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Precise Low-Cost Method for Checking Accuracy of Current Transformers Calibration Unit

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Abstract **– The paper presents a method for checking the accuracy of the commercial AC comparators used to calibrate current transformers. This method is simple and convenient and requires no special means of minimizing measurement uncertainty. Only conventional measuring instruments are used making this method cheaper for large amounts of laboratories. The analysis of the currents interrelation of a calibrated transformer and working standard allowed us to derive mathematical models of errors. The obtained models of the ratio error and phase displacement allow simulating different ratios of secondary currents. With the help of the proposed scheme, one can investigate the correctness of comparator readout. The obtained expressions of sensitivity coefficients made it possible to estimate the measurement uncertainty of the simulated reference values. The results of simulating errors from 1 to 1200 ppm for ratio error and phase displacement are presented. Reference values were compared with those obtained using a commercial comparator.**

I. INTRODUCTION

The applied metrology engineers often have a task to perform measurements to define the relative difference between two similar in amplitude and initial phase values of the alternating current. Determining the amplitude and phase corrections of the scale transducers of alternating current is performed in practical terms at measuring laboratories where the comparison technique often being applied using the comparator of the output current of the device under test (DUT) and the standard scale transducer [1] with acceptable uncertainty of measurements.

The paper is aiming at suggesting the reliable method for determining the metrological performance of the current transformer (CT) calibration unit and evaluating the uncertainty of measurements during its calibration. This is an urgent task as a large number of current scale converters, such as CTs, are used in all countries of the world.

To characterize the contribution of the work and to determine the place in the body of the instrumentation and measurement it should be noted that the mathematical models for determining the reference values of ratio error (RE) and phase displacement (PD) allow checking the accuracy of CT calibration unit (i.e., comparator of two approximately equal currents) in an alternative way using the proposed measurement scheme. According to the obtained models, it is easy to calculate the contribution of each input quantity and to estimate the expanded uncertainty both in determining RE and in determining PD.

II. RELATED MATERIALS

The energy sector deals with electricity accounting and the accuracy of energy accounting is steadily increasing. CTs have often accuracy class of 0.2S or 0.5S according to the IEC standard and contribute to the accuracy of electricity accounting [2]. Almost all states have calibration laboratories that perform CT calibration, but not every laboratory is capable of calibrating a working standard with a measurement uncertainty of 50 μA/A, and less.

When calibrating CTs with an accuracy class of 0.2S, the contribution to the total uncertainty from the use of the measuring bridge can be more than 90% of the contribution of all the influencing variables when determining RE value of 480 μA/A [3]. An important component of the CT calibration system is the means of comparing current of working standard and current of DUT, e.g., the contribution of the PTB's bridge (Germany) has a level of several hundredths of μA/A [4]. However, this level of measurement uncertainty is only reached by some National Metrology Institutes, providing special conditions for calibration.

The system for calibrating an automatic transformer test set using a current source with an operational amplifier was developed at the Czech Metrology Institute

(CMI). The procedure involves reaching the condition when the error current is in phase with the standard current when determining the ratio error. To determine the phase displacement, the shift of the error current by 90 degrees relative to the current through the standard current measurement circuit must be achieved [5]. The method, developed in TUBITAK UME (Turkey), intended for determining the errors of the current transformer test sets allows characterizing these tools with a total uncertainty of 10 ppm [6]. In this method, an increment of simulated errors is limited to the discreteness of the PC-controlled three-phase power source, and a step of changing the ratio of turns of the electronically-compensated current comparator corresponds to 0.5 %.

This paper proposes a method to achieve measurement uncertainty of several tenths of μA/A when calibrating a commercial CT calibration unit under normal common laboratory conditions. It should be noted that the proposed method allows characterizing commercial AC comparators without the requirement of in-phase currents or a 90° angle shift. In the method proposed, it is also possible to achieve the measurement uncertainty less than 1 ppm in simulating the lowest error values. Moreover, the proposed analytical expressions make it easy to calculate both the magnitude of the reference values and the associated measurement uncertainty.

The design features and factors that affect the accuracy of one of the commercial comparators are described in a developer article. In particular, it is stated that the accuracy of such a measuring instrument should not exceed 1 percent of the measurement result [7]. According to the user's guide of the CA507 comparator, the minimum intrinsic uncertainty is 2 μA/A when measuring RE. The analogous figure for PD measurement is 8.73 μrad.

There are a large number of commercial comparators, and the user could check the accuracy of such device using conventional precision measuring instruments by the method proposed. The measurement setup was tested repeatedly using CA507 comparators. Also, the results can be extended to other types of comparators of almost identical currents, such as AITTS (India) or HGQA-C (China), which were characterized by the method that differs from the described one by the use of an oscilloscope for determining the phase shift angle and has somewhat worse mathematical processing [8].

III. IMPLEMENTATION OF METHOD

A. Simulation of Current Difference

The comparator produced in Ukraine is structured in such a way that its design has a measuring circuit where the current phasor is measured. This phasor is a result of subtracting of two currents, i.e. DUT current and standard scale transducer current. This measuring circuit converts the specified current phasor and the output current phasor of the standard scale transducer into voltage drop during its passing through a certain measuring shunt. Further, the measurement information is converted into digital codes by the analog-to-digital converter to calculate the ratio of the current difference phasor to the phasor of the standard scale transducer current. In the usual operation of a comparator, there is a comparison of two currents. The current difference between two currents I_d flows through the certain input circuit and the current I_S of the reference transformer flows through the other measuring circuit. The DUT current I_X is absent inside the device and the comparator indicates the values of RE and PD.

Let us consider the case where the DUT current will exceed the amplitude of the reference transformer current, as shown in Fig. 1.

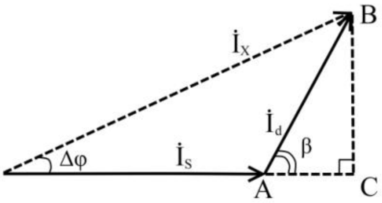

Fig. 1. Interrelation between currents.

The angle β is the angle between the phasors of I_d and I_S currents. To define the characteristics of the interrelation of both DUT current and the working standard current, it is necessary to determine the unknown elements of the triangle in Fig. 1. The segment AC is:

$$AC=\left|I_d\right|\cdot\cos\beta\ . \tag{1}$$

The segment BC is:

$$BC=\left|I_d\right|\cdot\sin\beta\ . \tag{2}$$

Since there is no secondary current I_X in the circuit during the simulation, its value must be expressed taking into account the expressions (1) and (2):

$$\left|I_X\right|=\sqrt{\left|I_S\right|^2+2\cdot\left|I_S\right|\cdot\left|I_d\right|\cdot\cos\beta+\left|I_d\right|^2}\ . \tag{3}$$

RE is the relative difference between the two currents, so taking into account the expression (3), the following equation can be obtained to determine RE (ε):

$$\varepsilon_X=\sqrt{1+2\cdot\left|I_d\right|/\left|I_S\right|\cdot\cos\beta+I_d^2/I_S^2}-1\ . \tag{4}$$

It should be added that when considering the variant of the interrelation of phasors I_d and I_S, in case of excess in the amplitude of the current I_S, in expression (4) the sign before 2 changes to the opposite. Moreover, the value of ε_X also is changed only by a sign.

Concerning PD (Δφ), it is determined from the ratio of the sides of the triangle in Fig. 1:

$$\tan\ \Delta\varphi\ = \mathrm{BC}\big/\ |\mathrm{I_S}| - \mathrm{AC}\ . \tag{5}$$

The use of an inverse trigonometric function allows us to determine the expression for PD determination:

$$\Delta\varphi_X = \mathrm{atan}\cdot\Big[|\mathrm{I_d}|\cdot\sin\beta\big/\ |\mathrm{I_S}| + |\mathrm{I_d}|\cdot\cos\beta\ \Big]. \tag{6}$$

When considering the variant of the relationship of phasors $\mathrm{I_d}$ and $\mathrm{I_S}$, in case of exceeding the amplitude of the current $\mathrm{I_S}$, there will be no change in expression (6). Since in this case, it is necessary to consider a right-angled triangle with a known angle (π – β).

B. Measurement Setup

The suggested technique allows calibrating the CT calibration unit by using the measuring scheme presented in Fig. 2.

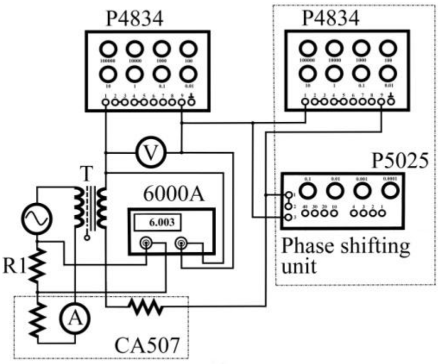

Fig. 2. The electrical scheme of AC comparator calibration.

Let us consider the elements of the measuring scheme for determining the relative current difference. It should be used, a precision CT (T) as a stable alternating current scaling element to calibrate AC comparator. The secondary current is estimated to be smaller than a percent (or one-tenth of a percent) of the primary current. It means that T secondary current simulates current difference $\mathrm{I_d}$ between DUT and reference transformer.

The elements of the measuring circuit are connected in such a way that $\mathrm{I_d}$ creates a voltage drop at the left P4834 resistance decade box as well as at the right measuring shunt of CA507 comparator. A precision AC voltmeter is used to estimate the value of $\mathrm{I_d}$ through the Ohm's law:

$$I_d = U_{RDB}/R_{RDB}\ , \tag{7}$$

where U_{RBD} is a voltage drop caused by current $\mathrm{I_d}$ that flows through the left P4834 resistance decade box; R_{RBD} is a true value of the left P4834 resistance decade box.

To account for the branching of the current between the left P4834 resistance decade box and the precision voltmeter input circuit, the value of $\mathrm{I_d}$ was also corrected by the input of the K_{IM} branching factor. The current flowing in the reference CT circuit can be estimated using the built-in ammeter of the CA507 comparator.

The right measuring shunt of CA507 comparator is an integral part of its design and is used for extracting information on the difference between two input currents. The CT primary current flows through CA507 internal ammeter, and also creates a voltage drop at both Fluke A40 current shunt (R1) and CA507 left shunt. The last shunt is used in the comparator design for extracting information on the current $\mathrm{I_S}$ of the reference CT.

A dual-channel Clarke-Hess 6000A phase meter is needed to determine the angle β between the currents flowing through the Fluke A40 current shunt and the left P4834 resistance decade box. Both the right P4834 resistance decade box and the P5025 capacitance box are connected in parallel to shift the angle β.

IV. DERIVING SENSITIVITY COEFFICIENTS OF INPUT QUANTITIES

Having analyzed the scheme in Fig. 2, the sequence of the measurement operations, given a mathematical model (4), one can evaluate the contribution of each input quantity. According to GUM 1995 [9], to determine the sensitivity coefficients of the input quantities according to the model (4), one must take the first partial derivatives for each input quantity. In previous work [8], expressions were obtained to calculate the sensitivity coefficients for estimating the contributions of input quantities. But, the model (4) should be transformed, taking into account the expression (7) and the K_{IM} branching factor:

$$\varepsilon_X = \sqrt{1 + \frac{2\cdot K_{IM}\cdot U_{RDB}\cdot\cos\beta}{I_S\cdot R_{RDB}} + \left(\frac{K_{IM}\cdot U_{RDB}}{I_S\cdot R_{RDB}}\right)^2} - 1\,. \tag{8}$$

Concerning expression (6), the approach to PD estimation was changed compared with the previously proposed expression [8]. The uncertainty evaluation of simulated PD was improved. To calculate the sensitivity coefficients for estimating the contribution of input quantities according to model (6), it is necessary to differentiate a similarly transformed expression:

$$\Delta\varphi_X = \mathrm{atan}\cdot\left[\frac{K_{IM}\cdot U_{RDB}\cdot\sin\beta/R_{RDB}}{I_S + K_{IM}\cdot U_{RDB}\cdot\cos\beta/R_{RDB}}\right]. \tag{9}$$

To estimate the contribution of branching current when measuring the voltage at terminals of P4834 resistance decade box, the expression presented below should be considered:

$$\frac{\partial(\Delta\varphi_X)}{\partial K_{IM}} = \frac{U_{RDB}\cdot R_{RDB}\cdot I_S\cdot\sin\beta}{\left(\begin{array}{l} I_S^2\cdot R_{RDB}^2 + 2\cdot K_{IM}\cdot U_{RDB}\cdot R_{RDB}\cdot \\ I_S\cdot\cos\beta + K_{IM}^2\cdot U_{RDB}^2 \end{array}\right)}. \quad (10)$$

The contribution of the uncertainty of voltage measurement at the resistance decade box differs a little from expression (10) and is estimated as follows:

$$\frac{\partial(\Delta\varphi_X)}{\partial U_{RDB}} = \frac{K_{IM}\cdot R_{RDB}\cdot I_S\cdot\sin\beta}{\left(\begin{array}{l} I_S^2\cdot R_{RDB}^2 + 2\cdot K_{IM}\cdot U_{RDB}\cdot R_{RDB}\cdot \\ I_S\cdot\cos\beta + K_{IM}^2\cdot U_{RDB}^2 \end{array}\right)}. \quad (11)$$

The expression for the calculation of the sensitivity coefficient for estimating the input contribution of the uncertainty of resistance of P4834 decade box is determined as follows:

$$\frac{\partial(\Delta\varphi_X)}{\partial R_{RDB}} = -\frac{K_{IM}\cdot U_{RDB}\cdot I_S\cdot\sin\beta}{\left(\begin{array}{l} I_S^2\cdot R_{RDB}^2 + 2\cdot K_{IM}\cdot U_{RDB}\cdot R_{RDB}\cdot \\ I_S\cdot\cos\beta + K_{IM}^2\cdot U_{RDB}^2 \end{array}\right)}. \quad (12)$$

To determine the contribution of the uncertainty of I_S current measurement, the expression is as follows:

$$\frac{\partial(\Delta\varphi_X)}{\partial I_S} = -\frac{K_{IM}\cdot U_{RDB}\cdot R_{RDB}\cdot\sin\beta}{\left(\begin{array}{l} I_S^2\cdot R_{RDB}^2 + 2\cdot K_{IM}\cdot U_{RDB}\cdot R_{RDB}\cdot \\ I_S\cdot\cos\beta + K_{IM}^2\cdot U_{RDB}^2 \end{array}\right)}. \quad (13)$$

When determining the contribution of the phase shift between I_d and I_S currents, the sensitivity coefficient must be calculated:

$$\frac{\partial(\Delta\varphi_X)}{\partial\beta} = \frac{K_{IM}^2\cdot U_{RDB}^2\cdot\left(1+\dfrac{R_{RDB}\cdot I_S\cdot\cos\beta}{K_{IM}\cdot U_{RDB}}\right)}{\left(\begin{array}{l} I_S^2\cdot R_{RDB}^2 + 2\cdot K_{IM}\cdot U_{RDB}\cdot R_{RDB}\cdot \\ I_S\cdot\cos\beta + K_{IM}^2\cdot U_{RDB}^2 \end{array}\right)}. \quad (14)$$

In general, it can be seen from the expressions (10)–(14) that the denominator is the same everywhere which simplifies the development of program code.

V. SIMULATING MEASUREMENT RESULTS

In Table 1 and Table 2, the results of simulating the errors of CT, using the scheme depicted in Fig. 2, are presented.

According to the specification of the CA507 comparator, the intrinsic uncertainty when measuring RE is determined in percentage by the formula:

$$u_{RE} = 0.005\cdot\varepsilon + 0.0002 + 0.0001\cdot\Delta\varphi\,. \quad (15)$$

Table1. Comparison of RE measuring data using CA507 comparator and calculated results

Current in A	RE in µA/A		RE measurement uncertainty in µA/A	
	Comparator readout	Reference value	Comparator readout	Reference value
2.975	1154	1167	8.3	9.2
2.960	393	399	3.9	3.1
2.993	31.3	32.03	2.2	0.45
3.0356	12.5	12.84	2.1	0.21
2.991	6.1	6.17	2.0	0.16
3.022	0.6	1.47	2.0	0.11

As can be seen in expression (15), the minimum uncertainty value cannot be less than 2 µA/A.

Table2. Comparison of PD measuring data using CA507 comparator and calculated results

Current in A	PD in µrads		PD measurement uncertainty in µrads	
	Comparator readout	Reference value	Comparator readout	Reference value
3.051	1132	1167	16	26
2.974	605	603	21	12
3.065	238	241.1	10	4.1
2.995	130.7	132.6	9.5	2.3
1.417	10,2	10.0	8.9	1.1
1.035	2.3	2.11	8.8	0.29

According to the specification of the CA507 comparator, the intrinsic uncertainty in PD measurement is determined in minutes by the formula:

$$u_{PD} = 0.005\cdot\Delta\varphi + 0.03 + 0.7/15\cdot\varepsilon\,. \quad (16)$$

As can be seen in expression (16), the minimum uncertainty value cannot be less than 8.73 µrad. In Table 2, the intrinsic uncertainty of CA507 is evaluated as 21.2 when measuring 605 µrad, and it exceeds the uncertainty when measuring 1132 µrad. One can see a clear upward trend in this characteristic with increasing measured value in formula (16). However, the interrelation between RE and PD at the simulated measurement point led to an increase in intrinsic uncertainty, due to the sufficiently strong effect of the amplitude component portion [10].

Fig. 3 shows that the measurement uncertainty, evaluated according to GUM 1995 [9] for measured REs less than 100 µA/A, has a large margin regarding the test uncertainty ratio. However, for the error above 200 µA/A, measurement uncertainty increases markedly under conditions without additional measures such as stabilization of the supply of the measuring circuit,

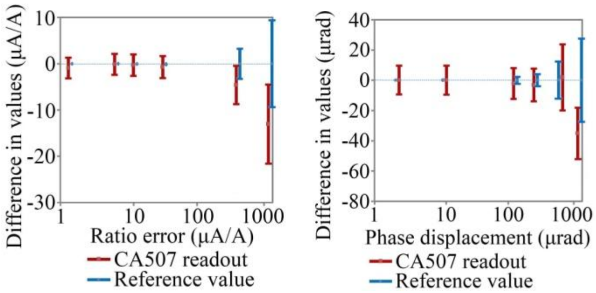

Fig. 3. The difference in values obtained with evaluated measurement uncertainties.

determination of the voltmeter input impedance, etc.

The analysis of the uncertainty budget gives grounds for claiming that the total uncertainty can be significantly reduced also in the simulation of CT errors of about 1000 μA/A when additional measures will be applied. In Fig. 3, it could be also seen that the difference between the comparator readout and the reference value increases with the increase of the simulated error value. The relationship between the amplitude and angular components of the simulated current difference has a great influence on the uncertainty estimation. The smaller the amplitude portion the smaller the measurement uncertainty of the angular component and vice versa. This is also a direction for refining the measurement result.

VI. CONCLUSION

The proposed method allows the determination of the metrological performance of the calibration unit for precision CT with an accuracy class of 0.05 or more precise. Simulating the errors over a wide range of values with a possibility of detailed investigation with both a small step and small measurement uncertainty is the main advantage of such a method.

Rectification of both the current measurement uncertainty (application of precision ammeter) and the branching factor (determination of the input impedance of the voltmeter) can lead to a reduction of the total uncertainty of measurements.

The proposed method can be applied for rigorous characterization, even for small changes in the readout, to provide metrological support for means of comparing two nearly identical currents which will be used to calibrate reference CTs.

The application of advanced technologies of data acquisition by replacement of voltmeter, phase meter by high-speed sample measuring devices with the subsequent automatic calculation of both reference values of errors and uncertainty of measurements should be the direction of further improvement.

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