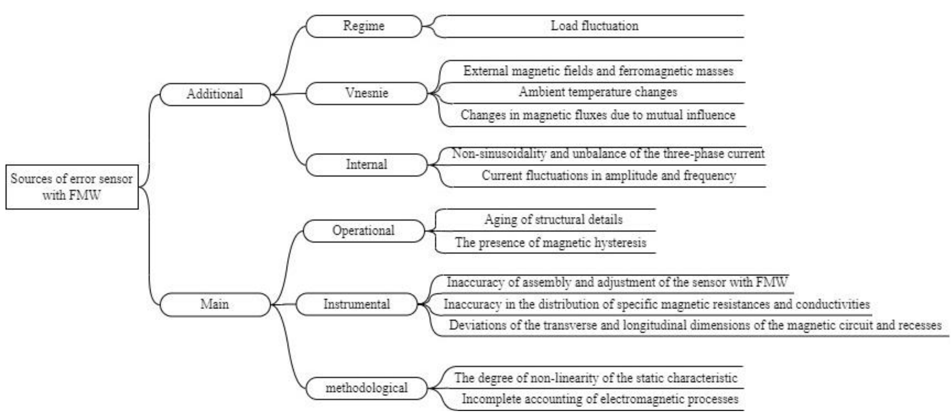

Fig.3. Classification of error sources of ECVC with FMW

Operational sources of ECVC with FMW are determined mainly by the presence of mechanical inaccuracies during installation, assembly, and offset planes of the measuring winding relative to the cross-section of the magnetic circuit in the area of the measuring pit.

In ECVC, internal source errors are caused by the appearance of current instability in the conductor in terms of amplitude and frequency, as well as the appearance of non-sinusoidality and asymmetry of the three-phase current [4,11,12].

External sources of error in ECVC with FMW most significantly manifest themselves with temperature fluctuations and the presence of external magnetic fields and ferromagnetic masses [2,9,13].

Regime sources of additional error ECVC with FMW occur; when the load at the converter output is not constant, for example, when the converter output is connected to an amplifier with a small input impedance, this error will occur and be reduced. This error requires increasing the value of the load resistance. Based on the above in Fig.3. The classification of error sources of ECVC with FMW is given.

3 Estimation of the total error of ECVC with FMW

The functional diagram of an ECVC with FMW has the form:

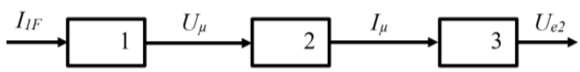

Fig 4. Block diagram of ECVC with FMW

In block 1, the phase current I1ph is converted into magnetomotive force U_μ Further, in block 2, the magnetomotive force U_μ determines the presence of magnetic flux I_μ in the corresponding magnetic circuit. In block 3, due to the location of the flat measuring winding in the recess at the output of the flat measuring winding, the electromotive force of the output U_{e2} is induced [14,15,18].

To estimate the total error of the ECVC with FMW, we separately estimate the errors occurring in blocks 1, 2, and 3.

The error of the conversion $I_{1F} \rightarrow U_\mu$ can be estimated by the limiting value y_1=0.2%. Next comes the transformation $U_\mu \rightarrow I_\mu$ also has a low error of the order of y_2=0.1%. The transformation at node 3 $I_\mu \rightarrow U_{e2}$ also occurs with an error of y_3=0.1%.

Let us divide all components of the error into additive and multiplicative and, by the law of distribution of the probability of their occurrence, find their standard deviations.

As has been shown, the entropy error y_e according to [17,19] is equal to:

$$y_e = K_e \sigma_e \tag{5}$$

where: K_e – entropy coefficient of the converter element, depending on the error distribution law;

σ_e – total standard deviation (error) of the element.

The error distribution law in block 1 can be assumed to be normal with the entropy coefficient K_{e1}=2.07. Hence the standard deviation σ_1 will be equal to:

$$\sigma_1 = \frac{y_1}{K_{e1}} = \frac{0.2}{2.07} = 0.097\% \tag{6}$$

Similarly, for block 2, with a normal error distribution law, we have K_{e2}=2.07:

$$\sigma_2 = \frac{y_2}{K_{e2}} = 0.048\% \tag{7}$$

and similarly, we get K_{e3}=2.07:

$$\sigma_3 = \frac{y_3}{K_{e3}} = 0.48\% \tag{8}$$

The adaptive error of the ECVC with FMW will be formed by the sum of three components σ_1, σ_2, and σ_3 and will amount to

$$\sigma_{a\Sigma} = \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2} = \sqrt{0.027^2 + 0.048^2 + 0.048^2} = 0.114 \tag{9}$$

The entropy coefficients of the error components are the same: $K_{e1}=K_{e2}=K_{e3}=2.07$ and therefore the entropy coefficient of the sum $\delta_{\sum}$ will also be equal to $K_{e\sum}=2.07$. Hence the entropy value of the adaptive error will be:

$$y_{\sum a} = 2.07 \cdot 0.114 = 0.235 \tag{10}$$

Moving on to the summation of multiplicative errors, we accept the following provisions:

1) temperature affects the magnetic resistance of the magnetic circuit and the degree of influence can be estimated by the coefficient:

$$K_{ECV} = \frac{0.05\%}{10°K} \tag{11}$$

2) temperature affects the electrical resistance of the flat measuring winding and the degree of influence can also be estimated by the coefficient:

$$K_{TFMW} = \frac{0.05\%}{10°K} \tag{12}$$

In the design of an ECVC with FMW, the magnetic circuit and the FMW are always at the same temperature, and their temperature errors are strictly correlated with each other and must be summed up algebraically, and the overall coefficient of the influence of temperature on the ECVC with FMW is equal to:

$$K_{T\sum} = \frac{0.1\%}{10°K} \tag{13}$$

ECVC usually operates at temperatures $(25\pm15)^{O}$C and all temperatures are equally probable and the multiplicative error is equal to:

$$y_m = \frac{0.1 \cdot 15}{10} = 0.15\% \tag{14}$$

$$\sigma_M = \frac{y_m}{K_{em}} = \frac{0.15}{2.07} = 0.072 \tag{15}$$

As a result, we determine the error of the ECVC with FMW at the end of the range by adding the adaptive and multiplicative errors according to the rules for summing independent errors in the form:

$$\sigma_k = \sqrt{\delta_a^2 + \delta_m^2} = \sqrt{0.114^2 + 0.072^2} = 0.15 \tag{16}$$

The entropy errors of the summing errors are the same $K_{\sum a} = 2.07$ and $K_{em} = 2.07$ and are quite large therefore the resulting distribution is equal to the normal distribution with $K_k = 2.07$.

Hence, the entropy value of the error of ECVC with FMW at the end of the scale is equal to

$$y_k = K_k \cdot \delta_k = 2.07 \cdot 0.15 = 0.31 \tag{17}$$

When normalizing a measuring device according to the standard, it is necessary to have data on aging of at least 25% of the physical error, and the normalized value of the accuracy of the ECVC with FMW can be selected from several estimated numbers provided by GOST. For those considering ECVC with FMW, the accuracy class with a margin is 0.5%.

4 Conclusion

Analysis of circuits, constructions, structures and relations in the conversion of the primary electric current of the consumer electricity receiver into a signal in the control of the power supply, the study of physical and technical effects based on simulation and the principle of research and the construction of the sensor. Based on the circuit model construction algorithm to convert the current into a signal, a model is created for the design of the Sensor. With the interrelationship between the structure and values of circuits of different physical natures, the transformation corresponds to the process of hybrid power supply management, in which different sources of electric energy are considered as controlled consumer sources.

References

1. H. Chen, T. Tong, H. Zhen, H. Shen and Y. Wu, *Effects of Eccentricity on the Cancellation-Based Calibration Method of Electromagnetic Current Transformers,* 2022 IEEE 2nd International Conference on Data Science and Computer Application (ICDSCA), Dalian, China, 2022, pp. 235-239, doi: 10.1109/ICDSCA56264.2022.9988513.
2. S. Wu, Q. Xu and Y. Huang, *"Research on Harmonic Error Characteristics of Electromagnetic Current Transformers,"* 2019 2nd Asia Conference on Energy and Environment Engineering (ACEEE), Hiroshima, Japan, 2019, pp. 59-63, doi: 10.1109/ACEEE.2019.8816925.
3. D. Gallo, C. Landi and M. Luiso, "*Evaluation of metrological performance of electromagnetic current measurement transformers in non-sinusofdal conditions,"* 2014 International Conference on Electromagnetics in Advanced Applications (ICEAA), Palm Beach, Aruba, 2014, pp. 671-674, doi: 10.1109/ICEAA.2014.6903942.
4. E. T. Morton, A. A. Allen, J. O'Donnell and C. Oates, *"Intercomparison of acoustic and electromagnetic current meters during leeway drift tests,"* Proceedings of the IEEE Sixth Working Conference on Current Measurement (Cat. No.99CH36331), San Diego, CA, USA, 1999, pp. 179-183, doi: 10.1109/CCM.1999.755237.
5. C. Li, Q. Li, J. Yao and M. Liu, "*The characteristics of electromagnetic current transformers with DC bias,"* 2009 International Conference on Sustainable Power Generation and Supply, Nanjing, China, 2009, pp. 1-6, doi: 10.1109/SUPERGEN.2009.5348387.
6. I. Siddikov, H. Khujamatov, D. Khasanov, E. Reypnazarov and A. Iminov, *"Data Transfer Methods and Algorithms in Wireless Sensor Networks for IoT-based Remote Monitoring System of Hybrid Energy Supply Sources,"* 2022 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2022, pp. 1-6, doi: 10.1109/ICISCT55600.2022.10146865.
7. I. Siddikov, H. Khujamatov, A. Temirov, E. Reypnazarov and D. Khasanov, *"Analysis of Energy Efficiency Indicators in IoT-based Systems,"* 2022 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2022, pp. 1-6, doi: 10.1109/ICISCT55600.2022.10146855.
8. I. K. Siddikov, K. A. Sattarov and K. E. Khujamatov, *"Modeling of the transformation elements of power sources control,"* 2017 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2017, pp. 1-5, doi: 10.1109/ICISCT.2017.8188581.
9. I. Siddikov, K. Sattarov, K. Khujamatov, O. Dekhkonov and M. Agzamova, "*Modeling of Magnetic Circuits of Electromagnetic Transducers of the Three-Phases Current,"* 2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE), Novosibirsk, Russia, 2018, pp. 419-422, doi: 10.1109/APEIE.2018.8545714.

10. S. I. Khakimovich, S. K. Abdishukurovich, D. O. Ravshanovich and K. K. Ergashevich, *"Modeling of the processes in magnetic circuits of electromagnetic transdusers,"* 2016 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2016, pp. 1-3, doi: 10.1109/ICISCT.2016.7777393.
11. K. E. Khujamatov, D. T. Khasanov and E. N. Reypnazarov, "*Research and Modelling Adaptive Management of Hybrid Power Supply Systems for Object Telecommunications based on IoT,"* 2019 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2019, pp. 1-5, doi: 10.1109/ICISCT47635.2019.9011831.
12. I. Siddikov, D. Khasanov, H. Khujamatov and E. Reypnazarov, *Communication Architecture of Solar Energy Monitoring Systems for Telecommunication Objects,* 2021 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2021, pp. 01-05, doi: 10.1109/ICISCT52966.2021.9670354.
13. K. Khujamatov, A. Lazarev and N. Akhmedov, *Intelligent IoT Sensors: Types, Functions and Classification,* 2021 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2021, pp. 01-06, doi: 10.1109/ICISCT52966.2021.9670340.
14. Sudeep Tanwar,Halim Khujamatov,Bairam Turumbetov,Ernazar Reypnazarov and Zamira Allamuratova, International Journal on Advanced Science, Engineering and Information Technology, **12**, 2, 437-445 (2022) http://dx.doi.org/10.18517/ijaseit.12.2.14950.
15. Khujamatov, K., Khasanov, D., Reypnazarov, E., Akhmedov, N. (2021). Existing Technologies and Solutions in 5G-Enabled IoT for Industrial Automation. In: Tanwar, S. (eds) Blockchain for 5G-Enabled IoT. Springer, Cham. https://doi.org/10.1007/978-3-030-67490-8_8
16. Khasanov, D., Khujamatov, K., Fayzullaev, B., Reypnazarov, E. (2021). IIUM Engineering Journal, **22(2),** 98–118. https://doi.org/10.31436/iiumej.v22i2.1464
17. S. I. Khakimovich, S. K. Abdishukurovich, D. O. Ravshanovich and K. K. Ergashevich, "*Modeling of the processes in magnetic circuits of electromagnetic transdusers,"* 2016 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2016, pp. 1-3, doi: 10.1109/ICISCT.2016.7777393.
18. I. K. Siddikov, K. A. Sattarov and K. E. Khujamatov, "*Modeling of the transformation elements of power sources control*," 2017 International Conference on Information Science and Communications Technologies (ICISCT), Tashkent, Uzbekistan, 2017, pp. 1-5, doi: 10.1109/ICISCT.2017.8188581.
19. I. Siddikov, K. Sattarov, K. Khujamatov, O. Dekhkonov and M. Agzamova, "*Modeling of Magnetic Circuits of Electromagnetic Transducers of the Three-Phases Current,"* 2018 XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE), Novosibirsk, Russia, 2018, pp. 419-422, doi: 10.1109/APEIE.2018.8545714.