Багато різних високоточних систем для визначення похибки коефіцієнта і фазового зміщення трансформаторів струму розроблено провідними фахівцями світу. У цих розробках використані останні дослідницькі рішення з використанням новітніх засобів вимірювання, техніки вибірки миттєвих значень, аналізу джерел невизначеності. Об'єктивні труднощі полягають у тім, що лише вузьке коло спеціалізованих інститутів реалізує такі проекти із залученням провідних фахівців галузі вимірювань і значних коштів. В першу чергу, це національні метрологічні інститути держав з високими економічними можливостями. На рівні звичайних калібрувальних лабораторій, оснащених сучасним обладнанням з висококваліфікованим персоналом, при калібруванні точних вимірювальних трансформаторів невизначеність вимірювань зростає в 10 разів і більше. У якій мірі еквівалентні покази серійних компараторів різних виробників при калібруванні вимірювальних трансформаторів класу 0,2S і точніше досліджено ще не було. Основним завданням даного дослідження є визначення рівня еквівалентності показів компараторів змінного струму різних типів при щоденному калібруванні вимірювальних трансформаторів струму. Досліджено понад 50 компараторів різних типів (з індуктивними або резистивними вхідними перетворювачами струму) відносно двох еталонних трансформаторів струму з ретельно визначеними метрологічними характеристиками. Порівняння результатів, отриманих двома приладами з різними принципами вимірювання, дало різницю в 23 мкА/А щодо похибки коефіцієнта і 52 мкрад щодо фазового зміщення. Висвітлено результати оцінювання стабільності показів сучасних компараторів серійного виробництва. Результати аналізу отриманих даних дозволяють припустити, що результати визначення похибки коефіцієнта величиною близько 50 мкА/А мають рівень еквівалентності в межах ±20 мкА/А. Результати визначення фазового зміщення величиною близько 50 мкрад мають рівень еквівалентності в межах ±15 мкрад. Що стосується результатів визначення метрологічних характеристик трансформаторів струму з класом точності 0,2S, їх еквівалентність треба розглядати з урахуванням всіх експлуатованих типів засобів компарування. Отримані результати ставлять питання про адекватність запасу точності при виробництві трансформаторів струму для перекриття розсіювання показів на інтервалі близько 260 мкА/А і 500 мкрад

Ключові слова: еквівалентність, вимірювання, компаратор, трансформатор струму, еталон, похибка коефіцієнта, фазове зміщення, невизначеність

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COMPARATOR EFFECT ON EQUIVALENCE OF RESULTS OF CALIBRATING CURRENT TRANSFORMERS

V. Isaiev
Senior Researcher*
E-mail: black2001w@gmail.com

O. Velychko
Doctor of Technical Sciences, Professor, Director
Scientific and Production Institute of Electromagnetic Measurements State Enterprise **
E-mail: velychko@hotmail.com

Y. Anokhin
Head of Department*
E-mail: y.l.anokhin@gmail.com

* Research and Development Department of Measurement of Electric Quantities State Enterprise
**"All-Ukrainian State Scientific and Production Centre for Standardization, Metrology, Certification and Protection of Consumer", (SE "Ukrmetrteststandard")
Metrolohychna str., 4, Kyiv, Ukraine, 03143

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1. Introduction

One of the important branches of the economy of each technically developed state is the energy sector. In the electric power industry, such technical means as instrument transformers (IT) have become very widespread. Such scaling transducers are used in solving measurement-related tasks, and the accuracy of such devices should be set by the international standard IEC 61869-1 [1]. The importance of the accuracy level of ITs is discussed in developing a medium voltage signal generator for testing voltage measuring transducers for the study of the quality of electricity [2]. An accuracy of ITs is also important when testing power transformers in part of the dynamic effects of a short circuit with the help of the method for accurate measurement [3]. It is difficult to count all cases of ITs application as well as to overestimate the importance of defining their accuracy.

Manufacturers of high precision ITs find new technical solutions for the improvement of their products. In turn, the critical importance of the accuracy of IT calibration means, in particular, of comparators, increases.

Traditionally, comparators are used to compare the secondary current of the device under test with the secondary current of the reference transformer to determine ratio error (RE) and phase displacement (PD). Comparators are quite complex devices, and their service, including calibration, is often provided at the manufacturer. The question arises, whether the readouts of such measuring instruments of different types relative to one object were compared. Do the elements of the internal structure of particular types, with an application of technical inventions of specialists of different manufacturers, affect the received readouts of actual metrological characteristics of transformers.

On a highly professional level, the equivalence of measurement results is investigated through international comparisons and the degrees of equivalence between results of the pairs of national metrology institutes are defined. The interlaboratory comparisons are also conducted at the level of calibration laboratories. In the above investigations, the results obtained with the help of precision measuring instruments (often sophisticated complexes of technical means) are compared. An example of such a complex system is the alternating current transformer standard measuring system developed by PTB (Germany), which allows defining RE with an uncertainty of about 1 μA/A [4]. But the assurance of high accuracy of the complex measuring system requires highly skilled scientific and technical personnel, as well as considerable funds for the purchase and maintenance of equipment.

The State Enterprise "Ukrmetrteststandard" as a calibration laboratory regularly performs defining the accuracy of AC comparators. During the research, REs and PDs of at least 50 comparators of different types and different manufacturers were defined, including devices of foreign production. During the previous study, a noticeable dispersion of the measurement results when determining the accuracy of the same measure of current difference was observed as indicated in [5]. It is not sufficiently reasoned to attribute the mentioned differences to the intrinsic uncertainty because the data provided by manufacturers about accuracy did not allow us to overcome these discrepancies. According to the user's guide of the CA507 comparator ("OLTEST" LLC, Ukraine), the intrinsic uncertainty is within 6 μA/A when measuring RE of 600 μA/A with comparing currents of 5 A, and the analogous figure is 20 μA/A for the K535 device. The intrinsic uncertainty is within 12 μrad when measuring PD of 150 μrad using the CA507 comparator with comparing currents of 5 A, and the analogous figure is 33 μrad for the K535 device.

This question is important because in the daily operation of the measuring system, sometimes there is damage or other problems, including in the operation of AC comparators. To replace the non-functioning instrument, another device of similar application may be included in the scheme. If another comparator has a different type, there may be a shift in the measurement result due to the load effect on the secondary transformer winding. To estimate the influence of internal measuring circuits of comparators on the results obtained, it is efficient to determine the level of equivalence of the readouts of these devices when calibrating reference transformers and current transformers (CT) with accuracy class 0.2S.

Manufacturers have likely studied such problems, but the results remain their technical and commercial secrets and relate, first of all, to their works. And even if the repetition of the readouts from a device to a device of the same type and one manufacturer has excellent realization, the elemental structure of the design may be changed and improved over time. Another manufacturer can use other design elements and know-how, and input circuits may have a significant influence on the readout during precision measurement. In general, determining the equivalence of IT calibration results can help improve the conditions for international recognition of measurement results when exporting measuring equipment.

2. Literature review and problem statement

The problems of determination of RE and PD in single-phase and three-phase transformers are discussed in the work devoted to one-phase and three-phase excitation for ratio measurement [6]. In particular, attention is focused on the advantages of three-phase excitation in determining the ratio of input and output voltage in three-phase IT. However, this study does not regard cases where an IT converts a non-ideal sinusoidal signal. RE and PD in the presence of harmonic components of 150 Hz, 250 Hz of currents 0.1 A/0.1 A were investigated, and an approach was proeposed to determine the characteristics of IT using a virtual instrument [7].

An important work in terms of the development of automatic devices for the calibration of ITs is an article on the constructive performance and analysis of errors of the comparator AITTS-98 [8]. Such a device is used when comparing the output signals of a reference and a calibrated IT, and the reference transformer should be taken into account when evaluating the uncertainty of measurements. In recent years, the technique of sample current measurement using the PC-based IT test set was proposed. This approach allows us to eliminate the reference transformer when determining RE and PD over the entire current range. This method showed a good concordance of the results obtained with the traditional method using a potentiometer for the current ratio of 200 A/5 A [9]. The same applies to the Hohle-bridge method for a voltage ratio of 1,100 V/100 V [10] for the measured values corresponding to the transformer accuracy class 1.

The trend of expanding the spectrum of engineering research solutions to determine the errors of ITs has been continued by the method of determining RE and PD based on the equivalent model of CT, which does not require a reference transformer [11]. To facilitate the measurement procedure in defining RE and PD, a method based on the low-voltage reciprocity principle was developed, in which the internal characteristics of the transformer are measured. Composite error, excitation characteristics and 10 % error curve are considered in this paper [12]. A large number of advanced approaches are complemented by digitization during calibration of IT as an alternative to complex methods of balancing the alternating current or measurement data acquisition systems. It increases the accuracy of the measurement of RE and PD because the conversion process delivers digital outputs of RE and PD of the test transformer directly [13].

Most of the above methods are related to the development of metrological support for ITs used in 50 or 60 Hz industrial power supply systems. However, there are also AC scale converters for operation over a wide frequency range. An efficient method, which allows defining the errors of both ordinary and electronic scaling converters of current or voltage with accuracy class 0.1 in the frequency range from 50 to 1,000 Hz, was developed by Italian researchers [14]. A large number of proposed methods for determining IT errors raises the question of the equivalence of the measurement results obtained with their application. The best way for solving the equivalence determination problem is outlined in the final report on the international comparison of the measurement results of RE and PD of IT [15]. One of the ratios of the scaling transformation of current was chosen 5 A/5 A in the current range from 0.05 A to 6 A. It should be noted that the uncertainty of the reference value was defined as 2 μA/A for RE and 3 μrad for PD. Besides, the best uncertainties were reported by the PTB (Germany) at 3 μA/A for RE and 4 μrad for PD, while the UME (Turkey) showed the greatest uncertainties of 100 μA/A and 100 μrad.

Unlike leading laboratories of leading countries, the level of equivalence of the measurement results of the ordinary calibration laboratories is considered to be somewhat worse than that of national metrology institutes. Calibration laboratories that determine RE and PD should provide the level of uncertainty of their standards sufficient to calibrate the reference transformers with accuracy class 0.02 as well as current transformers (CT) with accuracy class 0.2S. Objectively, the difficulty of ensuring uniformity of measurement is that the vast majority of conventional and unoriginal calibration laboratories are not equipped with expensive high-precision systems and have no highly qualified personnel. Moreover, there is different equipment and configuration of the measurement set-up, the influence of the measuring channel on the actual values of the errors is usually not taken into account. The current sources, standards, burdens, comparators, connecting conductors in the complement of the calibration systems are the sources of uncertainty too. One of the smallest sources of uncertainty is the device for comparing currents, for example, the contribution of the PTB bridge has a level of several hundredths of μA/A [4]. One of the methods for verification of the accuracy of AC comparators is a method for determining the reference values of RE and PD using the oscilloscope allowing metrological support of the comparators exploited [16]. However, it has not yet been investigated, what contribution to the uncertainty of the calibration laboratories involved in the daily calibration of CTs is made by various comparators of serial production. The equivalence of AC comparators readouts when calibrating reference transformers and CTs with an accuracy class of 0.2S has also not been investigated. Given the foregoing, a comparison of the results obtained with the help of different devices of serial production may be a direction in addressing the issue concerning the effect of comparators on the equivalence of the calibration results of accurate CTs. Besides, given the change of the characteristics of the internal structural elements of such devices in time, it is worth studying the contribution of the readout instability relative to a single reference object in the long run.

3. The aim and objectives of the study

The aim of the study is analyzing and evaluating the measurement parameters in the calibration of current transformers with accuracy class 0.2S and more accurate, taking into account the influence of means for comparing the currents of reference and test transformers. As a consequence, recommendations should be formulated for the use of instruments for determining the errors of current transformers to improve the state of measurement uniformity and equivalence of results.

To achieve the set goal, the following objectives were set:

– to determine basic design differences for in-service devices for calibration of instrument transformers, which can affect readouts and lead to a discrepancy of measurement results;

– to determine the metrological characteristics of laboratory CTs with accuracy classes 0.05 and 0.2 using comparators of different types and to analyze the results obtained concerning their differences;

– to evaluate the difference in the readouts of devices with different measurement principles in the characterization of a laboratory CT with an accuracy class of 0.02;

– to conduct a study of the readout stability of AC comparators designed with a modern element base in the characterization of CTs with accuracy classes 0.05 and 0.2.

4. Determination of basic design differences of devices for calibration of instrument transformers

Among the devices for the comparison of two approximately identical alternating currents, comparators with resistive or inductive input measuring elements are widely used today. In particular, there are several types of resistive and several types of inductive comparators in operation in Ukraine, Russian Federation, Kazakhstan, and other countries. The oldest of them is the K507 apparatus (Tocheleke troprylad Plant, USSR) with mechanical means of balancing common and quadrature component and a galvanometer. This device has input chains of resistive type and two rotation scales with divisions. The absence of a sufficient number of intermediate divisions leads to additional uncertainty of measurements since the operator determines the number of decimal places by himself.

Over the past decade, the K507 apparatus has gradually lost its position by giving way to the CA507 comparator, a modern microprocessor-based measuring unit. This device has much smaller mass-dimensional parameters as well as a liquid crystal display with a sufficiently large number of digits to display measured values, and the above-specified source of uncertainty was compensated in such a way. The measurement shunts are used in the CA507 comparator design to convert the secondary current of the reference transformer as well as to convert the difference of secondary currents. The simplified circuit diagram of input chains of the CA507 comparator is shown in Fig. 1, *a*.

As can be seen from Fig. 1, comparable secondary currents of both the standard I_{2S} and the device under test I_{2X} flow in the measuring circuit in the opposite direction. The terminals S_{1S} and S_{2S} are intended for connecting the working standard, and terminals S_{1X} and S_{2X} are intended for connecting a device under test. It is necessary to pay attention to the presence of a galvanic connection between the secondary windings of comparable transformers because this fact creates additional difficulties in verifying the accuracy of a comparator using the above method [15].

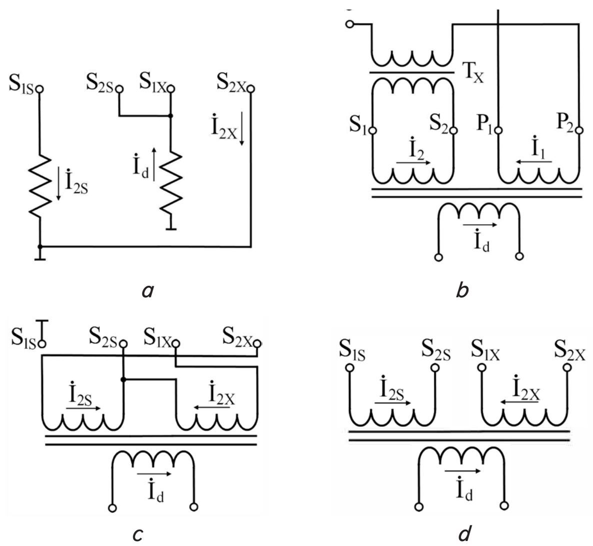

Fig. 1. Simplified circuit diagram of input chains: *a* — CA507 comparator; *b* — K535 calibration device using internal standard; *c* — K535 calibration device without internal standard; *d* — AITTS-98 comparator.

Regarding devices with inductive input transducers, the K535 device for calibration of the instrument transformers (Joint-Stock Company "ROSTOK", Ukraine) was developed in the 1980s, and it is used till now. Such a device consists of two blocks (transformer-electronic and electronic-computing) and contains an internal reference transformer. Due to the presence of the standard, the K535 device allows for the implementation of two variants of comparison: using the built-in standard or using an external reference CT. When using the first option, the simplified electrical circuit of the input measuring elements has the form shown in Fig. 1, *b*. Such a scheme compares the magnetic fluxes created by the scalable primary I_1 and secondary I_2 currents of the calibrated transformer using the standard inductive transducers of the transformer-electronic block of the K535 device. The signal generated by the secondary winding of the magnetic flux comparator is proportional to the difference between scaled currents.

The second implementation option of the K535 device requires the presence of two CTs with the same transformation coefficients. The simplified electrical scheme of the second version is shown in Fig. 1, *c*. As can be seen, in this case, there is also a galvanic connection between secondary windings of the compared transformers.

The AITTS-98 comparator (LLC "Mikro-kod" Ltd, Ukraine) is the second comparator used, which has inductive input elements. This is a more modern automated device, which has a better resolution of readouts and much smaller dimensions because it has no built-in standard. A simplified electrical circuit of the input measuring elements for the AITTS-98 comparator is shown in Fig. 1, *d*. Fig. 1 indicates the absence of a galvanic connection between secondary windings of the compared transformers. This option is the most convenient to perform operations of verifying the accuracy of a comparator.

It is necessary to mention the foreign devices, for example, HGQA-C produced by Wuhan Hance Electric Co. (China), to complete the overview of the AC comparators, which implement the principle of comparing currents in the range from 0.01 A to 6 A, that is, allow to determine the normalized RE and PD of CTs according to IEC 61869-2. Unfortunately, the high-cost devices for alternating current comparison like the 2767 automatic instrument transformer test set, produced by Tettex Instruments Inc. (Switzerland), were not distributed on the territory of the mentioned countries of Eastern Europe.

It should also be noted that the CT Analyzer device for testing the transformer parameters, produced by Omicron Electronics GmbH (Austria), is also used at a few enterprises. Note that the operation principle of such a device is fundamentally different from the previously described instruments.

5. Methods of researching the equivalence of measurement results when using AC comparators

The equivalence level of the measurement results of RE and PD of reference transformers was investigated using a measure of current difference consisting of the I512 transformer (Tochelektroprylad Plant, USSR) with accuracy class 0.05 and I515 transformer (Tochelektroprylad Plant, USSR) with accuracy class 0.2. In addition to the specified CTs, the I561 transformer (Tochelektroprylad Plant, USSR) with accuracy class 0.02 was also used to specify the dubious results of the research.

As noted above, RE and PD are determined by special devices, which should also pass the procedure for checking the accuracy of the readouts. The specified measure of current difference is used by the laboratory to determine metrological characteristics of the AC comparators during calibration. The AC comparator is a device that compares 2 almost identical currents. The working range of an industrial CT is from 0.01 A (0.05 A) to 1.2 A (6 A) and the most relevant is the frequency of the industrial power systems since TCs are mainly used for electricity metering. Conventional comparators operate in the current range corresponding to the working range of CTs, which according to the standard IEC 61869-2 should operate in the range from 1 to 120 % of the rated current [17]. Rated current usually is 1 or 5 A. To maximally cover the specified current range, we selected rated primary current of 5 A, and a rated secondary current of 5 A of both the I512 and I515 transformers. Reference CT with accuracy class 0.05 allows estimating the level of equivalence in measuring RE of about 30 μA/A, and PD of about 30 μrad. Reference CT with accuracy class 0.2 allows estimating the equivalence level when measuring RE of about 650 μA/A, and PD of about 120 μrad (2,000 μA/A, and 1,500 μrad at a current of 0.05 A).

In this research, the readouts of 5 devices for calibration of the instrument transformers were compared: comparators CA507, AITTS-98, HGQA-C, calibration device K535, and a means for testing the transformers CT Analyzer CT1 (Omicron Electronics GmbH, Austria). We recorded displayed readouts of the devices listed above with tenfold repetition at 5 points of the current range according to IEC 61869-2: 0.05 A, 0.25 A, 1 A, 5 A, and 6 A at an industrial frequency of 50 Hz. The measurement scheme is shown in Fig. 2.

The CTs with only two windings were used in the research, and this circumstance minimized the number of uncertainty sources in the measurement. During the research, the same conductors were used all the time to connect to the terminals of the comparator to eliminate this source of uncertainty. Since the reference transformer is usually used in the calibration laboratory as a standard, it is rational to connect its secondary winding to the comparator terminals intended for the reference CT. Therefore, its primary winding must be connected to the terminals intended for the device under test. The current source should be included in the primary current circuit to bring the measurement procedure as close as possible to the calibration process.

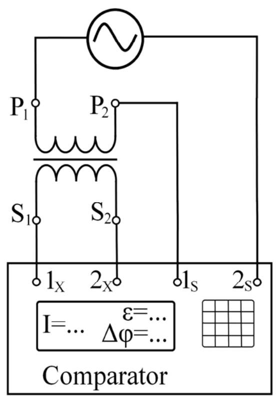

Fig. 2. Measurement scheme for recording readouts of comparators

The measurement results were analyzed for the discrepancy between the obtained values. To determine the possible change in the instrument readouts, in the long run, six CA507 comparators were also investigated in a 1-year interval. The scheme, depicted in Fig. 2, was also used to study the latest characteristic. The CA507 type of comparators was selected as a type that is most commonly used in Ukraine, Russian Federation, Kazakhstan, and other countries and a maximum duration of exploitation of the CA507 comparators did not exceed 12 years from the date of production.

More meticulous attention was paid to comparing and analyzing the device readouts with the alternative method of determining RE and PD of CTs (produced by Omicron Electronics GmbH, Austria). According to the user manual, the processor of this instrument calculates the required characteristics based on the formulas derived from the equivalent circuit, and the result is influenced by ambient temperature, electrical resistance of the secondary winding, etc. The calculation of the RE is based on the excitation table. With a given excitation voltage, the excitation table allows finding the corresponding excitation current and the phase between them [18]. According to the technical documentation, the accuracy of the measurement by this device is 200 μA/A for RE and 290 μrad for PD. The calibration certificate issued by the KEMA lab gives an uncertainty of measurement 220 μA/A for RE and 290 μrad for PD.

6. Research results of the effect of means for determining errors of calibrating current transformers on the equivalence of the results obtained

6. 1. Differences in measurement results in the characterization of laboratory current transformers with accuracy classes 0.05 and 0.2

During the research, determining RE and PD of 2 reference CTs (I512 with an accuracy class of 0.05 and I515 with an accuracy class of 0.2) for the ratio 5 A/5 A was performed according to Fig. 2. The ambient conditions were maintained within normal limits. Each measurement consisted of 10 repetitions, but to simplify the perception of information and due to small magnitude, standard deviations have not been given. Table 1 shows the readouts of instruments when the I512 transformer was connected to the measuring circuit.

Table 1

Readouts of instruments in determining metrological characteristics of I512 current transformer

Devicetype	Error	Value of error[b] depending on magnitude ofcompared currents in amperes				
		0.05	0.25	1.00	5.00	6.00
CA507	ε	–19	–23	–24	–34	–37
	Δϕ	116	111	90	41	35
K535	ε	–160	–60	–95	–50	–55
	Δϕ	29	58	29	0	29
K535[a]	ε	–120	–20	–60	–20	–20
	Δϕ	–29	–58	–29	29	0
AITTS-98	ε	–63	–60	–60	–68	–70
	δ	105	87	70	26	20
HGQA-C	ε	–20	–20	–21	–28	–31
	Δϕ	87	93	76	32	26
CT Analyzer	ε	–30	–30	–30	–50	–50
	Δϕ	99	96	81	52	47
Mean	ε	–69	–36	–48	–42	–44
	Δϕ	67	64	52	29	26

Note: [a] – Readouts obtained using the built-in standard; [b] – Measurement error consists of 2 components: ratio error (ε) expressed in μA/A and phase displacement (Δϕ) expressed in μrad

In Table 1, one can see that all the devices gave similar values of REs and PDs of the I512 transformer in the range of current from 0.25 A to 6 A except the K535 calibration device. This device in the mode of using the internal reference transformer gave a relatively lower value of PD at 6 A, and significantly larger value of RE at 1 A without the internal measure. It should be noted that this calibration device has been in operation for more than 30 years and is likely to have some technical wear and tear of the internal elements and is morally obsolete. The contribution of an internal reference transformer, which shifts the errors of the investigated I512 transformer, should also be considered. We have to pay attention to a significant difference in the K535 device readouts at the lower point of 0.05 A, which may be explained by high vulnerability to noise at the lower limit of the current measurement range. In general, the maximum difference in readouts in the whole current range with regard to the readouts of all the devices studied was 140 μA/A at 0.05 A for RE, and 169 μrad for PD at 0.25 A. Excluding the K535 calibration devices from the list of devices analyzed, the maximum difference was 43 μA/A at 0.05 A for the RE, and 29 μrad for PD at 0.05 A.

Table 2 shows the readouts of instruments when the I515 transformer was connected to the measuring circuit. The devices gave relatively close values of the REs and PDs of the I515 transformer in the current range from 1 to 6 A taking into account the accuracy class. The noticeable deviation of the readouts of the K535 device of the phase component in both application modes may be attributed to the technical wear of internal elements. In this case, the contribution of the internal reference transformer is less noticeable due to the larger magnitude of the I515 errors. The sharp difference in readouts of the comparator HGQA-C at 0.25 A could be caused by a slightly lower load of the secondary winding of CT, which could result in a slight shift in the change point of the RE sign.

Table 2

Readouts of instruments in determining metrological characteristics of I515 current transformer

Device type	Error	Value of error[b] depending on magnitude of compared currents in amperes				
		0.05	0.25	1.00	5.00	6.00
CA507	ε	–2,110	–490	500	660	660
	Δϕ	–1,661	–1,274	–198	148	148
K535	ε	–2,010	–810	310	580	590
	Δϕ	–1,280	–1,673	–553	–320	–305
K535[a]	ε	–2,030	–840	270	540	560
	Δϕ	–1,193	–1,716	–524	–335	–320
AITTS-98	ε	–2,100	–500	510	660	670
	Δϕ	–1,161	–1,219	–218	116	119
HGQA-C	ε	–2,010	–90	530	640	640
	Δϕ	–1,076	–559	–61	143	145
CT Analyzer	ε	–2,052	–546	424	616	624
	Δϕ	–1,274	–1,288	–311	–50	–43
Mean	ε	–2,110	–490	500	660	660
	Δϕ	–1,661	–1,274	–198	148	148

Note: [a] – Readouts obtained using the built-in standard; [b] – Measurement error consists of 2 components: ratio error (ε) expressed in µA/A and phase displacement (Δϕ) expressed in µrad

In general, according to Table 2 in the whole range of current, the maximum difference in readouts was 750 µA/A at 0.25 A for RE, and 1157 µrad for PD at 0.25 A taking into account the readouts of all the devices studied. Excluding the K535 calibration devices from the list of devices analyzed, the maximum difference was 456 µA/A at 0.25 A for RE, and 729 µrad for PD at 0.25 A. The obtained results show that RE of the investigated TC changes the sign from plus to minus in the current range from 0.25 A to 1 A. In this case, the value of RE strongly depends on the accuracy of setting the current of 0.25 A and the load of the measuring elements of the comparator. Therefore, given this circumstance, as well as the requirements of the IEC 61869-2 standard for errors of CT with accuracy class 0.2S, it is worth considering the scattering of the readouts of the devices in the range of current from 0.25 A to 6 A. The maximum span between readings in this range was 260 µA/A for RE, and 492 µrad for PD at 0.25 A.

One can conclude about the equivalence of the measurement results by determining the difference between the most different results obtained by different means under approximately the same conditions. In the study, better value can be obtained by excluding the results of the obsolete K535 calibration device. Thus, a better equivalence value would be 43 µA/A for RE, and 29 µrad for PD, or (assuming some conditional average) approximately ±20 µA/A and ±15 µrad when rounded. As for the errors of CT with an accuracy class of 0.2S, it is expedient to evaluate the equivalence level taking into account all the comparators in use. A large number of laboratories are concerned with the determination of RE and PD of transformers and, to a greater or lesser extent, affect the overall state of uniformity of measurements in this area. The 0.05 A point can be excluded since there is a significant influence of electromagnetic interference on the readouts of the K535 device, as well as the three times reduced requirement for the errors of CT. Given this, the equivalence level will be approximately ±130 µA/A and ±250 µrad when rounded.

6. 2. Difference in the readouts of devices with different measurement principles in the characterization of a laboratory CT with an accuracy class of 0.02

During multiple experiments, a few measurement results were recorded that are significantly different from the others. The technical characteristics of CT Analyzer CT1 were analyzed [18]. It is noted that the readouts of this device depend on the resistance of the secondary winding, ambient temperature, connection diagram with the measurement object and so on. Concerning the use of a 2-wire or 4-wire scheme, no significant difference in CT Analyzer CT1 readouts was detected. The ambient temperature of 21 °C was entered into the memory of the instrument to calculate the measurement result. This value had no decisive influence on the result of the calculation. The result of the measurement of the secondary winding resistance of the I515 transformer, which was 0.096 Ohms, was recorded (for the I512 transformer, this parameter was 0.819 Ohms). The discrepancy in the values of the resistance created the assumption that the measurement results of the I515 errors were distorted due to this factor. Therefore, it was further decided to compare the measurement results of the I561 transformer with an accuracy class of 0.02. This object had a secondary winding resistance of 0.16 Ohms, which is much closer to the I515 winding resistance value. To test the consistency of the readouts, we compared the results obtained using two devices (CA507 comparator and CT Analyzer CT1) with fundamentally different measurement principles. To increase the amount of information received, we decided to get RE and PD of an object depending on the load of the secondary winding of 1.25 VA and 5 VA. The results are presented in Table 3.

Table 3

Readout comparison of CA507 comparator and CT Analyzer CT1

Device type, load	Error	Value of error[a] depending on magnitude of compared currents in amperes				
		0.05	0.25	1.00	5.00	6.00
CA507 1.25 VA	ε	10	8	4	–11	–13
	Δϕ	218	198	183	140	134
CA507 5 VA	ε	–90	–101	–100	–96	–94
	Δϕ	262	259	236	160	145
CT Analyzer 1.25 VA	ε	20	20	20	10	10
	Δϕ	166	163	154	125	119
CT Analyzer 5 VA	ε	–90	–90	–90	–80	–80
	Δϕ	262	253	230	154	143

Note: [a] – Measurement error consists of 2 components: ratio error (ε) expressed in µA/A and phase displacement (Δϕ) expressed in µrad

The results of the comparison are also presented in graphical form for more convenient perception in Fig. 3 and Fig. 4.

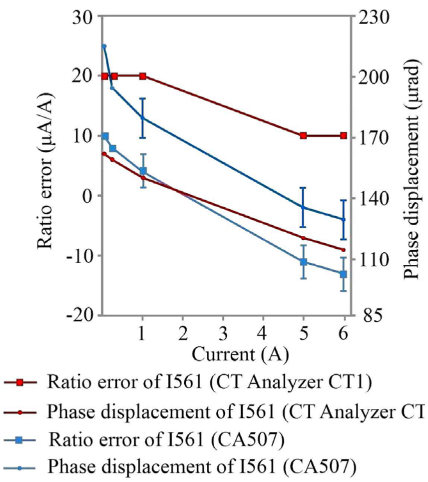

Fig. 3. Comparison of readouts of both CA507 comparator and CT Analyzer CT1 with I561 transformer loaded by 1.25 VA

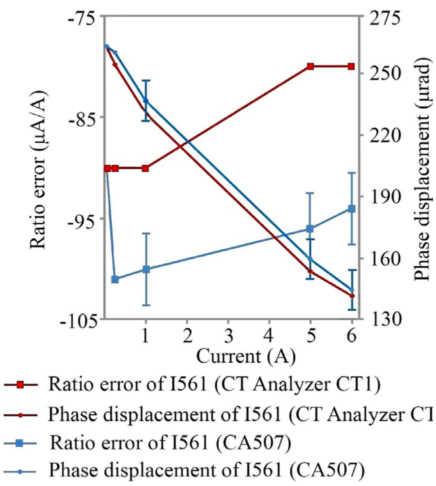

Fig. 4. Comparison of readouts of both CA507 comparator and CT Analyzer CT1 with I561 transformer loaded by 5 VA

Fig. 3 shows that the results obtained by two different devices are fairly tightly spaced relative to each other at all measurement points, including 0.05 A. In the form of an error bar, the intrinsic uncertainty of the CA507 comparator is shown in accordance with the specification for points 1 A, 5 A and 6 A. For points 0.05 A and 0.25 A, uncertainty is not reflected due to its large magnitude (15 and 75 times larger than for 1 A). The intrinsic uncertainty of CT Analyzer CT1 is also not reflected in the figure because of a large value. This characteristic is 220 μA/A, and 290 μrad, and the error bars would be out of the picture, and additional lines would complicate the perception of graphical information. The maximum difference in the readouts of the two devices when setting the load of 1.25 V·A was 23 μA/A for RE and 52 μrad for PD. The difference obtained for RE exceeds approximately 10 times the measurement uncertainty when using the CA507 comparator, and for PD, it is about 6 times. However, the CT Analyzer CT1 has a large margin of uncertainty in this sense, which makes it easy to cover the differences. It should be noted that the resulting difference in the readouts is about 10 times less for RE and 6 times for PD compared to the measurement uncertainty when using CT Analyzer CT1.

As for the difference in the readouts when setting the load of 5 V·A, the maximum difference was 16 μA/A for RE and 6 μrad for PD. As can be seen in Fig. 4, the PD results are overlapped with only intrinsic uncertainty of CA507. For RE, the ratio of the difference in the readouts to the intrinsic uncertainty of CA507 was about 8 times. It is noticeable that the difference in the readouts of the tested devices decreased with the increase in load. However, when applying burden during calibration, another source of uncertainty arises that affects the equivalence level. Each calibration laboratory has its burden with unique metrological characteristics.

The results of the comparison showed a fairly high level of equivalence of the measurement results with a maximum difference of 23 μA/A for RE and 52 μrad for PD at a load of 1.25 VA.

6. 3. Comparator readout stability in the characterization of current transformers

To evaluate the 1-year readout stability of the comparator, reference CTs can be used from a complement of the measure of current difference, which was described earlier. These are I515 and I512 transformers, the errors of which were repeatedly determined over the last 3 years. The readouts of about 50 comparators were recorded in determining their metrological characteristics, which allowed us to find the reference values of RE and PD [5]. But in the mentioned work, we evaluated the readouts of several types of comparators. In contrast to the previous work, in the study of the stability of the comparator readouts in the long-term application, measuring RE and PD was performed using 4 or 6 comparators of the same CA507 type. In the operating range of current from 0.05 A to 6 A at an interval of 1 year, the errors of the I515 and I512 transformers were determined using the measurement scheme depicted in Fig. 2. Ambient conditions were maintained within normal limits. Each measurement consisted of 10 repetitions, but to simplify the perception of information and due to small magnitude, standard deviations have not been given.

Fig. 5 represents graphically the results of determining the 1-year readout stability as the difference of the readouts separated in time at an interval of 1 year. The current range point of 0.05 A for the I512 transformer and the I515 transformer is presented as variant *a* and variant *d*, respectively. The current range point of 0.25 A for the I512 transformer and the I515 transformer is presented as variant *b* and variant *e*, respectively. The current range point of 1 A for the I512 transformer and the I515 transformer is presented as variant *c* and variant *f*, respectively. The readouts at a point of 1 A did not differ much from the readouts at points of 5 or 6 A. For all variants of the determined stability values in Fig. 6, the average values (solid lines) and the type B uncertainties corresponding to measured RE and PD (dash lines) according to the manufacturer specification are depicted by the appropriate colors.

One can see in Fig. 5 that the maximum 1-year shift at a current of 0.05 A using the I512 transformer did not exceed 17 μA/A, which is almost 100 % of the measured value for RE. At the same current, the maximum 1-year shift in the PD measurement was 23 μrad, that is, about 20 % of the measured value. At a current of 0.25 A, the maximum 1-year shift did not exceed 5 μA/A, which is about 20 % of the measured RE value. At the same current, the maximum 1-year shift in the PD measurement was about 15 μrad, that is, about 12 % of the measured value. One can see in Fig. 5, *c* that the maximum 1-year shift for the investigated instruments at a current of

1 A did not exceed 5 μA/A, which is about 20 % of the measured RE value using the I512 transformer. The maximum 1-year shift was about 15 μrad when measuring PD at a current of 1 A, which is about 8 % of the measured value.

which is about 10 % of the measured RE value at a current of 0.25 A. At the same current, the maximum 1-year shift in the PD measurement was about 190 μrad, that is, about 15 % of the measured value.

Concerning current of 1 A, the maximum 1-year shift did not exceed 38 μA/A, which is about 8 % of the measured RE value. For PD, this parameter was about 110 μrad, that is, almost 50 % of the measured value.

7. Discussion of results of researching the effect of means for current transformer characterization on the equivalence of results obtained

According to the results of determining the 1-year readout stability of the CA507 comparators, it should be noted that there were random errors relative to the mean of the readouts of the comparators studied. The span of the obtained results can be considered as an expanded uncertainty when determining RE and PD of CT with an accuracy class of 0.05 or 0.2. Thus, the expanded uncertainty evaluated for the compared currents of about 0.05 A and in the range of compared currents from 0.25 A to 6 A is presented in Table 4. Also, Table 4 shows the results of CA507 comparator readout stability.

One can see the existence of a relationship between the readout stability and the magnitude of RE and PD, as follows from Table 4. The same applies to the dispersal of measurement results (Tables 1, 2). The larger the measured value, the smaller the relative instability.

Since observations were made in a measuring circuit consisting of CT, a comparator, and connecting conductors, probable sources of random displacement of the readouts may be parasitic elements of the circuit, electromagnetic interference, characteristic change or damage of the circuit elements.

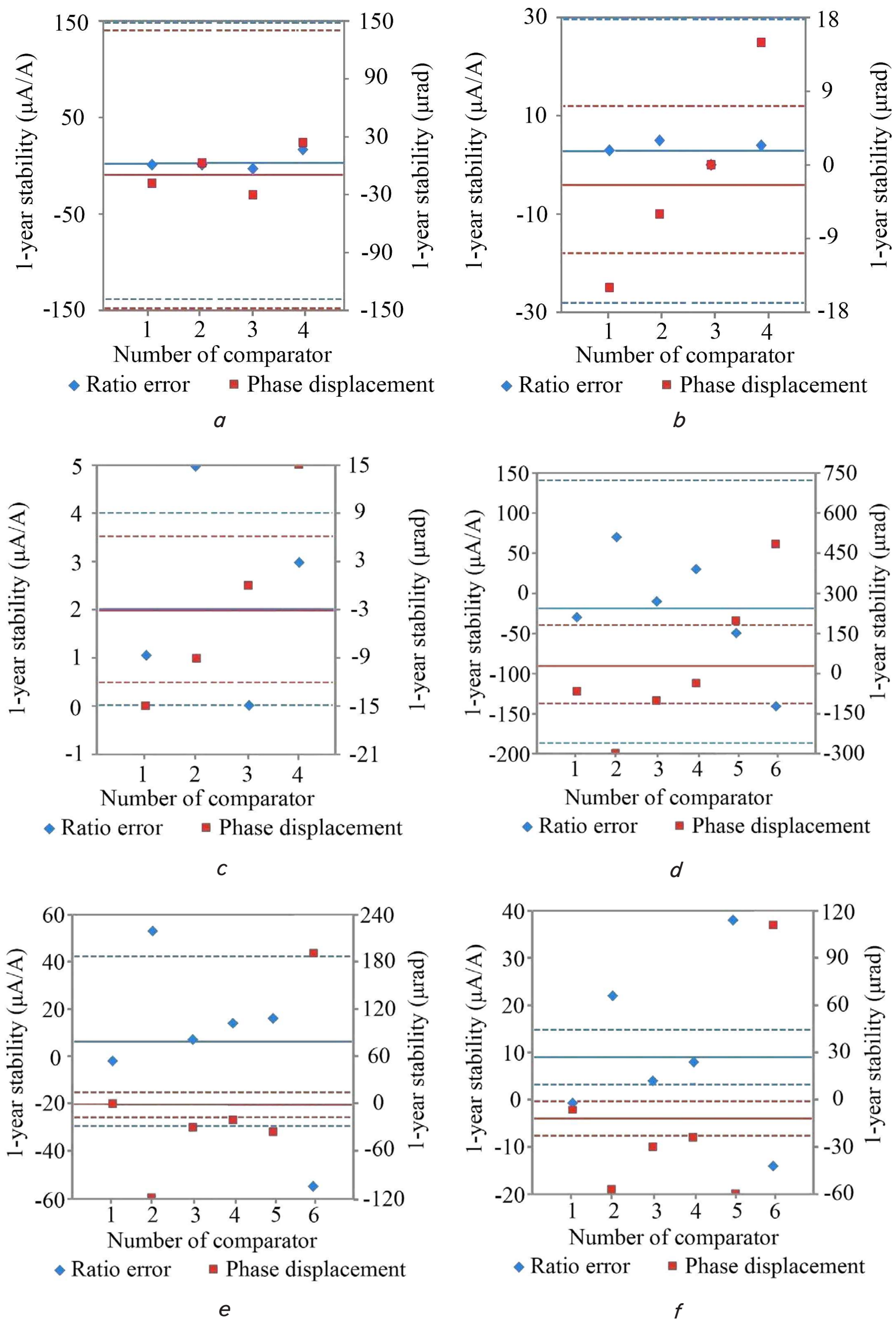

Fig. 5. Results of determining the 1-year readout stability of CA507 comparators at points: *a* – 0.05 A using I512 transformer; *b* – 0.25 A using I512 transformer; *c* – 1 A using I512 transformer; *d* – 0.05 A using I515 transformer; *e* – 0.25 A using I515 transformer; *f* – 1 A using I515 transformer

The analysis of the results obtained in studying the readouts of the comparators using the I515 transformer has shown (Fig. 5) that the maximum 1-year shift did not exceed 140 μA/A, which is about 7 % of the measured RE value at a current of 0.05 A. The maximum 1-year shift in the PD measurement at the same current was about 470 μrad, that is, about 30 % of the measured value. One can see in Fig. 5, *e* that the maximum 1-year shift did not exceed 55 μA/A,

If we consider the values of the measured RE and PD at a current of 1 A as the equivalent values of the current difference, one can estimate the ratio between the current difference and its amplitude component. In the case of determining RE and PD of the I512 transformer, the amplitude component gives a significantly lower contribution to the total value of the current difference, and the orthogonal components in the vector-measuring ADC are measured on an appropriate scale. In the case of the I515 transformer, the ratio is less relevant due to the significant magnitude of the amplitude component.

Table 4

Expanded uncertainty and readout stability of CA507 comparators

Current, A	Ratio error, μA/A			Phase displacement, μrad		
	Mean	Expanded uncer-tainty	Readout stability	Mean	Expanded uncer-tainty	Readout stability
0.05	–21	16	17	122	30	23
0.25...6	–32	6	5	41	16	15
0.05	–2,140	360	140	–1,130	340	470
0.25...6	620	90	55	135	150	190

In general, the results of the comparison of two fundamentally different devices (CA507 comparator and CT Analyzer CT1) for the determination of RE and PD of CTs gave approximately one level with the results of evaluating the annual readout stability of several comparators of the same type.

With the elimination of technically and morally obsolete devices for comparison, the results of the study allow us to assume the level of equivalence of the RE measurement results of about 50 μA/A within ±20 μA/A. For the PD measurement results, such a parameter can be assumed within ±15 μrad when measuring about 50 μrad.

In the case of calibration of CT with an accuracy class of 0.2S regarding all the exploited comparators except CT Analyzer CT1, the level of equivalence can be within ±130 μA/A in the current range from 1 A to 6 A. For PD measurement results, such a parameter can be assumed within ±250 μrad, and this is also part of the uncertainty of the transformation coefficient. Such a contribution to the uncertainty of measurements in conjunction with the influence of load and connecting conductors sets additional requirements for the accuracy margin in the production of CTs with an accuracy class of 0.2S.

Fig. 5 shows that the intrinsic uncertainty of the CA507 comparator stated in the specification is insufficient to overlap the dispersal of the measurement results of PD for both accuracy classes 0.05 and 0.2 at currents higher than 0.25 A. Furthermore, the uncertainty (200 μA/A) due to the application of the investigated CT Analyzer CT1 is underestimated. The results obtained using such a device had an order of magnitude better concordance with the readouts of the other comparators.

Comparing the results with the results of international comparisons for the current ratio 5 A/5 A, it should be noted that the latter relates to the highest level of accuracy of the leading national labs. The comparison was implemented mainly by scientific personnel at unique facilities, including complexes of measuring instruments. At the same time, the discrepancies in the measurement results of some participants were 20 μA/A, 30 μA/A and even 70 μA/A for RE when the rated current flowed. The present research relates to the level of equivalence of day-to-day measurement results and considers the impact of only comparators, including the contribution of long-term readout stability.

According to the research, several comments and recommendations can be formulated. According to the results of determining the magnitude of the discrepancy between the measurement results, it should be noted that the decommissioning of obsolete K535 (also K507) devices can have a positive effect on the state of uniformity of measurements in the area. At the very least, we should refuse applying the measurement results using the K535 calibration device at 0.05 A. Clarifying the loading effect of the comparator measuring circuit and taking it into account in the uncertainty budget can also be the way of reducing the discrepancy between the results obtained.

According to the results of studying the difference in the CA507 comparator and CT Analyzer CT1 readouts, the question arises whether the intrinsic uncertainty of the second instrument is not too overestimated. It is more expedient to reduce its magnitude, for example, by calibration when compared with a comparator that has a much smaller measurement uncertainty.

When determining the stability of the CA507 comparator readouts, the values that exceed the allowable specification limits were recorded. Thus, according to Table 4, the stability of measuring –32 μA/A was 5 μA/A, although the manufacturer defined the uncertainty of this device as 2 μA/A. Although the 1-year change in the comparator readouts is affected by both instrument instability and CT instability, the results of the study showed a discrepancy in measurement results over one day above 2 μA/A. This fact cannot be attributed to the instability of the laboratory TC. Therefore, it would be advisable for the manufacturer to increase the margin of error set in the specification for a current greater than 1 A.

The consumer of calibration services in the context of the research should avoid using different types of comparators simultaneously (or as a substitute). This approach will avoid, or minimize, the shift of the results of the error determination of CT if the loading effect of the comparator is not taken into account. ITs manufacturers must either take into account the comparator loading effect or minimize the errors of TC with an accuracy class of 0.2S to overlap the readout discrepancy of about 260 μA/A and 500 μrad.

The results of the study may also be of interest in the context of the international recognition of measurement results in exporting measuring equipment. The reason is that an accuracy class of 0.2S of CTs is often used in power engineering, and the deviations recorded in the study can make a critical contribution to calibration results.

The direction of further development of the current research may be determining the impact of the load means of the CT secondary winding, that is, a burden, on the equivalence of the results. In this case, one option may be loading one CT using one burden when using different comparators. An alternative may be loading one CT using the burdens of different types when using one comparator.

It may also be interesting to study the degree of influence of ambient temperature on the measurement results obtained. In the design of the CA507 comparator, one measuring channel is used both to determine the current difference and to determine the current of the reference CT. Two measuring shunts are different, but the shunt manufacturer is the same, and the temperature shift is probably going in one direction. The shift of RE and PD under the influence of temperature on laboratory CT within ±5 °C probably has a small value. Therefore, it may be appropriate to extend the temperature range for laboratory calibration without a significant increase in measurement uncertainty.

8. Conclusions

1. It has been found that one of the factors in the discrepancy of measurement results of comparators of different types is the structural difference of measuring circuits. Two main types of input measuring elements (resistive or inductive) of measuring equipment intended for calibration of current transformers were distinguished. Among such comparators in service, four options of measuring circuits were distinguished. Each option has connection features that affect comparator readouts.

2. The study of the discrepancy of measurement results in determining the metrological characteristics of CTs clearly showed the existence of a direct correlation between the measured value and the span between the measurement results and, consequently, the equivalence level. Analyzing the results obtained, it has been found that the maximum difference in readouts was 140 μA/A at 0.05 A for the ratio error. For phase displacement at 0.25 A, the maximum difference was 169 μrad for the accuracy class of 0.05. As for the 0.2 accuracy class, the maximum difference in readouts was 750 μA/A at 0.25 A for the ratio error. For phase displacement, this parameter was 1157 μrad at point of 0.25 A.

3. The study of the difference in the readouts of two instruments with fundamentally different measurement methods in determining the errors of a high-precision transformer allowed us to assume an overestimation of intrinsic uncertainty of CT Analyzer CT1. The ratio of the intrinsic uncertainty of CT Analyzer CT1 to the resulting difference in readouts (23 μA/A, and 52 μrad) was at least 10 times in determining the errors of the transformer with an accuracy class of 0.02.

4. An important parameter for the precision measurement industry has been determined, that is, the stability parameter of the modern CA507 comparators developed using an actual elemental base. When determining the metrological characteristics of both current transformers I512 with a class of accuracy of 0.05 and I515 with a class of accuracy of 0.2, the results have been obtained with an interval of 1 year. In this case, the poorer value of stability has been determined at the level of 140 μA/A for ratio error, and 470 μrad for phase displacement.

Summarizing, it should be noted that the better equivalence level of the calibration results of current transformers with an accuracy class of 0.2S and more precise, taking into account the effect of comparators of different manufacturers, has been estimated for: a) the result of determining the ratio error of about 50 μA/A –within ±20 μA/A; b) the result of determining the phase displacement of about 50 μrad – within ±15 μrad.

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