Final report

Euramet Project 1187

COMPARISON OF INSTRUMENT CURRENT TRANSFORMERS UP TO 10 kA

Karel Draxler
Renata Styblíková
Jan Hlaváček
Gert Rietveld

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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](image)

3. Quantity to be measured

Quantity to be measured is the current ratio error $\varepsilon$ and phase displacement $\delta$. The current ratio error ($\varepsilon$) is defined as:

$$\varepsilon = \frac{I_S \cdot K_I - I_P}{I_P} \cdot 10^6,$$

(1)

where $\varepsilon$ 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 $\delta$ (° 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

Czech Metrology Institute  
Laboratory of Fundamental Metrology  
Department of Electromagnetic Quantities  
Renata Styblikova, Karel Draxler, Jan Hlaváček  
V Botanice 4  
150 72 Prague 5  
Czech Republic  
E-mail: rstyblikova@cmi.cz  
Phone: +420 257 288 335  
Fax: +420 257 328 077

4. 2. Supporting group

INRIM Torino, Italy – Gabriella Crotti [g.crotti@inrim.it]  
NPL Teddington, United Kingdom – Adrian Wheaton [adrian.wheaton@npl.co.uk]  
SP Boras, Sweden – Anders Bergman [anders.bergman@sp.se]  
VTT Espoo, Finland – Jari Hällström [Jari.Hallstrom@vtt.fi]

4. 3. Participants

BEV Vienna, Austria – Michael Schnaitt [michael.schnaitt@bev.gv.at]  
BIM Sofia, Bulgaria – Emil Dimitrov [e.dimitrov@bim.govt.bg]  
CMI Prague, Czech Republic – Renata Stybliková [rstyblikova@cmi.cz]  
DMDM Belgrade, Serbia – Tanja Cincar-Vujovic [tanjacin@mdm.rs]  
GUM Warsaw, Poland – Boguslaw Paczek [b.paczek@gum.gov.pl]  
INRIM Torino, Italy – Gabriella Crotti [g.crotti@inrim.it]  
LCOE Madrid, Spain – Ricardo Martín [RMartin@lcoe.etsii.upm.es]  
LNE Paris, France – Isabelle Blanc [isabelle.blanc@lne.fr]  
METAS Bern, Switzerland – Christian Mester [Christian.Mester@metas.ch]  
NPL Teddington, United Kingdom – Adrian Wheaton [adrian.wheaton@npl.co.uk]  
PTB Braunschweig, Germany – Enrico Mohns [Enrico.Mohns@ptb.de]  
RISE (SP) Boras, Sweden – Anders Bergman [anders.bergman@sp.se]  
UME Gebze, Turkey – Hüseyin Çayci [Huseyin.CAYCI@ume.tubitak.gov.tr]  
VSL Delft, the Netherlands – Gert Rietveld [grietveld@vsl.nl]  
VTT MIKES Espoo, Finland – Jari Hällström [jari.hallstrom@vtt.fi]

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

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.
− 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 $23 ^\circ C \pm 2 ^\circ C$. 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 \delta_r = \frac{\sum_{L=1}^{n} \delta_L u^{-2}(\delta_L)}{\sum_{L=1}^{n} u^{-2}(\delta_L)}, \tag{2} \]

where \( \varepsilon_r, \delta_r \) are reference values for the ratio error and phase displacement, \( \varepsilon_L, \delta_L \) 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

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

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
\[ \Delta \varepsilon = \varepsilon_L - \varepsilon_r, \quad \Delta \delta = \delta_L - \delta_r. \] (5)

The uncertainties of these differences are
\[ u(\Delta \varepsilon) = \sqrt{u^2(\varepsilon_L) - u^2(\varepsilon_r)}, \quad u(\Delta \delta) = \sqrt{u^2(\delta_L) - u^2(\delta_r)} \] (6)
and the expanded uncertainties of these differences \((k = 2)\) are given as
\[ U(\Delta \varepsilon) = 2 \cdot u(\Delta \varepsilon), \quad U(\Delta \delta) = 2 \cdot u(\Delta \delta). \] (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 \(u(\varepsilon_{\text{std}})\) for ratio error and \(u(\delta_{\text{std}})\) for phase displacement.

The pilot laboratory evaluated components of ratio error \(u(\varepsilon_{\text{std}})\) and phase displacement \(u(\delta_{\text{std}})\). 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
\[ u(\Delta \varepsilon_{\text{std}}) = \sqrt{u^2(\varepsilon_L) + u^2(\varepsilon_{\text{std}}) - u^2(\varepsilon_r)}, \quad u(\Delta \delta_{\text{std}}) = \sqrt{u^2(\delta_L) + u^2(\delta_{\text{std}}) - u^2(\delta_r)} \] (8)

The confidence coefficients were calculated for all laboratories according to the following formulae
\[ E(\varepsilon) = \frac{|\Delta \varepsilon|}{2u(\Delta \varepsilon_{\text{std}})}, \quad E(\delta) = \frac{|\Delta \delta|}{2u(\Delta \delta_{\text{std}})} \] (9)

Results with \(E > 1.0\) (outliers) are underlined in the tables and were extracted from calculation of the corrected CRV \(\text{C} - \text{C}\) – see eq. (2), i.e. their contributions in the sum operations (2) were null. The CRV \(\text{C}\) calculated such a way (\(\varepsilon_{\text{C}}\) and \(\delta_{\text{C}}\)) were used for following calculation.
\[ \Delta \varepsilon_{\text{C}} = \varepsilon_L - \varepsilon_{\text{rc}}, \quad \Delta \delta_{\text{C}} = \delta_L - \delta_{\text{rc}}. \] (10)

\[ u(\Delta \varepsilon_{\text{std C}}) = \begin{cases} \sqrt{u^2(\varepsilon_L) + u^2(\varepsilon_{\text{std}}) - u^2(\varepsilon_{\text{rc}})}, & E \leq 1.0 \\ \sqrt{u^2(\varepsilon_L) + u^2(\varepsilon_{\text{std}}) + u^2(\varepsilon_{\text{rc}})}, & E > 1.0 \end{cases} \]

\[ u(\Delta \delta_{\text{std C}}) = \begin{cases} \sqrt{u^2(\delta_L) + u^2(\delta_{\text{std}}) - u^2(\delta_{\text{rc}})}, & E \leq 1.0 \\ \sqrt{u^2(\delta_L) + u^2(\delta_{\text{std}}) + u^2(\delta_{\text{rc}})}, & E > 1.0 \end{cases} \] (11)

where \(\varepsilon_{\text{C}}\) and \(\delta_{\text{C}}\) are CRV \(\text{C}\)’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 \(\text{C}\), the formulae for their uncertainties \(u(\Delta \varepsilon_{\text{std C}})\) and \(u(\Delta \delta_{\text{std C}})\) change in case of the confidence coefficient value \(E > 1.0\).

Corrected confidence coefficients were then calculated by the following formulae
\[ E_{\text{C}}(\varepsilon) = \frac{|\Delta \varepsilon_{\text{C}}|}{2u(\Delta \varepsilon_{\text{std C}})}, \quad E_{\text{C}}(\delta) = \frac{|\Delta \delta_{\text{C}}|}{2u(\Delta \delta_{\text{std C}})}. \] (12)
6.2. Results of the comparison

1. Annex 1

At the first step the CRVs ($\varepsilon$ and $\delta$), their uncertainties ($u(\varepsilon)$ and $u(\delta)$), 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 $\varepsilon_t$ (ppm) and $\delta_t$ (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 ($\varepsilon_C$ and $\delta_C$) and their uncertainties ($u(\varepsilon_C)$ and $u(\delta_C)$). Then the $\Delta\varepsilon$, $\Delta\delta$, $u(\Delta\varepsilon_{std})$, $u(\Delta\delta_{std})$, $E_C(\varepsilon)$ and $E_C(\delta)$ are calculated. The differences $\Delta\varepsilon$, $\Delta\delta$ (see eq. (10), $u(\Delta\varepsilon_{std})$, $u(\Delta\delta_{std})$ - see eq. (11) 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 ($u(\Delta\varepsilon_{std})$ and $u(\Delta\delta_{std})$) 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 $\varepsilon_t$, resp. $\delta_t$ and CRV $\varepsilon_C$ ($\varepsilon_C$ and $\delta_C$), 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 $2\cdot u(\Delta\varepsilon_{std})$ and $2\cdot u(\Delta\delta_{std})$ 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 $\varepsilon_t$ and $\delta_t$ (CRV) and their uncertainties $u(\varepsilon_t)$ and $u(\delta_t)$ 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 $\varepsilon_C$ ($\varepsilon_C$ and $\delta_C$) 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 \( \varepsilon \) and phase displacement \( \delta \) 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) \( \mu \)rad 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 \( \varepsilon \) with \( E(\varepsilon) > 1 \), and 26 results for phase displacement \( \delta \) 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:


EURAMET.EM-S37

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Links to annexes

ANNEX 1  Results – Tables
ANNEX 2  Results – Graphs
ANNEX 3  Uncertainty budgets
ANNEX 4  Data treatment
ANNEX 5  Declarations of CMC consistency
ANNEX 6  Measurement methods