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Final report

Euramet Project 1187

COMPARISON OF INSTRUMENT CURRENT TRANSFORMERS UP TO 10 kA

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1. Introduction

AC current ratio is one of two basic parameters in the area of metrology of instrument transformers and it is very important by the measurement of electric energy. In trade with electric energy it is important to ensure the accuracy of measurement. So it is necessary to compare national standards of European states.

The relevant quantity for the measurement of AC current is the ratio of the primary and secondary current, which is a complex value. The errors of this ratio are given as the ratio error and phase displacement. These two quantities are a subject of this international comparison.

This comparison was proposed in order to demonstrate the capabilities of the NMIs in Europe in the area of AC current ratio measurement.

2. Transfer standard

Standard Current Transformer I 523 [1]**:**

Rated primary current: (4-5-6-8-10) kA
Rated secondary current: 5 A

Rated burden: 15 VA resistive

Ser. number: 18/1981

Class: 0.05

Mass: approx. 24 kg

Fig. 1. Travelling standard

3. Quantity to be measured

Quantity to be measured is the current ratio error ε_I and phase displacement δ_I. The current ratio error (ε_I) is defined as:

$$\varepsilon_{\mathrm{I}} = \frac{I_{\mathrm{S}} \cdot K_{\mathrm{I}} - I_{\mathrm{P}}}{I_{\mathrm{P}}} \cdot 10^6 \quad , \tag{1}$$

where ε_I is current ratio error (ppm),
I_P actual value of the primary current (V),
I_S actual value of the secondary current (V),
K_I transformation ratio (-).

The phase displacement δ_I (' or μrad) is defined as the phase difference between the secondary I_S and primary I_P currents. The phase displacement is considered as positive when the secondary current phasor I_S leads the primary current phasor.

4. Organization of the comparison

4. 1. Pilot laboratory

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4. 2. Supporting group

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4. 3. Participants

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4.4. Circulation scheme and time schedule

Four weeks were allowed for each participant and includes transportation time to the next participant. The circulation scheme and time schedule are shown in the Table 1.

Participant	Measurement date	Results delivered
CMI Prague, Czech Republic	October 2011	October 2011
METAS Bern, Switzerland	March 2012	October 2012
BEV Vienna, Austria	April 2012	November 2013
DMDM Belgrade, Serbia	May 2012	May 2012
LCOE Madrid, Spain	June 2012	July 2012
PTB Braunschweig, Germany	December 2012	November 2014
CMI Prague, Czech Republic	January 2013	January 2013
LNE Paris, France	March 2013	February 2015
NPL Teddington, United	April, May 2013	July 2013
RISE (SP) Boras, Sweden	June 2013	January 2014
INRIM Torino, Italy	June, July 2013	July 2015
GUM Warshaw, Poland	July, August 2013	September 2013
LNE Paris, France	November 2013	February 2015
VSL Delft, the Netherlands	December 2013	November 2014
VTT MIKES Espoo, Finnland	February 2014	November 2014
BIM Sofia, Bulgaria	April 2014	November 2014
UME Gebze, Turkey	July 2014	November 2014
LNE Paris, France	April 2016	May 2016
CMI Prague, Czech Republic	May 2016	May 2016

Table 1. Time schedule

4. 5. Transportation

Participants were responsible for arranging transportation to the next participant. Transportation was each laboratory's own responsibility and cost.

The transfer standard was packed in a wooden container with dimensions (75x50x28) cm, weight approx. 40 kg. The container did not need to be transported personally because the standard is rather robust device.

5. Measurements

5.1. Measurement conditions

The travelling transformer has ratios of rated currents (4-5-6-8-10) kA/5 A. Each laboratory measured those ratios that are within its capabilities. On the lowest and the highest ratios that could be measured, results were obtained for two burdens (5 VA and 15 VA at unity power factor). For intermediate ratios results were given for one burden only (15 VA at unity power factor). The measuring points were I_M: (120, 100, 50, 20, 10, 5 & 2) % (1 % optional) of rated current value I_R. Measurements were performed at 50 Hz frequency. It was recommended to keep the value of connected burden and its power factor within 3 % of the nominal values and establish it with an uncertainty better than 0.5 %.

For correct determining the reference value was necessary – see Fig. 2.

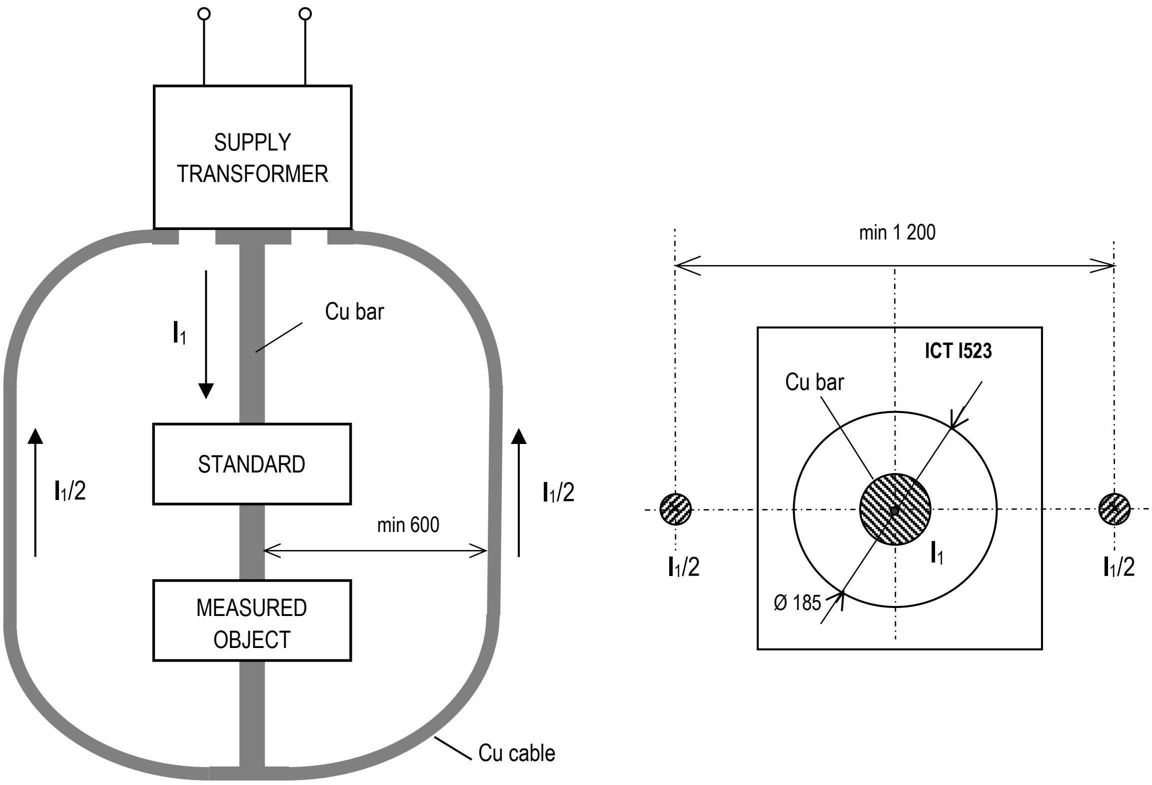

Fig. 2. Recommended arrangement of primary circuit

- Use a primary conductor with a circular cross-section and to place it in the centre of transformer opening with maximum deviation 10 mm. An unsymmetrical position causes a big measurement error.
- When using more parallel primary conductors it was necessary to fix them in to a concentric bundle and place it to the centre of transformer opening.
- Use two return conductors placed symmetrically with the longitudinal axis of the primary conductor in the distance at least 60 cm from the longitudinal axis the primary conductor.
- The recommended time for adjusting of the primary current from zero to 120% I_R was maximally 40 seconds. Errors needed to be read immediately after adjusting of the primary current. Then the primary current was immediately decreased on the value 100% I_R and 50% I_R, respectively.
- When the comparative method with a standard was used it was recommended to provide the each measurement twice. The second measurement should be performed with commutated (swapped) primary conductors, especially for measuring points less than 20% I_R. This could be also achieved by swapping of primary winding of a supply transformer. The result of measurement was then given as the mean value of the two measurements.

5.2. Ambient conditions

The standard transformer should be kept in the laboratory before the measurements for such a time that it reaches stable temperature. It was recommended to keep the ambient temperature on the value 23 °C ± 2 °C. The relative humidity was reported.

The data of the ambient conditions during the measurements are given in the measurement report.

5.3. Measuring methods

The participating laboratories followed their usual measurement procedure to achieve their best measurement capabilities with respect to the allowed time frame for the comparison. Measurement results of individual laboratories included also a description of the method used and a layout of the primary current circuit with dimensions.

5.4. Uncertainty of measurement

All participants provided their results with the associated uncertainty of measurement and a complete uncertainty budget. The uncertainty of the measurement was determined according to the ISO Guide to the Expression of Uncertainty in Measurement (GUM). All participants supplied a statement of traceability in SI units.

6. Results of measurement

6. 1. Method of result evaluation

The participating laboratories reported the measurement results including uncertainties to the pilot laboratory CMI in Prague, where they were evaluated according to [2], [3], [4] and [5]. The pilot laboratory calculated the resulting comparison reference value (CRV) as the weighted mean according to the formula

$$\varepsilon_r = \frac{\sum_{L=1}^{n} \varepsilon_L \, u^{-2}(\varepsilon_L)}{\sum_{L=1}^{n} u^{-2}(\varepsilon_L)} \quad , \qquad \delta_r = \frac{\sum_{L=1}^{n} \delta_L \, u^{-2}(\delta_L)}{\sum_{L=1}^{n} u^{-2}(\delta_L)} \quad , \tag{2}$$

where ε_r, δ_r are reference values for the ratio error and phase displacement,

ε_L, δ_L, are results of ratio error and phase displacement of each participating laboratory,

$u(\varepsilon_L)$, $u(\delta_L)$ are standard deviations (standard uncertainties) of the ratio error and phase displacement results as reported by the individual laboratories,

n is the number of participating laboratories.

The standard uncertainties of the CRV for the ratio error $u(\varepsilon_r)$ and the phase displacement $u(\delta_r)$ are given by the formulae

$$u(\varepsilon_r) = \frac{1}{\sqrt{\sum_{L=1}^{n} u^{-2}(\varepsilon_L)}} \quad , \qquad u(\delta_r) = \frac{1}{\sqrt{\sum_{L=1}^{n} u^{-2}(\delta_L)}} \; . \tag{3}$$

The expanded uncertainties of the reference values for the ratio error $U(\varepsilon_r)$ and the phase displacement $U(\delta_r)$ for a coverage factor k = 2 (95 % confidence level) are

$$U(\varepsilon_r) = 2 \cdot u(\varepsilon_r) \; , \quad U(\delta_r) = 2 \cdot u(\delta_r) \; . \tag{4}$$

The differences of the participant's results to the comparison reference values are given as

$$\Delta\varepsilon = \varepsilon_L - \varepsilon_r \ , \qquad \Delta\delta = \delta_L - \delta_r \ . \tag{5}$$

The uncertainties of these differences are

$$u(\Delta\varepsilon) = \sqrt{u^2(\varepsilon_L) - u^2(\varepsilon_r)} \ , \quad u(\Delta\delta) = \sqrt{u^2(\delta_L) - u^2(\delta_r)} \tag{6}$$

and the expanded uncertainties of these differences (k = 2) are given as

$$U(\Delta\varepsilon) = 2 \cdot u(\Delta\varepsilon) \ , \quad U(\Delta\delta) = 2 \cdot u(\Delta\delta) \ . \tag{7}$$

After remarks of some participating laboratories the uncertainty of the difference $u(\Delta\varepsilon)$ resp. $u(\Delta\delta)$ was expanded by a transfer standard stability during the whole comparison. These stability changes were evaluated according to pilot laboratory results measured in years 2011, 2013 and 2016 [6]. The participants recommended changes of the parameters expressed as a transfer standard uncertainty $u(\varepsilon_{std})$ for ratio error and $u(\delta_{std})$ for phase displacement.

The pilot laboratory evaluated components of ratio error $u(\varepsilon_{std})$ and phase displacement $u(\delta_{std})$. The uncertainty of the difference $u(\Delta\varepsilon)$ and $u(\Delta\delta)$ according to (6) may be then expressed with respect to the transfer standard uncertainty as

$$u(\Delta\varepsilon_{std}) = \sqrt{u^2(\varepsilon_L) + u^2(\varepsilon_{std}) - u^2(\varepsilon_r)} \ , \ u(\Delta\delta_{std}) = \sqrt{u^2(\delta_L) + u^2(\delta_{std}) - u^2(\delta_r)} \tag{8}$$

The confidence coefficients were calculated for all laboratories according to the following formulae

$$E(\varepsilon) = \frac{|\Delta\varepsilon|}{2 \cdot u(\Delta\varepsilon_{std})} \ , \quad E(\delta) = \frac{|\Delta\delta|}{2 \cdot u(\Delta\delta_{std})} \ . \tag{9}$$

Results with E > 1.0 (outliers) are underlined in the tables and were extracted from calculation of the corrected CRV_C – see eq. (2), i.e. their contributions in the sum operations (2) were null. The CRV_C calculated such a way (ε_{rC} and δ_{rC}) were used for following calculation.

$$\Delta\varepsilon_C = \varepsilon_L - \varepsilon_{rC} \ , \qquad \Delta\delta_C = \delta_L - \delta_{rC} \ . \tag{10}$$

$$u(\Delta\varepsilon_{std\ C}) = \begin{cases} \sqrt{u^2(\varepsilon_L) + u^2(\varepsilon_{std}) - u^2(\varepsilon_{rC})}, & E \le 1.0 \\ \sqrt{u^2(\varepsilon_L) + u^2(\varepsilon_{std}) + u^2(\varepsilon_{rC})}, & E > 1.0 \end{cases} \ ,$$

$$u(\Delta\delta_{std\ C}) = \begin{cases} \sqrt{u^2(\delta_L) + u^2(\delta_{std}) - u^2(\delta_{rC})}, & E \le 1.0 \\ \sqrt{u^2(\delta_L) + u^2(\delta_{std}) + u^2(\delta_{rC})}, & E > 1.0 \end{cases} \ , \tag{11}$$

where ε_{rC} and δ_{rC} are CRV_C's, calculated according to the eq. (2) without contribution of outliers, i.e. without participants which have E > 1.0. As the outliers are no longer correlated with the CRV_C, the formulae for their uncertainties $u(\Delta\varepsilon_{stdC})$ and $u(\Delta\delta_{stdC})$ change in case of the confidence coefficient value E > 1.0.

Corrected confidence coefficients were then calculated by the following formulae

$$E_C(\varepsilon) = \frac{|\Delta\varepsilon_C|}{2 \cdot u(\Delta\varepsilon_{std\ C})} \ , \quad E_C(\delta) = \frac{|\Delta\delta_C|}{2 \cdot u(\Delta\delta_{std\ C})} \ . \tag{12}$$

6.2. Results of the comparison

1. Annex 1

At the first step the CRVs (ε_r and δ_r), their uncertainties ($u(\varepsilon_r)$ and $u(\delta_r)$), and confidence coefficients ($E(\varepsilon)$ and $E(\delta)$) were calculated for all participating laboratories according to (2) up to (9). Results of this calculation are in Annex 4 TAB A4-1. Results of individual laboratories and the CRV ε_r (ppm) and δ_r (µrad) (weighted mean) with results of all labs are shown in tables Annex 1 A1-1 to A1-4. The transfer standard uncertainties $u(\varepsilon_{std})$ and $u(\delta_{std})$ are shown in table A1-5.

At the second step laboratories with E > 1.0 were excluded from the calculation of the CRVs (ε_{rC} and δ_{rC}) and their uncertainties ($u(\varepsilon_{rC})$ and $u(\delta_{rC})$). Then the $\Delta\varepsilon_C$, $\Delta\delta_C$, $u(\Delta\varepsilon_{stdC})$, $u(\Delta\delta_{stdC})$, $E_C(\varepsilon)$ and $E_C(\delta)$ are calculated. The differences $\Delta\varepsilon_C$, $\Delta\delta_C$ (see eq. (10), $u(\Delta\varepsilon_{stdC})$, $u(\Delta\delta_{stdC})$ - see eq. (11) and $E_C(\varepsilon)$, $E_C(\delta)$ - see eq. (12) are shown in the tables A1-6 to A1-9. In these tables, the values with $E_C > 1.0$ are underlined and red highlighted. Uncertainties of the outliers ($u(\Delta\varepsilon_{stdC})$ and $u(\Delta\delta_{stdC})$) were calculated according to eq. (11), for the case $E > 1.0$.

2. Annex 2

Graphical representation of results is given on pages 2 up to 114. The differences between ε_L, resp. δ_L and CRV_C (ε_{rC} and δ_{rC}), i.e. the values $\Delta\varepsilon_C$ and $\Delta\delta_C$, are plotted on the vertical axis where vertical abscissas demonstrate expanded uncertainties of these differences $2\cdot u(\Delta\varepsilon_{stdC})$ and $2\cdot u(\Delta\delta_{stdC})$ according to eq. (11).

3. Annex 3

Uncertainty budgets of individual laboratories are given on pages pages 3 up to 35.

4. Annex 4

Calculations were performed in Excel 2010.

In the table A4-1 are given calculations of references values ε_r and δ_r (CRV) and their uncertainties $u(\varepsilon_r)$ and $u(\delta_r)$ of all laboratories according to (2) and (3). Further is there given calculation of differences $\Delta\varepsilon$ and $\Delta\delta$ between results of individual laboratories and the reference value according to (5) and uncertainties of these differences $u(\Delta\varepsilon_{std})$ and $u(\Delta\delta_{std})$ according to (8) with transferstandard uncertainty. Calculation of confidence coefficients $E(\varepsilon)$ and $E(\delta)$ when transfer standard uncertainties $u(\varepsilon_{std})$ and $u(\delta_{std})$ are taken in to account – see (9) are also given. Results of laboratories with $E(\varepsilon) > 1.0$ and $E(\delta) > 1.0$ are underlined and red highlighted.

In the table A4-2 are given calculations of the CRV_C (ε_{rC} and δ_{rC}) values calculated from results of these laboratories whose confidence coefficients $E(\varepsilon) \leq 1.0$ or $E(\delta) \leq 1.0$. Calculations are performed according to (10) up to (12). The table A4-3 serves for automatic data plots in the excel graphs.

Note: Individual results were processed gradually as they have been delivered by individual laboratories.

5. Conclusion

15 national European laboratories took part at the comparison. A standard instrument current transformer I 523 with transformation ratios of (4; 5; 6; 8 and 10) kA/5 A, class 0.05, rated real burden of 15 VA served as a transferstandard. Ratio error ε and phase displacement δ were measured at 56 measuring points.

Results of the comparison were processed according to equations (1) to (12). Eq. (6) for the uncertainty of the difference between the results of individual participating laboratories and CRV is derived in [5]. After discussion among some participants it was recommended to expand eq. (6) by a transfer standard uncertainty, caused by time instability of its parameters during the comparison, see eq. (8). The transfer standard uncertainty was determined as the biggest error difference measured by the pilot laboratory in years 2011, 2013 and 2016 [6].

Three laboratories were limited in their maximum current to 5 kA, three other laboratories measured up to 8 kA, and only four laboratories were able to measure up to the maximum current of 12 kA.

All participants provided their results with measurement uncertainties and uncertainty budget. The typical reported uncertainties varied between (5 and 20)$\cdot 10^{-6}$ for the ratio error and between (10 and 40) μrad for the phase displacement.

Out of the total number of 760 results of $E(\varepsilon)$ and the same number of results of $E(\delta)$ there were only 32 results for ratio error ε with $E(\varepsilon) > 1$, and 26 results for phase displacement δ where $E(\delta) > 1$. Since the predominant majority of the results have $E \leq 1.5$ (there is only one case where $E = 1.9$), the comparison can be considered as successful.

References:

[1] B. A. Globa, B. V. Zakharov and V. A. Khizhinskaya, “Laboratory class 0.05 instrument transformer up to 10000 A,” *Izmeritel'naya Tekhnika*, No. 1, pp. 46-47, January 1965.

[2] European co-operation for accreditation (EA) – publication on references EA-4/02 "Expression of the uncertainty of measurement in calibration", December 1999.

[3] R. Styblíková, K. Draxler and B. Jeckelmann: Comparison of voltage ratio standards. Final report of Euromet project 599.

[4] S. Harmon and L. Henderson, “EUROMET Projects 473 & 612: Comparison of current transformers,” *NPL Report TQE 4*, March 2009.

[5] Cox M. G.: The Evaluation of Key Comparison Data. Metrologia 39, pp. 589-595, 2002.

[6] K. Draxler at al: International Comparison of Instrument Current Transformers up to 10 kA at 50 Hz Frequency. CPEM 2016.