Key Comparison EURAMET.EM-K5.1
EURAMET Project No. 687

Comparison of 50/60 Hz Power

Final Report

Hüseyin Çaycı

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UME
TÜBİTAK Ulusal Metroloji Enstitüsü
Power & Energy Laboratory
PO Box: 54, Gebze, 41470 Kocaeli
TURKEY

Abstract

To support the Calibration and Measurement Capabilities (CMCs) declared by members of EURAMET (formerly EUROMET) in the framework of the CIPM-MRA, a EURAMET Key Comparison was organised. Electrical standards of low-frequency (50/60 Hz) power were compared at 10 National Metrology Institutes (NMIs) of EURAMET member states and at 2 NMIs of COOMET and APMP member states, to establish the relationship between the electrical units of AC power at these laboratories. The results of this comparison are described. The differences between almost all laboratory's values and the reference values were within the expanded measurement uncertainties at a coverage factor k=2.

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Introduction

At the end of the EURAMET.EM-K5 Key Comparison (Project no. 385) [1], some more European countries showed their interest to the comparison and were willing to participate in the measurements. Moreover, some NMIs participated in the comparison were improved their capabilities for ac power measurements and their measurement uncertainties. Therefore, it was decided to start a *new comparison* at the same measurement points and using the same kind of travelling standard. And, all of the EURAMET laboratories were invited to participate in this new Key Comparison.

TÜBİTAK Ulusal Metroloji Enstitüsü (UME) was proposed as the *pilot laboratory*, which would be responsible for providing the travelling standard, coordinating the schedule, collecting and analyzing the comparison data, and preparing the draft report.

PTB, the pilot laboratory of the previous comparison, was proposed to play a key role in the new comparison by taking measurements as much as the number of measurements taken by the pilot laboratory. By this way, the measurement results of PTB would be used to estimate the drift effect of the travelling standard. Moreover, PTB was proposed to be the *linking NMI* for the linking process between CCEM-K5 [2, 3] and the new key comparison since PTB would be the only NMI which participated in both comparisons.

Peter Raether from PTB and Andreas Jakab from OMH were selected as the support group members of the comparison. The support group member from OMH was retired within the comparison schedule. As a consequence, the coordinator of the comparison has been proposed as the second member of the comparison support group.

The new key comparison was approved as EURAMET.EM-K5.1 (project no. 687) and began in December 2003. 10 National Metrology Institutes (NMIs) of EURAMET member states and at 2 NMIs of COOMET and APMP member states were participated in this new key comparison and comparison schedule had to be changed several times. Delays with respect to the original schedule were caused not only by new participations but also by some of the participants and by customs problems (e.g. loss of ATA carnet). As a consequence, the measurements period for the comparison took more than four years. Moreover, there were some more delays depending on the collecting of measurement results and reports from some participants. The final NMI results were received in Nov 2009.

The method used in the calculation of the drift effect, reference values and equivalence is based on the method proposed by Statistical Engineering Division of NIST [3]. This successful statistical approach was used not only in the final report of CCEM-K5 but also in the EURAMET.EM-K5 reports since both comparisons followed the same internal structure.

The link between the comparisons of CCEM-K5 and EURAMET.EM-K5.1 is carried out by following the example of F. Delahaye and T. J. Witt [4] as in the previous comparison. And, the link report is prepared as a separate document.

Participants

At the start, 7 NMIs (UME in Turkey, PTB in Germany, DMDM in Serbia, NCM in Bulgaria, OMH in Hungary, SIQ in Slovenia and SMU in Slovakia) had agreed to participate. During the comparison, one NMI (SIQ in Slovenia) withdrew from participation, but during 2003 to 2006 six additional NMIs (MIKES in Finland, VSL in Netherlands, INM in Romania, LNE in France, NPLI in India and UMTS in Ukraine) asked for inclusion in the comparison.

Table 1. List of participants, in the sequence of measurements performed

Laboratory	Measurement Date
UME, TÜBİTAK Ulusal Metroloji Enstitüsü, Turkey (Pilot Laboratory)	Jan 2004 - Mar 2008
PTB, Physikalisch-Technische Bundesanstalt, Germany (Linking Laboratory)	Dec 2003 - Jul 2007
NCM, National Centre of Metrology, Bulgaria now BIM, Bulgarian Institute of Metrology	Apr 2004
SMU, Slovensky Metrologicky Ustav, Slovakia	Jul 2004
OMH, Országos Mérésügyi Hivatal; Hungary now MKEH, Hungarian Trade Licensing Office	Aug 2004
INM, National Institute of Metrology, Romania	Nov 2004 - May 2005
ZMDM, Bureau of Measures and Precious Metals, Serbia now DMDM, Directorate of Measures and Precious Metals	Jun 2005
MIKES, Mittatekniikan Keskus, Centre for Metrology and Accreditation, Finland	Sep 2005
NMi/VSL, Nederlands Meetinstituut-Van Swinden Laboratorium now VSL, Netherlands	Dec 2005 - Apr 2006
NPLI, National Physical Laboratory of India, India	Jun 2006
LNE, Laboratoire National de Métrologie et d'Essais, France	Apr 2007
UMTS, Ukrmetrteststandard, Ukraine	Sep 2007

Travelling Standard

During the kick-off meeting at PTB in 2002 it was agreed to use a power measuring instrument as travelling standard, which is similar to the devices normally tested at the calibration laboratories, as most local NMI power standards are intended to calibrate measuring instruments and not sources. The travelling instrument should be easily transportable, and most of all it should show good measurement stability.

The selected instrument was a HEG C1-2 Power-Converter, based on a time-division-multiplication scheme developed by Miljanić, Stojanović and Bošnjaković [5]. It has separate (electrically isolated) voltage and current inputs on the front panel. There is only one voltage range, 120 V, and one current range, 5 A. The internal dc reference voltages (nominally +7 V and -7 V) can be monitored at the front panel.

The instrument is configured as an ac-power-to-dc-voltage transducer, with a nominal full-scale dc output of 10 V, which is also available on the front panel. In addition, the instrument has a built-in voltage to frequency converter, with two nominal full-scale output frequencies of 10 Hz and 10 kHz, available on the front panel. The nominal supply voltage is 220-240 V at 50 Hz, but the instrument can be powered at any frequency between 45 Hz and 65 Hz with no measurable change in error.

The instrument used as the travelling standard for the comparison (serial number 46043) had been used in the previous comparison, as well. And, it had been regularly monitored for several years. Measurements of the standard between 20 ºC and 23 ºC indicated a negligible temperature coefficient in this range. Short-term changes in relative humidity between 30 % and 60 % produced no measurable effect. Voltage, current, and power factor coefficients were negligible within ±0,2 % of nominal values.

With no voltage or current applied, there was a small dc offset at the output. Each NMI measured this offset and the dc reference voltages. *Although there were small drifts in these voltages, they were compensated for by the normalization procedure described below, thus the measured voltages were not directly used in the analysis of the key comparison reference values and the degree of equivalence of measurements.*

Test Points

During the meeting at PTB in 2002 the UME and PTB decided to perform the comparison at 120 V, 5 A, 53 Hz, at 1,0, 0,5 and 0,0 power factors, in order to be in line with the global CCEM and EURAMET comparisons. Instructions to the participants were as follows:

Main measurements (nominal test power) shall be performed at:

Voltage	: 120 V
Current	: 5 A
Power Factor	: 1; 0,5i/c; 0i/c (i: inductive, c: capacitive)
Frequency	: 53 Hz (slightly aside from 50 Hz)

DC output voltage of the travelling standard (10 V nominal at the rated input) shall be measured from the VOLT.OUT sockets (10 V DC). The DC output voltage is measured using a digital voltmeter of high resolution (e.g. Agilent 3458A), which is calibrated with a dc voltage standard immediately before the test. The integration time of the multimeter shall be selected long enough to eliminate the travelling standard's input frequency dependence. Example: The integration time is set to a multiple integer of the period of the second harmonic of the measuring frequency. The integration time T_i is then 11,4 s (570 NPLC at 50 Hz).

Additional measurements (with no test power applied) shall be performed at the following three "no power" conditions:

Voltage:	120 V	Current: 0 A
Voltage:	0 V (input shorted)	Current: 5 A
Voltage:	0 V (input shorted)	Current: 0 A

With no voltage or current applied, there will be a small DC offset at the output. Participants shall record the mean output offset voltage, but will not correct for the offset.

DC reference voltage measurements (+7,044...V and -7,044...V) shall be performed from the REF.VOLTAGE OUT sockets. The mean DC ref voltages shall be recorded during the measurements.

Particular requirements for ambient conditions:

The power-converter shall not be exposed to draught of cold or hot air (e.g. fan-output of neighbouring power amplifier).

Measurements shall be made at the temperature of 23°C.

Ideally, each NMI would have tested and returned the travelling standard to the pilot lab; however, the large number of participants and the limited schedule mandated a more efficient approach. Therefore, the travelling standard was cycled through two, three or through more NMIs before returning to PTB. In these cases the NMIs reported the dc reference voltages of the travelling instrument in between in order to have at least one indication of its stability. Additionally, this approach was strengthened with the similar cycles between the measurements of UME.

Results

The final results submitted by each participant are given in Table 2.

Table 2. Relative deviations from nominal values in µW/(VA) and Standard Uncertainties (k=1)

$x_{i,j}$ =	Results of measurements carried out by laboratory i at power factor j										
$u_{i,j}$ =	Combined standard uncertainty (k=1) of $x_{i,j}$										
	1.0		0.5 Lead		0.5 Lag		0.0 Lead		0.0 Lag		
Lab$_i$	$x_{i,1.0}$	$u_{i,1.0}$	$x_{i,0.5\ Lead}$	$u_{i,0.5\ Lead}$	$x_{i,0.5\ Lag}$	$u_{i,0.5\ Lag}$	$x_{i,0.0\ Lead}$	$u_{i,0.0\ Lead}$	$x_{i,0.0\ Lag}$	$u_{i,0.0\ Lag}$	Meas. Date
	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	
PTB	31	5	16	5	12	5	0	5	-6	5	Dec 03
UME	40	10	30	10	-1	10	10	10	-18	10	Jan 04
BIM	15	36	24	47	-4	49	23	52	-13	51	Apr 04
UME	10	10	2	10	10	10	-17	10	-12	10	May 04
PTB	29	5	14	5	11	5	-2	5	-6	5	Jun 04
SMU	45	29	40	30	5	30	8	31	-25	31	Jul 04
OMH	37	31	10	30	7	30	-15	30	-13	30	Aug 04
PTB	32	5	15	5	11	5	-3	5	-7	5	Oct 04
UME	32	10	15	10	17	10	-9	10	-17	10	Nov 04
INM	53	41	47	41	6	41	26	41	-30	41	Apr 05
DMDM*	52	23	38	19	44	19	-5	18	0	18	Jun 05
MIKES	35	16	22	13	10	13	3	12	-11	12	Sep 05
UME	25	10	15	10	2	10	-15	10	-20	10	Oct 05
VSL	14	6	-1	9	-6	9	7	10	0	10	Apr 06
NPLI	14	40	25	33	8	33	15	31	-22	31	Jun 06
PTB	25	5	13	5	8	5	0	5	-6	5	Sep 06
PTB	25	5	13	5	8	5	0	5	-7	5	Nov 06
UME	30	10	15	10	5	10	-2	10	-15	10	Mar 07
LNE	34	14	17	9	13	9	-2	6	-7	6	Apr 07
PTB	33	5	18	5	10	5	1	5	-8	5	Jul 07
UMTS	47	15	-33	46	75	46	-6	73	6	77	Sep 07
UME	36	10	19	10	11	10	1	10	-6	10	Mar 08

The uncertainty values of a participant (DMDM-Serbia) marked with an asterisk are corrected values. The NMI concerned discovered errors in their uncertainty calculation method, and therefore asked for upgrade in the Draft A stage. The preliminary uncertainty values of 10,6 µW/VA, 14,3 µW/VA and 15,3 µW/VA given for 1,0, 0,5i/c and 0,0i/c power factors, respectively, were replaced with the revised ones as shown above (Table 2). The new uncertainty values of the NMI were used in the final results with the agreement of all participants.

UME, the pilot lab, and PTB performed 6 measurements for each power factor. However, as decided in the beginning of the comparison, the results of PTB are taken into account while calculating the drift effect of the travelling standard and the reference value of the comparison.

Data from Table II are plotted for each power factor in figures 1 through 5, with trend lines (fit to the PTB values) to show how the travelling standard drifted during the comparison.

Figure 1. Reported Results, 120 V, 5 A, PF=1.0 (k=1)

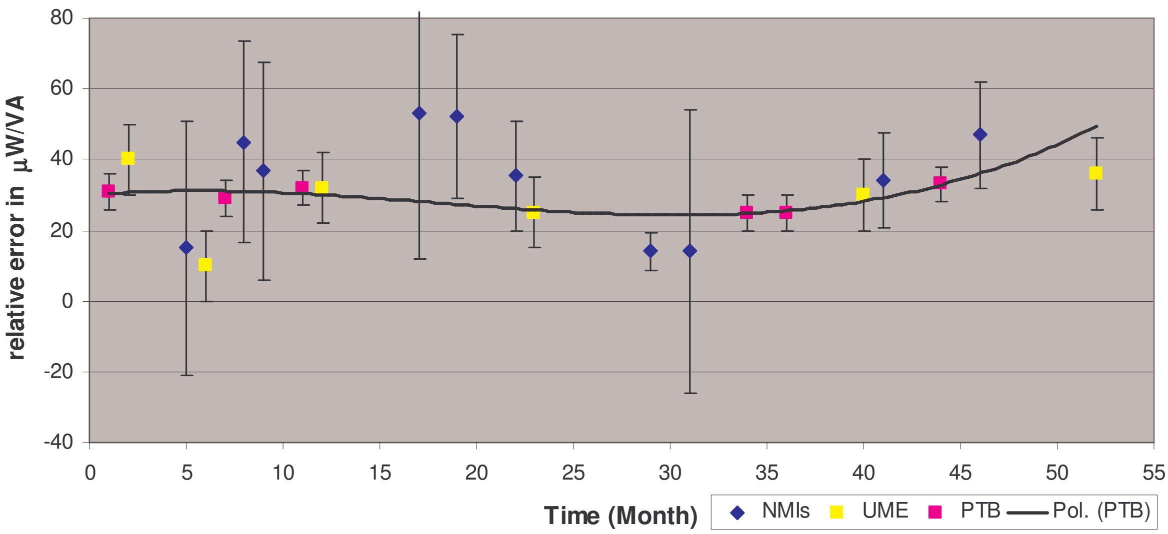


Figure 2. Reported Results, 120 V, 5 A, PF=0.5 Lead (cap) (k=1)

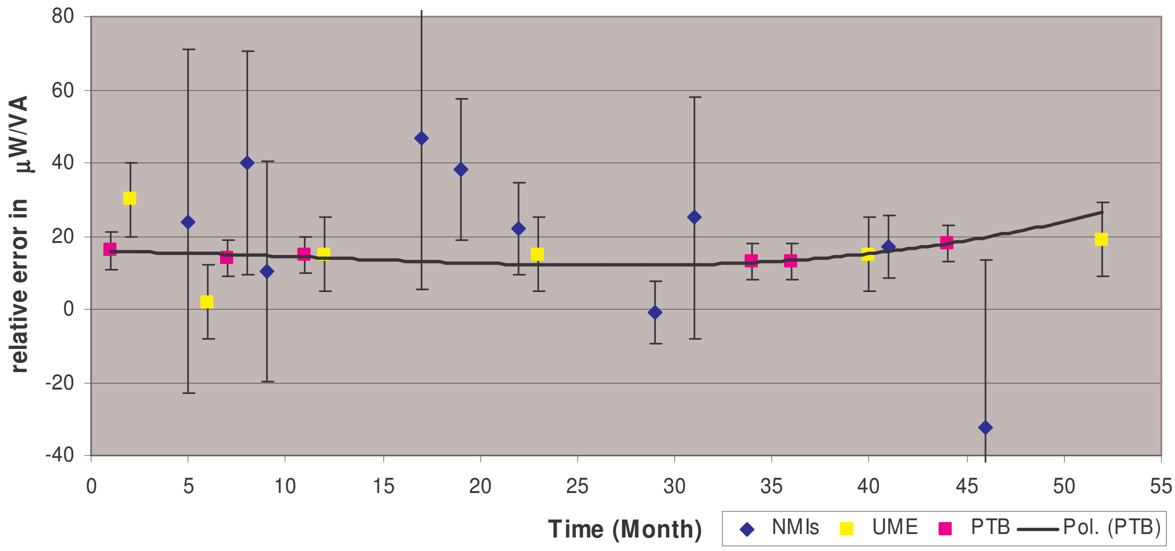
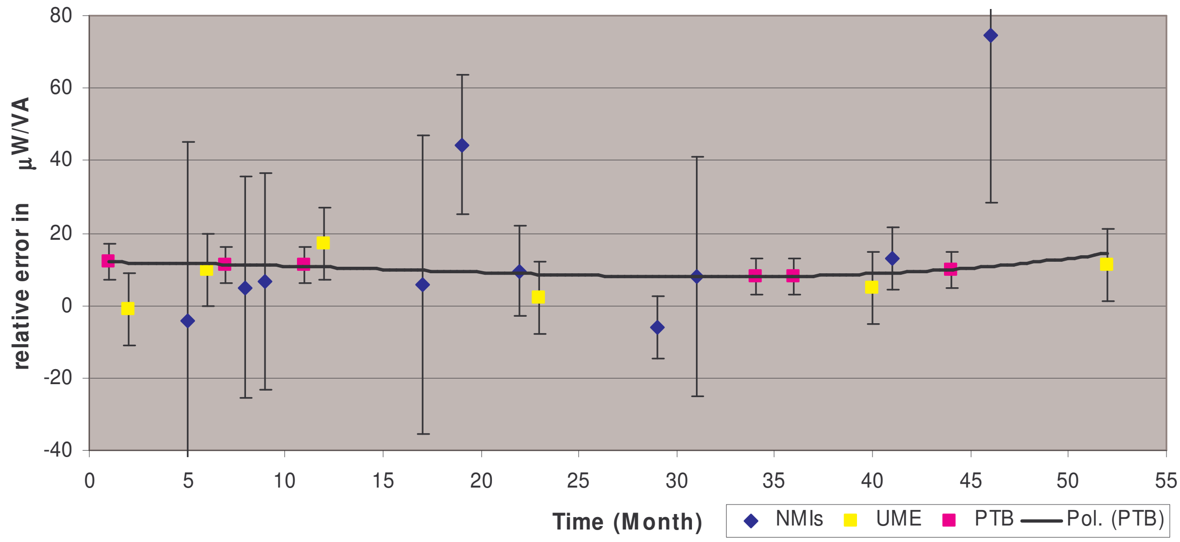


Figure 3. Reported Results, 120 V, 5 A, PF=0.5 Lag (ind) (k=1)



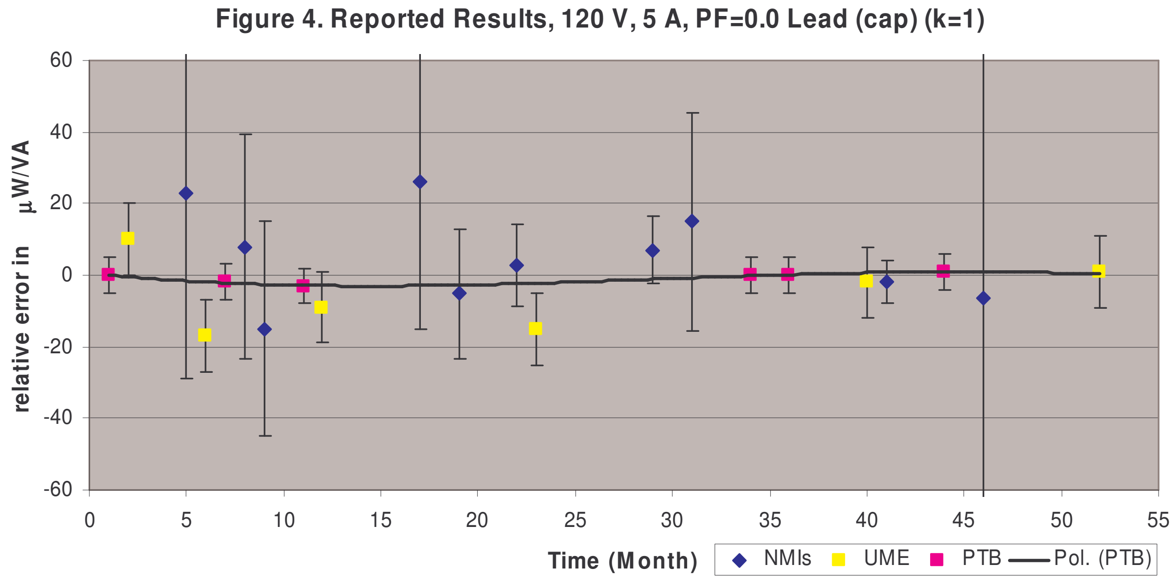


Figure 4. Reported Results, 120 V, 5 A, PF=0.0 Lead (cap) (k=1)
relative error in µW/VA
60
40
20
0
-20
-40
-60
0
5
10
15
20
25
30
35
40
45
50
55
Time (Month)
NMIs
UME
PTB
Pol. (PTB)

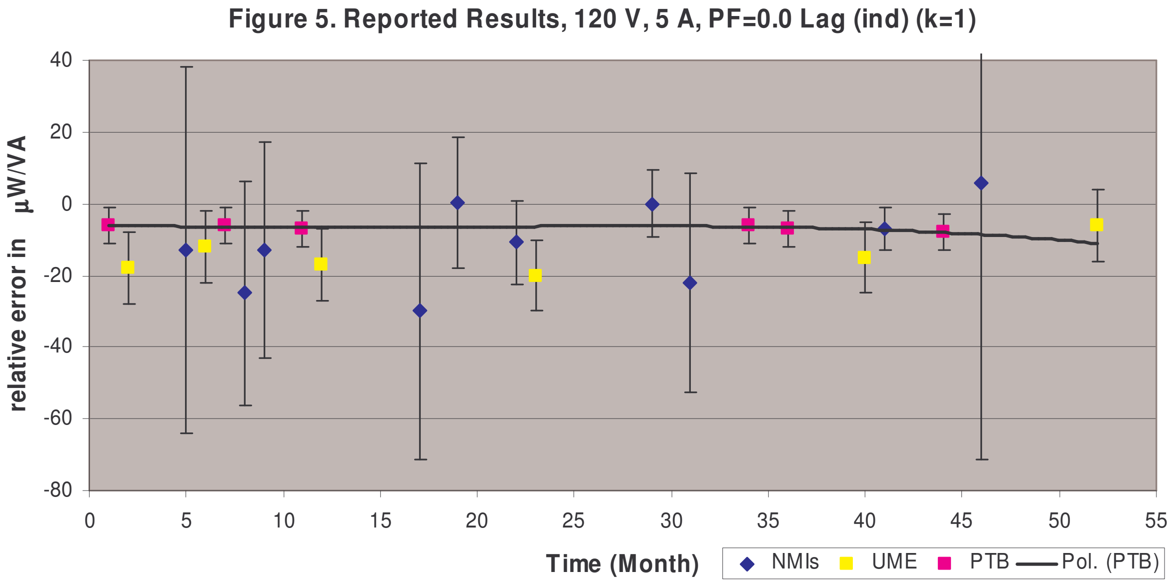


Figure 5. Reported Results, 120 V, 5 A, PF=0.0 Lag (ind) (k=1)
relative error in µW/VA
40
20
0
-20
-40
-60
-80
0
5
10
15
20
25
30
35
40
45
50
55
Time (Month)
NMIs
UME
PTB
Pol. (PTB)

The Drift Effect

To estimate drifts in the travelling standard, a polynomial regression was fitted to the six PTB measurements for each power factor. A 3rd-order polynomial regression[1] was selected to track the drift behaviour of the travelling standard. The regressions are as follows:

$$x_{PTB,1}(k) = +29{,}969 + 0{,}4647 \times t_{PTB}(k) - 0{,}049 \times t^2_{PTB}(k) + 0{,}0009 \times t^3_{PTB}(k) + \varepsilon_1(k)$$

$$x_{PTB,2}(k) = +15{,}753 - 0{,}0305 \times t_{PTB}(k) - 0{,}0136 \times t^2_{PTB}(k) + 0{,}0003 \times t^3_{PTB}(k) + \varepsilon_2(k)$$

$$x_{PTB,3}(k) = +11{,}927 - 0{,}0184 \times t_{PTB}(k) - 0{,}0108 \times t^2_{PTB}(k) + 0{,}0002 \times t^3_{PTB}(k) + \varepsilon_3(k)$$

$$x_{PTB,4}(k) = +0{,}5756 - 0{,}5568 \times t_{PTB}(k) + 0{,}0254 \times t^2_{PTB}(k) - 0{,}0003 \times t^3_{PTB}(k) + \varepsilon_4(k)$$

$$x_{PTB,5}(k) = -5{,}7142 - 0{,}173 \times t_{PTB}(k) + 0{,}0104 \times t^2_{PTB}(k) - 0{,}0002 \times t^3_{PTB}(k) + \varepsilon_5(k)$$

where $x_{PTB,j}(k)$ = the k^{th} measurements made by PTB for the j^{th} case ($j=1$ for 1,0, $j=2$ for 0,5 Lead, $j=3$ for 0,5 Lag, $j=4$ for 0,0 Lead, and $j=5$ for 0,0 Lag power factor), and $t_{PTB}(k)$ = the k^{th} time (in months) from the beginning of the comparison when PTB made the measurements, k = 1, 2, 3, 4, 5, 6, $\varepsilon_j(k)$ = random error with zero mean and variance of $\sigma_r^2(j)$ due to the j^{th} regression.

The corresponding standard deviations of the residuals are:

$s_r(1) = 3{,}543$, $s_r(2) = 1{,}942$, $s_r(3) = 1{,}664$, $s_r(4) = 1{,}650$, and $s_r(5) = 0{,}776$,

which are estimates of $\sigma_r(j)$ for j = 1, 2, 3, 4, 5. These standard deviations are used as transfer uncertainties in the linking document.

For the j^{th} case, the regression can be expressed in a matrix form:

$$\vec{X}_{PTB,j} = T_{PTB} \times \vec{\beta}(j)$$

where $\vec{X}_{PTB,j} = (x_{PTB,j}(1),...,x_{PTB,j}(6))'$ is a column vector, $\vec{\beta}(j)$ is the 4 by 1 column vector of the regression parameters, and T_{PTB} is a 6 by 4 matrix with the elements of the first column being 1's and other (k,n) elements (for $k = 1,2,3,4,5,6$ and $n = 2,3,4$) being $t^{n-1}_{PTB}(k)$. For a matrix *A* or a vector, A' is the transpose of *A*.

[1] The 3rd order polynomial method has insignificant effect on the drift values. In the worst case, it is not larger than 2 µW/(VA).

For all the 12 NMIs, the difference $D_i(j)\ (i = 1,2,...,12)$ for the i^{th} NMI and the j^{th} case is defined as

$$D_i(j) = x_{i,j} - xp_{i,j}$$

where $x_{i,j}$ is the measurement made by the i^{th} NMI at time of t_i for the j^{th} case and $xp_{i,j}$ is the prediction of the measurement of the i^{th} NMI at t_i based on the j^{th} regression described in the above. When the i^{th} NMI is PTB, the corresponding difference $AVE[D_{PTB}(j)]$ for the j^{th} case is defined as the average of the differences at $t_{PTB}(k)$ for $k = 1,2,...,6$. Namely,

$$AVE[D_{PTB}(j)] = \frac{\sum_{k=1}^{6}[x_{PTB,j}(k) - xp_{PTB,j}(k)]}{6}$$

where $xp_{PTB,j}(k)$ is the prediction from the j^{th} regression at $t_{PTB}(k)$. $AVE[D_{PTB}(j)]$ has zero mean and thus is estimated by zero.

Similarly, when the i^{th} NMI is UME, which is the pilot NMI, the corresponding difference $AVE[D_{UME}(j)]$ for the j^{th} case is defined as the average of the differences at $t_{UME}(k)$ for $k = 1,2,...,6$. Namely,

$$AVE[D_{UME}(j)] = \frac{\sum_{k=1}^{6}[x_{UME,j}(k) - xp_{UME,j}(k)]}{6}$$

where $xp_{UME,j}(k)$ is the prediction from the j^{th} regression at $t_{UME}(k)$.

The uncertainty of $D_i(j)$ is given by

$$u^2_{D_i(j)} = u_i^2(j) + s_r^2(j)(1 + \vec{t}_i(T'_{PTB}T_{PTB})^{-1}\vec{t}_i^{\,'})$$

where the row vector $\vec{t}_i = (1, t_i, t_i^2, t_i^3)$ and $u_i(j)$ is the uncertainty of the measurements made by the i^{th} NMI for the j^{th} case and $s_r^2(j)$ is the estimate of the residual variance of the j^{th} regression based on the measurements of the PTB.

Note: The influence of the term for the correction of the measurement date is in the largest case not larger than 2,0 µW/(VA).

When the i^{th} NMI is PTB, the corresponding uncertainty for $AVE[D_{PTB}(j)]$ is given by

$$u^2_{AVE[D_{PTB}(j)]} = u^2_{B,PTB}(j) + \frac{u^2_{A,PTB}(j)}{6}$$

where $u_{A,PTB}(j)$ and $u_{B,PTB}(j)$ are the uncertainties due to Type A and Type B evaluations from the uncertainty budget of PTB for the j^{th} case.

When the i^{th} NMI is UME, which the pilot NMI, the corresponding uncertainty is for $AVE[D_{UME}(j)]$ is given by

$$u^2_{AVE[D_{UME}(j)]} = \frac{\sum_{k=1}^{6} u^2_{D_{UME}(j)}(k)}{6}$$

where $u^2_{D_{UME}(j)}(k)$ is the calculated uncertainty of UME for the j^{th} case at $t_{UME}(k)$.

Reference Values

Key comparison reference values $X_{KCRV}(j)$ for each of the five test points were calculated as the weighted mean of $D_i(j)$ from the 12 NMIs including PTB and UME as the first and second NMIs, respectively. That is,

$$X_{KCRV}(j) = \sum_{i=1}^{12} w_i(j) \times D_i(j)$$

where the weights $w_i(j)$ are determined by the uncertainties of $D_i(j)$:

$$w_i(j) = \frac{\dfrac{1}{u^2_{D_i(j)}}}{\sum_{k=1}^{12} \dfrac{1}{u^2_{D_k(j)}}}$$

Note that, $D_1(j) = AVE[D_{PTB}(j)] \equiv 0$, $u_{D_1(j)} = u_{AVE[D_{PTB}(j)]}$ for PTB, and $D_2(j) = AVE[D_{UME}(j)]$, $u_{D_2(j)} = u_{AVE[D_{UME}(j)]}$ for UME.

Note also that while each NMI measurement is realized independently of the other NMI measurements, the predictions, which are based on the regression of the PTB measurements, are not statistically independent from each other. Therefore all $D_i(j)$ in the weighted mean are statistically correlated and thus the traditional formula for calculating the uncertainty of the weighted mean cannot be applied.

The uncertainty of the reference value is given by

$$u_{KCRV}^{2}(j) = \frac{1}{\sum_{i=1}^{12} \frac{1}{u_{D_i(j)}^{2}}} + \frac{2s_r^2(j)}{(\sum_{i=1}^{12} \frac{1}{u_{D_i(j)}^{2}})^2} \times \sum_{i>k,i=2}^{17} \sum_{k=2}^{17} \frac{\vec{t}_i (T_{PTB}^{'} T_{PTB})^{-1} \vec{t}_k^{\,'}}{u_{D_i(j)}^{2} \times u_{D_k(j)}^{2}}$$

Note: The contribution of the right hand part of this equation to $u_{KCRV}(j)$ is not larger than 0,15 μW/VA.

Note that, $u_{D_2(j)}^{2} = u_{AVE[D_{UME}(j)]}^{2}$ for the left hand part of this equation while not for the right hand part.

The reference values and their uncertainties are given in Table 3.

Table 3. Reference Values and Uncertainties

Power Factor	***x*KCRV**	***u*KCRV**
	in μW/(VA)	in μW/(VA)
1,0	-1,5	3,2
0,5 Lead	-0,7	3,3
0,5 Lag	-2,1	3,3
0,0 Lead	-0,1	3,2
0,0 Lag	-1,5	3,1

Equivalence to the Comparison Reference Value (CRV)

The differences between each of the NMI values and the predicted value (based on 6 independent measurements performed at PTB) were adjusted by the reference values to generate $D_{i,KCRV}(j)$ the NMI- Reference differences:

$$D_{i,KCRV}(j) = D_i(j) - X_{KCRV}(j)$$

The corresponding uncertainty when the i^{th} NMI is not PTB is given by

$$u^2_{D_{i,KCRV}}(j) = [1 - 2w_i(j)] \times u^2_{D_i(j)} + u^2_{KCRV}(j) - 2 \times s_r^2(j) \sum_{k \neq i, k=2}^{17} w_k(j)[\vec{t}_i (T'_{PTB} T_{PTB})^{-1} \vec{t}_k^{\,'}]$$

Note: The contribution of the right hand part of this equation to $u_{D_{i,KCRV}}(j)$ is in all cases less than 0,4 μW/(VA).

For UME, the difference is $D_{2,KCRV}(j)$, which is defined as

$$D_{UME,KCRV}(j) = AVE[D_{UME}(j)] - X_{KCRV}(j)$$

and its uncertainty is given by

$$u^2_{D_{2,KCRV}}(j) = u^2_{AVE[D_{UME,KCRV}(j)]} = \frac{\sum_{k=1}^{6} u^2_{D_{UME,KCRV}(j)}(k)}{6}$$

For PTB, the difference is $D_{1,KCRV}(j)$, which is defined as

$$D_{PTB,KCRV}(j) = AVE[D_{PTB}(j)] - X_{KCRV}(j)$$

and its uncertainty is given by

$$u^2_{D_{PTB,KCRV}}(j) = [1 - 2w_1(j)] \times (u^2_{B,PTB}(j) + \frac{u^2_{A,PTB}(j)}{6}) + u^2_{KCRV}(j)$$

where w_1 is the corresponding weight for PTB.

The differences and the expanded combined uncertainty (using a coverage factor of k=2) denoted by $U_{D_{i,KCRV}}$ are listed in Table 4 and plots of these data are shown in Figures 6 through 10.

The degree of equivalence between two NMIs ($i \neq k$) for the j^{th} case is defined as

$$D_{i,k}(j) = D_i(j) - D_k(j)$$

The uncertainty of $D_{i,k}(j)$ when neither is PTB, is given by

$$u_{i,k}^2(j) = u_i^2(j) + u_k^2(j) + s_r^2(j)[2 + \vec{t}_i(T_{PTB}^{'}T_{PTB})^{-1}\vec{t}_i^{\,'} + \vec{t}_k(T_{PTB}^{'}T_{PTB})^{-1}\vec{t}_k^{\,'} - 2\times\vec{t}_i(T_{PTB}^{'}T_{PTB})^{-1}\vec{t}_k^{\,'}]$$

When one NMI is the pilot lab, UME, the degree of equivalence is

$$D_{2,k}(j) = D_{UME,k}(j) = AVE[D_{UME}(j)] - D_k(j)$$

The corresponding uncertainty is given by

$$u_{2,k}^2(j) = u_{AVE[UME,k(j)]}^2 = \frac{\sum_{m=1}^{6} u_{UME,k(j)}^2(m)}{6}$$

When one NMI is PTB, the degree of equivalence is

$$D_{1,k}(j) = D_{PTB,k}(j) = AVE[D_{PTB}(j)] - D_k(j)$$

The corresponding uncertainty is given by

$$u_{1,k}^2(j) = u_{PTB,k}^2(j) = u_{B,PTB}^2(j) + \frac{u_{A,PTB}^2(j)}{6} + u_k^2(j) + s_r^2(j)[1 + \vec{t}_k(T_{PTB}^{'}T_{PTB})^{-1}\vec{t}_k^{\,'}]$$

Matrices of Equivalence are listed in Tables 5-9. They show the difference between laboratory pairs and the expanded combined uncertainties (k=2) of those differences.

Table 4. Differences and Combined Standard Uncertainties in µW/(VA)

$D_{i,KCRV}$	**Differences**										
$U_{Di,KCRV}$	**Expanded combined standard uncertainties of** $D_{i,KCRV}$ (k=2)										
i		**1.0 pf**		**0.5 Lead**		**0.5 Lag**		**0.0 Lead**		**0.0Lag**	
	NMI	$D_{i,KCRV}$	$U_{Di,KCRV}$	$D_{i,KCRV}$	$U_{Di,KCRV}$	$D_{i,KCRV}$	$U_{Di,KCRV}$	$D_{i,KCRV}$	$U_{Di,KCRV}$	$D_{i,KCRV}$	$U_{Di,KCRV}$
1	**PTB (AVE)**	0,5	5,0	-0,1	5,4	0,2	5,3	-0,9	4,9	0,7	4,6
2	**UME (AVE)**	0,2	22,4	1,1	20,5	-2,5	20,3	-5,6	20,3	-7,3	19,7
3	**BIM**	-13,5	72,4	9,1	94,1	-13,8	98,1	22,5	104,0	-5,7	101,9
4	**SMU**	16,5	57,5	25,1	61,0	-4,8	60,9	7,6	62,7	-17,7	62,5
5	**OMH**	8,2	62,5	-4,6	60,2	-3,1	60,1	-15,4	60,1	-5,7	59,9
6	**INM**	24,7	82,9	31,7	82,7	-4,0	82,5	25,9	82,4	-22,7	82,5
7	**DMDM**	23,6	47,0	23,5	38,8	34,5	38,7	-5,5	36,5	7,7	36,2
8	**MIKES**	6,8	31,8	7,2	25,3	-0,3	25,1	2,6	23,1	-3,5	22,7
9	**VSL**	-14,7	12,8	-15,9	17,4	-15,8	17,2	6,8	19,2	7,3	18,7
10	**NPLI**	-14,7	80,3	10,1	66,1	-1,8	66,1	14,8	61,1	-14,7	60,9
11	**LNE**	5,2	27,8	2,1	17,4	3,2	17,2	-2,1	12,2	0,4	11,5
12	**UMTS**	18,2	30,6	-47,4	92,1	64,7	92,0	-6,3	146,0	13,1	154,0

Figure 6. Deviation from Reference Value 120 V, 5 A, PF=1.0 (k=2)

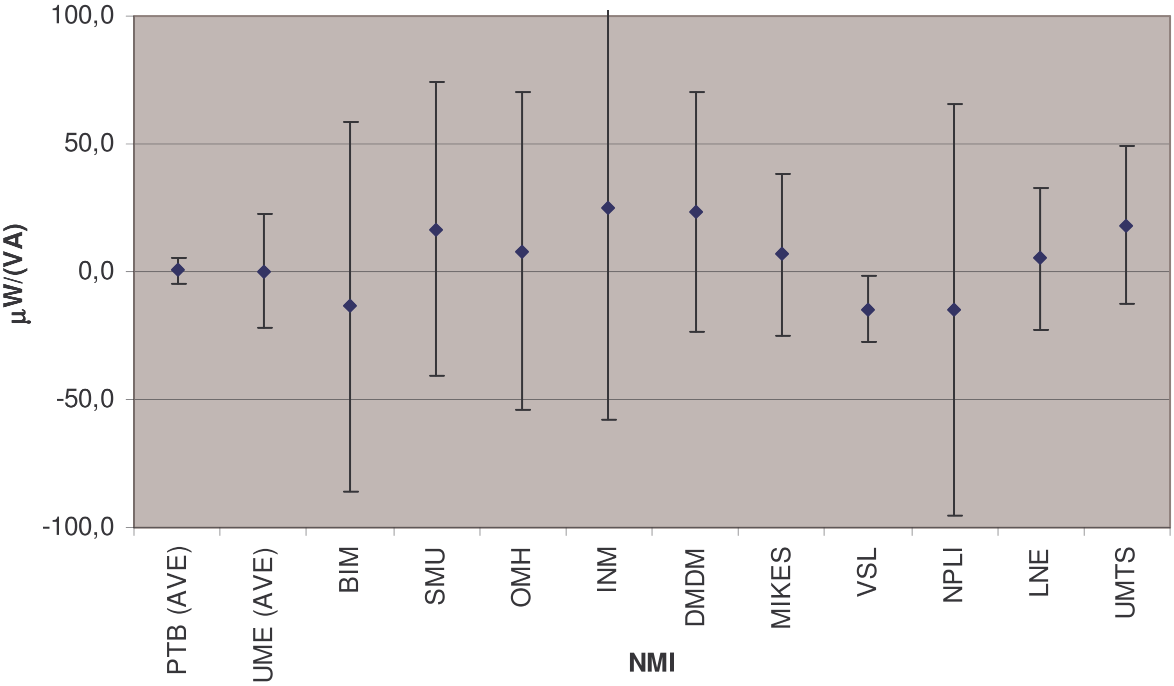


Figure 7. Deviation from Reference Value 120 V, 5 A, PF=0.5 Lead (k=2)

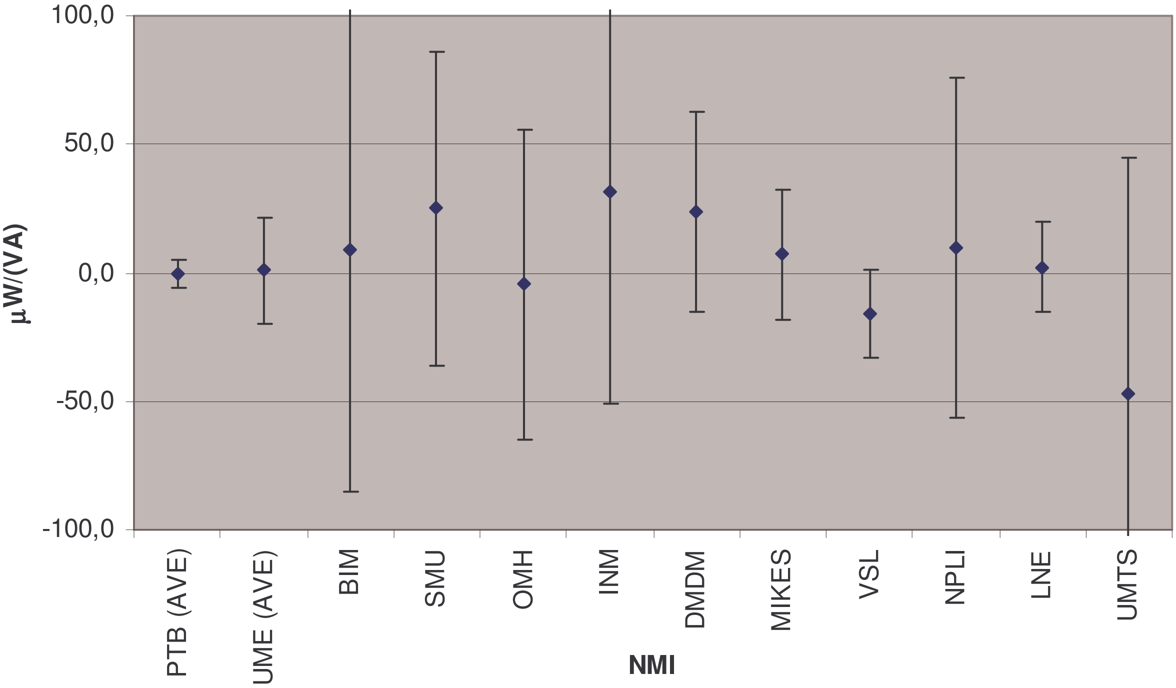


Figure 8. Deviation from Reference Value 120 V, 5 A, PF=0.5 Lag (k=2)

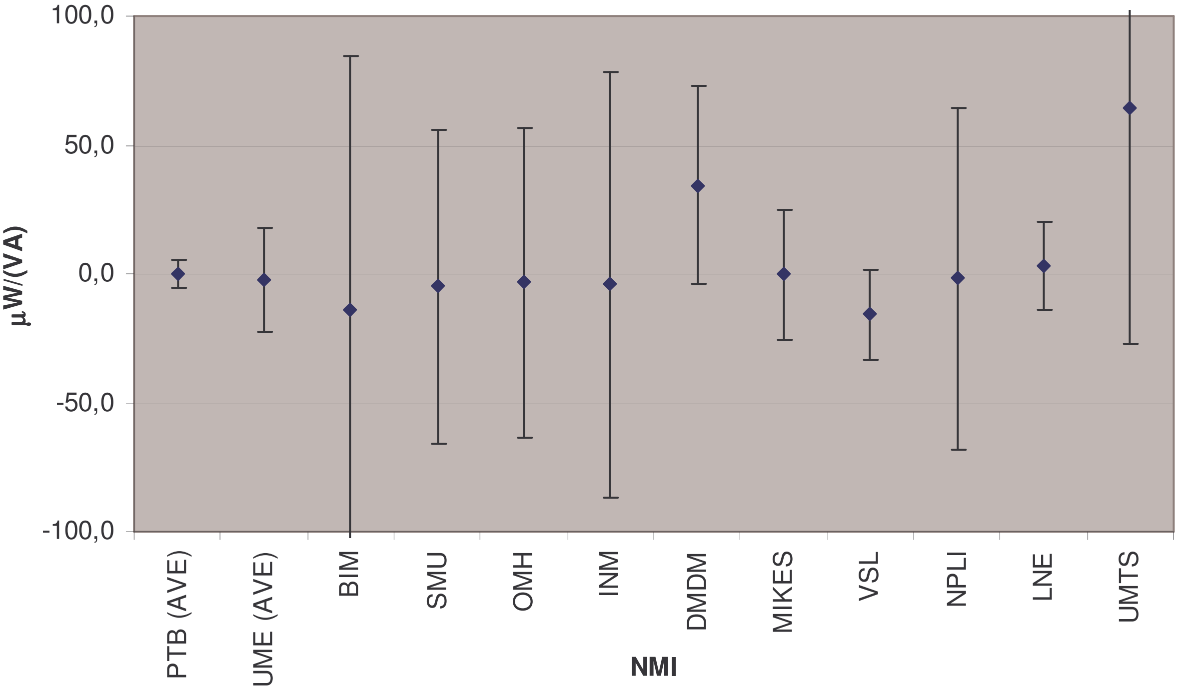


Figure 9. Deviation from Reference Value 120 V, 5 A, PF=0.0 Lead (k=2)

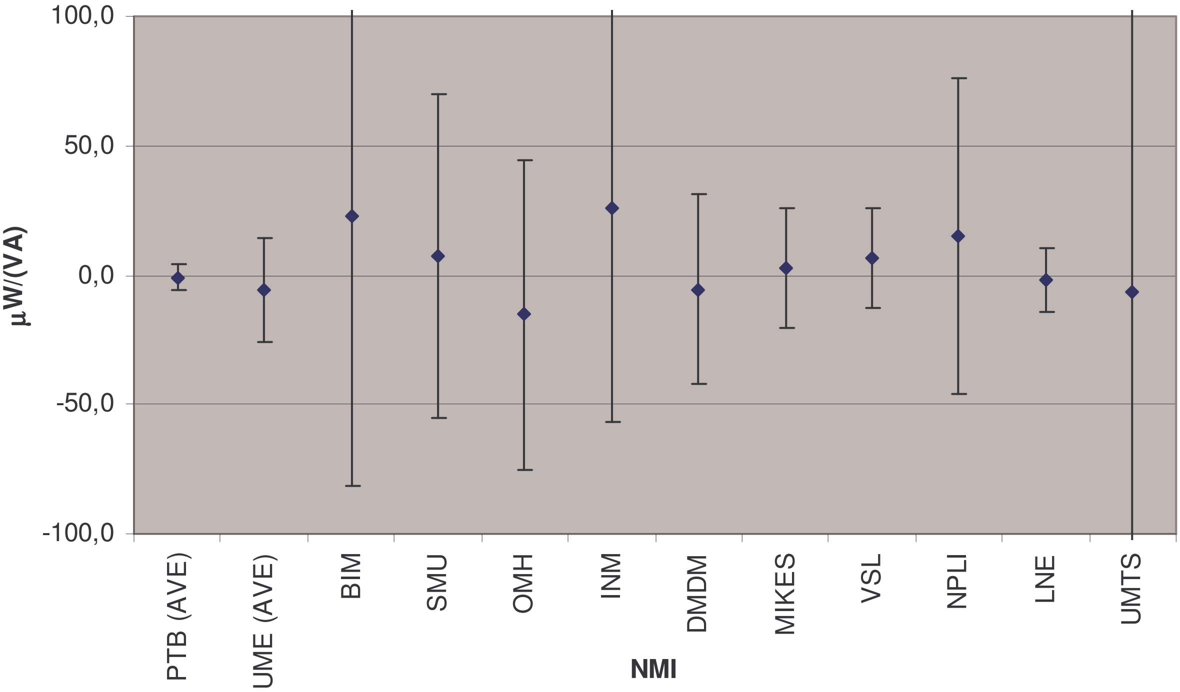


Figure 10. Deviation from Reference Value 120 V, 5 A, PF=0.0 Lag (k=2)

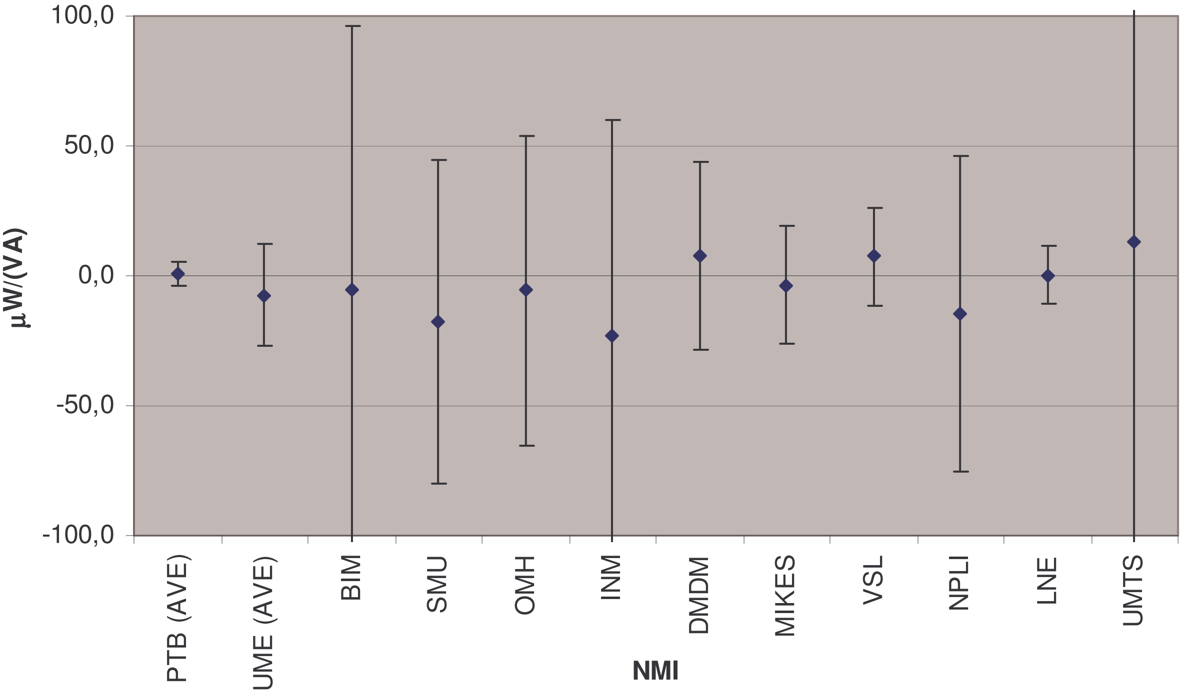


Table 5. Equivalence at 1.0 Power Factor

	PTB (AVE)	UME (AVE)	BIM	SMU	OMH	INM	DMDM	MIKES	VSL	NPLI	LNE	UMTS
PTB (AVE)	-	0,3 ± 23,0	14,0 ± 72,8	-16,0 ± 57,8	-7,7 ± 62,7	-24,2 ± 83,0	-23,1 ± 47,1	-6,3 ± 32,1	15,2 ± 14,3	15,2 ± 80,5	-4,7 ± 28,7	-17,7 ± 31,4
UME (AVE)	-0,3 ± 23,0	-	13,7 ± 75,5	-16,3 ± 61,5	-8,0 ± 66,2	-24,5 ± 85,9	-23,4 ± 52,2	-6,6 ± 39,2	14,9 ± 26,7	14,9 ± 83,6	-5,0 ± 36,1	-18,0 ± 38,1
BIM	-14,0 ± 72,8	-13,7 ± 75,2	-	-30,0 ± 92,5	-21,7 ± 95,7	-38,2 ± 110,2	-37,1 ± 86,5	-20,3 ± 79,3	1,2 ± 73,7	1,2 ± 108,2	-18,7 ± 77,6	-31,7 ± 78,8
SMU	16,0 ± 57,8	16,3 ± 60,9	30,0 ± 92,3	-	8,3 ± 84,8	-8,2 ± 101,0	-7,1 ± 74,3	9,7 ± 65,8	31,2 ± 59,0	31,2 ± 98,8	11,3 ± 63,8	-1,7 ± 65,3
OMH	7,7 ± 62,7	8,0 ± 65,5	21,7 ± 95,4	-8,3 ± 84,8	-	-16,5 ± 103,9	-15,4 ± 78,2	1,4 ± 70,2	22,9 ± 63,8	22,9 ± 101,7	3,0 ± 68,3	-10,0 ± 69,6
INM	24,2 ± 83,0	24,5 ± 85,2	38,2 ± 109,9	8,2 ± 100,7	16,5 ± 103,7	-	1,1 ± 95,3	17,9 ± 88,8	39,4 ± 83,9	39,4 ± 115,4	19,5 ± 87,3	6,5 ± 88,4
DMDM	23,1 ± 47,1	23,4 ± 50,9	37,1 ± 86,0	7,1 ± 74,0	15,4 ± 78,0	-1,1 ± 95,3	-	16,8 ± 56,7	38,3 ± 48,6	38,3 ± 92,9	18,4 ± 54,4	5,4 ± 56,0
MIKES	6,3 ± 32,1	6,6 ± 37,5	20,3 ± 78,8	-9,7 ± 65,5	-1,4 ± 69,9	-17,9 ± 88,8	-16,8 ± 56,7	-	21,5 ± 34,2	21,5 ± 86,3	1,5 ± 42,1	-11,4 ± 44,2
VSL	-15,2 ± 14,3	-14,9 ± 24,0	-1,2 ± 73,3	-31,2 ± 58,8	-22,9 ± 63,7	-39,4 ± 84,0	-38,3 ± 48,8	-21,5 ± 34,5	-	0,0 ± 81,4	-19,9 ± 30,7	-32,9 ± 33,5
NPLI	-15,2 ± 80,5	-14,9 ± 82,8	-1,2 ± 108,0	-31,2 ± 98,7	-22,9 ± 101,7	-39,4 ± 115,5	-38,3 ± 93,1	-21,5 ± 86,4	0,0 ± 81,4	-	-19,9 ± 85,0	-32,9 ± 86,0
LNE	4,7 ± 28,7	5,0 ± 34,6	18,7 ± 77,4	-11,3 ± 63,8	-3,0 ± 68,4	-19,5 ± 87,6	-18,4 ± 54,8	-1,5 ± 42,5	19,9 ± 31,0	19,9 ± 85,1	-	-13,0 ± 41,7
UMTS	17,7 ± 31,4	18,0 ± 36,9	31,7 ± 78,5	1,7 ± 65,1	10,0 ± 69,5	-6,5 ± 88,5	-5,4 ± 56,2	11,4 ± 44,4	32,9 ± 33,5	32,9 ± 86,0	13,0 ± 41,5	-

Table 6. Equivalence at 0.5 Lead (capacitive)

	PTB (AVE)	UME (AVE)	BIM	SMU	OMH	INM	DMDM	MIKES	VSL	NPLI	LNE	UMTS
PTB (AVE)	-	-1,2 ± 22,4	-9,2 ± 94,5	-25,2 ± 61,5	4,5 ± 60,7	-31,8 ± 83,1	-23,6 ± 39,7	-7,3 ± 26,6	15,8 ± 19,4	-10,2 ± 66,7	-2,2 ± 19,5	47,3 ± 92,5
UME (AVE)	1,2 ± 22,4	-	-8,0 ± 96,3	-24,0 ± 64,3	5,7 ± 63,6	-30,6 ± 85,3	-22,4 ± 44,1	-6,1 ± 32,8	17,0 ± 27,3	-9,0 ± 69,4	-1,0 ± 27,2	48,5 ± 94,4
BIM	9,2 ± 94,5	8,0 ± 96,2	-	-16,0 ± 112,1	13,7 ± 111,7	-22,6 ± 125,3	-14,4 ± 101,8	1,9 ± 97,5	25,0 ± 95,7	-1,0 ± 115,0	7,0 ± 95,7	56,5 ± 131,7
SMU	25,2 ± 61,5	24,0 ± 64,1	16,0 ± 112,1	-	29,7 ± 85,6	-6,6 ± 102,7	1,6 ± 72,3	17,9 ± 66,0	41,0 ± 63,4	15,0 ± 89,9	23,0 ± 63,4	72,5 ± 110,4
OMH	-4,5 ± 60,7	-5,7 ± 63,4	-13,7 ± 111,6	-29,7 ± 85,6	-	-36,3 ± 102,3	-28,1 ± 71,6	-11,8 ± 65,3	11,3 ± 62,6	-14,7 ± 89,4	-6,7 ± 62,6	42,8 ± 110,0
INM	31,8 ± 83,1	30,6 ± 85,1	22,6 ± 125,2	6,6 ± 102,7	36,3 ± 102,2	-	8,2 ± 91,3	24,5 ± 86,5	47,6 ± 84,5	21,6 ± 105,8	29,6 ± 84,5	79,1 ± 123,7
DMDM	23,6 ± 39,7	22,4 ± 43,6	14,4 ± 101,7	-1,6 ± 72,2	28,1 ± 71,5	-8,2 ± 91,3	-	16,3 ± 46,3	39,4 ± 42,5	13,4 ± 76,6	21,4 ± 42,4	70,9 ± 99,9
MIKES	7,3 ± 26,6	6,1 ± 32,2	-1,9 ± 97,4	-17,9 ± 65,9	11,8 ± 65,2	-24,5 ± 86,5	-16,3 ± 46,3	-	23,1 ± 30,7	-2,9 ± 70,8	5,1 ± 30,6	54,6 ± 95,5
VSL	-15,8 ± 19,4	-17,0 ± 26,6	-25,0 ± 95,6	-41,0 ± 63,3	-11,3 ± 62,6	-47,6 ± 84,5	-39,4 ± 42,6	-23,1 ± 30,8	-	-26,0 ± 68,4	-18,0 ± 24,6	31,5 ± 93,7
NPLI	10,2 ± 66,7	9,0 ± 69,1	1,0 ± 115,0	-15,0 ± 89,9	14,7 ± 89,4	-21,6 ± 105,9	-13,4 ± 76,7	2,9 ± 70,8	26,0 ± 68,4	-	8,0 ± 68,4	57,5 ± 113,4
LNE	2,2 ± 19,5	1,0 ± 26,6	-7,0 ± 95,7	-23,0 ± 63,4	6,7 ± 62,6	-29,6 ± 84,5	-21,4 ± 42,6	-5,1 ± 30,8	18,0 ± 24,7	-8,0 ± 68,4	-	49,5 ± 93,7
UMTS	-47,3 ± 92,5	-48,5 ± 94,2	-56,5 ± 131,6	-72,5 ± 110,4	-42,8 ± 110,0	-79,1 ± 123,8	-70,9 ± 99,9	-54,6 ± 95,5	-31,5 ± 93,7	-57,5 ± 113,4	-49,5 ± 93,7	-

Table 7. Equivalence at 0.5 Lag (inductive)

	PTB (AVE)	UME (AVE)	BIM	SMU	OMH	INM	DMDM	MIKES	VSL	NPLI	LNE	UMTS
PTB (AVE)	-	2,7 ± 22,3	14,0 ± 98,5	5,0 ± 61,5	3,3 ± 60,7	4,2 ± 82,9	-34,3 ± 39,7	0,5 ± 26,7	16,0 ± 19,4	2,0 ± 66,7	-3,0 ± 19,5	-64,5 ± 92,5
UME (AVE)	-2,7 ± 22,3	-	11,3 ± 100,2	2,3 ± 64,2	0,6 ± 63,5	1,5 ± 85,0	-37,0 ± 43,9	-2,2 ± 32,6	13,3 ± 27,0	-0,7 ± 69,3	-5,7 ± 27,0	-67,2 ± 94,3
BIM	-14,0 ± 98,5	-11,3 ± 100,1	-	-9,0 ± 115,4	-10,7 ± 115,0	-9,8 ± 128,2	-48,3 ± 105,5	-13,5 ± 101,3	2,0 ± 99,6	-12,0 ± 118,3	-17,0 ± 99,6	-78,5 ± 134,5
SMU	-5,0 ± 61,5	-2,3 ± 64,1	9,0 ± 115,4	-	-1,7 ± 85,6	-0,8 ± 102,5	-39,3 ± 72,2	-4,5 ± 65,9	11,0 ± 63,3	-3,0 ± 89,9	-8,0 ± 63,3	-69,5 ± 110,4
OMH	-3,3 ± 60,7	-0,6 ± 63,3	10,7 ± 115,0	1,7 ± 85,5	-	0,9 ± 102,1	-37,6 ± 71,5	-2,8 ± 65,2	12,7 ± 62,5	-1,3 ± 89,3	-6,3 ± 62,5	-67,8 ± 109,9
INM	-4,2 ± 82,9	-1,5 ± 84,8	9,8 ± 128,1	0,8 ± 102,5	-0,9 ± 102,0	-	-38,5 ± 91,1	-3,7 ± 86,2	11,8 ± 84,2	-2,2 ± 105,7	-7,2 ± 84,2	-68,7 ± 123,6
DMDM	34,3 ± 39,7	37,0 ± 43,6	48,3 ± 105,4	39,3 ± 72,1	37,6 ± 71,5	38,5 ± 91,1	-	34,8 ± 46,2	50,3 ± 42,4	36,3 ± 76,6	31,3 ± 42,4	-30,2 ± 99,9
MIKES	-0,5 ± 26,7	2,2 ± 32,2	13,5 ± 101,2	4,5 ± 65,9	2,8 ± 65,1	3,7 ± 86,2	-34,8 ± 46,2	-	15,5 ± 30,6	1,5 ± 70,7	-3,5 ± 30,5	-65,0 ± 95,4
VSL	-16,0 ± 19,4	-13,3 ± 26,5	-2,0 ± 99,5	-11,0 ± 63,3	-12,7 ± 62,5	-11,8 ± 84,3	-50,3 ± 42,5	-15,5 ± 30,6	-	-14,0 ± 68,3	-19,0 ± 24,5	-80,5 ± 93,7
NPLI	-2,0 ± 66,7	0,7 ± 69,1	12,0 ± 118,2	3,0 ± 89,8	1,3 ± 89,3	2,2 ± 105,7	-36,3 ± 76,6	-1,5 ± 70,8	14,0 ± 68,3	-	-5,0 ± 68,3	-66,5 ± 113,3
LNE	3,0 ± 19,5	5,7 ± 26,5	17,0 ± 99,6	8,0 ± 63,3	6,3 ± 62,5	7,2 ± 84,3	-31,3 ± 42,5	3,5 ± 30,7	19,0 ± 24,5	5,0 ± 68,3	-	-61,5 ± 93,7
UMTS	64,5 ± 92,5	67,2 ± 94,2	78,5 ± 134,5	69,5 ± 110,4	67,8 ± 109,9	68,7 ± 123,6	30,2 ± 99,9	65,0 ± 95,5	80,5 ± 93,7	66,5 ± 113,3	61,5 ± 93,7	-

Table 8. Equivalence at 0.0 Lead (capacitive)

	PTB (AVE)	UME (AVE)	BIM	SMU	OMH	INM	DMDM	MIKES	VSL	NPLI	LNE	UMTS
PTB (AVE)	-	4,7 ± 22,3	-23,4 ± 104,5	-8,5 ± 63,3	14,5 ± 60,7	-26,8 ± 82,9	4,6 ± 37,6	-3,5 ± 24,8	-7,7 ± 21,2	-15,7 ± 61,7	1,2 ± 15,3	5,4 ± 146,3
UME (AVE)	-4,7 ± 22,3	-	-28,2 ± 106,0	-13,2 ± 65,9	9,8 ± 63,5	-31,5 ± 85,0	-0,1 ± 42,0	-8,2 ± 31,1	-12,4 ± 28,3	-20,4 ± 64,5	-3,5 ± 24,1	0,7 ± 147,5
BIM	23,4 ± 104,5	28,2 ± 106,0	-	15,0 ± 121,5	38,0 ± 120,2	-3,3 ± 132,8	28,1 ± 110,3	19,9 ± 106,7	15,8 ± 105,9	7,7 ± 120,7	24,6 ± 104,8	28,8 ± 179,3
SMU	8,5 ± 63,3	13,2 ± 65,8	-15,0 ± 121,5	-	23,0 ± 86,8	-18,3 ± 103,6	13,1 ± 72,6	5,0 ± 66,9	0,8 ± 65,6	-7,2 ± 87,5	9,7 ± 63,9	13,9 ± 158,9
OMH	-14,5 ± 60,7	-9,8 ± 63,3	-38,0 ± 120,1	-23,0 ± 86,8	-	-41,3 ± 102,1	-9,9 ± 70,4	-18,0 ± 64,5	-22,2 ± 63,1	-30,2 ± 85,7	-13,3 ± 61,4	-9,1 ± 157,9
INM	26,8 ± 82,9	31,5 ± 84,8	3,3 ± 132,7	18,3 ± 103,6	41,3 ± 102,0	-	31,4 ± 90,2	23,2 ± 85,7	19,1 ± 84,7	11,1 ± 102,6	28,0 ± 83,4	32,2 ± 167,7
DMDM	-4,6 ± 37,6	0,1 ± 41,6	-28,1 ± 110,2	-13,1 ± 72,5	9,9 ± 70,3	-31,4 ± 90,2	-	-8,1 ± 43,3	-12,3 ± 41,3	-20,3 ± 71,2	-3,4 ± 38,5	0,8 ± 150,5
MIKES	3,5 ± 24,8	8,2 ± 30,6	-19,9 ± 106,6	-5,0 ± 66,8	18,0 ± 64,4	-23,2 ± 85,7	8,1 ± 43,3	-	-4,2 ± 30,2	-12,2 ± 65,3	4,7 ± 26,3	8,9 ± 147,9
VSL	7,7 ± 21,2	12,4 ± 27,8	-15,8 ± 105,8	-0,8 ± 65,6	22,2 ± 63,1	-19,1 ± 84,7	12,3 ± 41,4	4,2 ± 30,2	-	-8,0 ± 64,1	8,9 ± 22,9	13,1 ± 147,3
NPLI	15,7 ± 61,7	20,4 ± 64,3	-7,7 ± 120,6	7,2 ± 87,5	30,2 ± 85,7	-11,1 ± 102,6	20,3 ± 71,2	12,2 ± 65,4	8,0 ± 64,1	-	16,9 ± 62,3	21,1 ± 158,3
LNE	-1,2 ± 15,3	3,5 ± 23,6	-24,6 ± 104,8	-9,7 ± 63,9	13,3 ± 61,4	-28,0 ± 83,4	3,4 ± 38,7	-4,7 ± 26,4	-8,9 ± 23,0	-16,9 ± 62,4	-	4,2 ± 146,6
UMTS	-5,4 ± 146,3	-0,7 ± 147,4	-28,8 ± 179,3	-13,9 ± 158,9	9,1 ± 157,9	-32,2 ± 167,7	-0,8 ± 150,5	-8,9 ± 147,9	-13,1 ± 147,3	-21,1 ± 158,3	-4,2 ± 146,6	-

Table 9. Equivalence at 0.0 Lag (inductive)

	PTB (AVE)	UME (AVE)	BIM	SMU	OMH	INM	DMDM	MIKES	VSL	NPLI	LNE	UMTS
PTB (AVE)	-	8,0 ± 22,2	6,4 ± 102,4	18,4 ± 63,3	6,4 ± 60,7	23,4 ± 83,1	-7,0 ± 37,6	4,1 ± 24,9	-6,7 ± 21,2	15,3 ± 61,7	0,3 ± 15,3	-12,5 ± 154,3
UME (AVE)	-8,0 ± 22,2	-	-1,6 ± 104,0	10,4 ± 65,8	-1,6 ± 63,3	15,3 ± 85,0	-15,1 ± 41,6	-3,9 ± 30,6	-14,7 ± 27,8	7,3 ± 64,3	-7,7 ± 23,5	-20,5 ± 155,3
BIM	-6,4 ± 102,4	1,6 ± 104,0	-	12,0 ± 119,7	0,0 ± 118,4	17,0 ± 131,3	-13,4 ± 108,3	-2,3 ± 104,6	-13,1 ± 103,8	8,9 ± 118,9	-6,1 ± 102,7	-18,9 ± 184,7
SMU	-18,4 ± 63,3	-10,4 ± 65,7	-12,0 ± 119,7	-	-12,0 ± 86,7	5,0 ± 103,7	-25,4 ± 72,5	-14,2 ± 66,7	-25,1 ± 65,5	-3,1 ± 87,4	-18,1 ± 63,8	-30,9 ± 166,3
OMH	-6,4 ± 60,7	1,6 ± 63,3	0,0 ± 118,4	12,0 ± 86,7	-	17,0 ± 102,1	-13,4 ± 70,2	-2,2 ± 64,3	-13,1 ± 63,0	8,9 ± 85,6	-6,1 ± 61,2	-18,9 ± 165,3
INM	-23,4 ± 83,1	-15,3 ± 85,0	-17,0 ± 131,3	-5,0 ± 103,7	-17,0 ± 102,1	-	-30,4 ± 90,3	-19,2 ± 85,8	-30,0 ± 84,8	-8,0 ± 102,7	-23,1 ± 83,5	-35,8 ± 174,8
DMDM	7,0 ± 37,6	15,1 ± 41,6	13,4 ± 108,3	25,4 ± 72,4	13,4 ± 70,2	30,4 ± 90,3	-	11,2 ± 43,1	0,4 ± 41,1	22,4 ± 71,1	7,3 ± 38,4	-5,4 ± 158,3
MIKES	-4,1 ± 24,9	3,9 ± 30,5	2,3 ± 104,6	14,2 ± 66,7	2,2 ± 64,3	19,2 ± 85,8	-11,2 ± 43,1	-	-10,8 ± 29,9	11,2 ± 65,2	-3,9 ± 26,0	-16,6 ± 155,7
VSL	6,7 ± 21,2	14,7 ± 27,6	13,1 ± 103,8	25,1 ± 65,5	13,1 ± 63,0	30,0 ± 84,8	-0,4 ± 41,1	10,8 ± 29,9	-	22,0 ± 63,9	7,0 ± 22,6	-5,8 ± 155,2
NPLI	-15,3 ± 61,7	-7,3 ± 64,2	-8,9 ± 118,9	3,1 ± 87,4	-8,9 ± 85,6	8,0 ± 102,7	-22,4 ± 71,1	-11,2 ± 65,2	-22,0 ± 63,9	-	-15,0 ± 62,2	-27,8 ± 165,7
LNE	-0,3 ± 15,3	7,7 ± 23,4	6,1 ± 102,7	18,1 ± 63,8	6,1 ± 61,2	23,1 ± 83,5	-7,3 ± 38,4	3,9 ± 26,1	-7,0 ± 22,6	15,0 ± 62,2	-	-12,8 ± 154,5
UMTS	12,5 ± 154,3	20,5 ± 155,3	18,9 ± 184,7	30,9 ± 166,2	18,9 ± 165,3	35,8 ± 174,8	5,4 ± 158,3	16,6 ± 155,7	5,8 ± 155,2	27,8 ± 165,7	12,8 ± 154,5	-

Uncertainty budgets for each participant are given in the Appendix.

Conclusions

The EURAMET.EM-K5.1 Comparison of 50/60 Hz Power began in November 2003 and the measurements were completed in March 2008. Of the 12 NMIs that performed tests during the comparison, 12 asked to be included in the final report. Each NMI performed tests on the travelling standard (power-to-dc-voltage converter) at 120 V, 5 A, 53 Hz at 1,0, 0,5 lead, 0,5 lag, 0,0 lead, and 0,0 lag power factors. This resulted in the 60 data points, the uncertainty budgets of which are reported in the appendix; only a few of the results deviated from the reference values by more than the expanded standard uncertainties. In more general terms, almost all of the NMIs' measurements agreed with the reference values to within 25 µW/(VA), which is about five times larger than the recognized state-of-the-art for sinusoidal power and about 40 times better than the best commercial measurements made for revenue purposes.

The EURAMET.EM-K5.1 key comparison gave an opportunity to the relevant NMIs which have similar power measurement setups based on the sampling theory and use of Agilent 3458A multimeters to see their measurement system performance. The comparison measurement results of those similar measurement systems showed a good agreement which means that the use of 3458A multimeters for the power measurements is not only a practical solution but also reliable within certain uncertainty levels.

References

[1] Rainer Bergeest, “Final report on EUROMET.EM-K5: Comparison of 50/60 Hz power (EUROMET project 385)”, Metrologia, Vol. 44, Technical Supplement, 01001, 2007

[2] N. Oldham et al., "An international comparison of 50/60 Hz power (1996-1999)", IEEE Trans. Instrum. Meas. Vol. 50, no. 2, April 2001.

[3] N. Oldham et al., "CCEM-K5 comparison of 50/60 Hz power", Metrologia, Vol. 40, Technical Supplement, 01003, 2003.

[4] F. Delahaye, T. J. Witt, “Linking the Results of Key Comparison CCEM-K4 with the 10 pF Results of EUROMET Project 345”, Metrologia, Vol. 39, Technical Supplement, 01005, 2002.

[5] P. Miljanić et al., "The development of a high precision time-division power meter," in CPEM 84 Dig., Delft, the Netherlands, pp. 67-68, 1984.

Acknowledgements

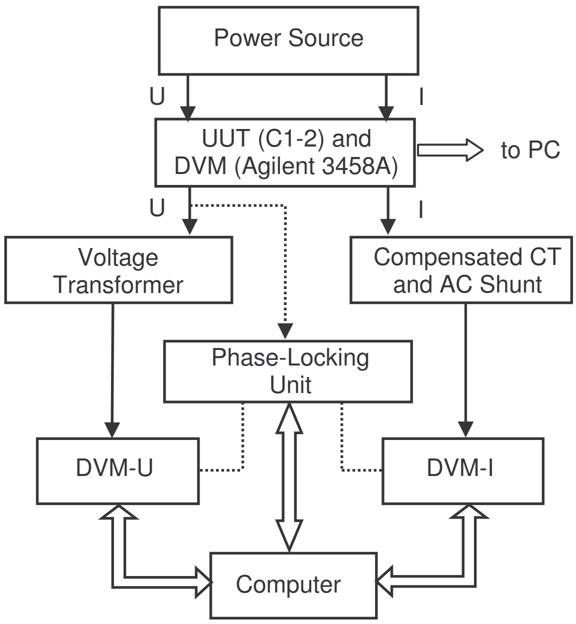
The author wishes to thank all the participants for their valuable assistance during this comparison.

APPENDIX A1. Methods of Measurement

1. UME

The operating principle of this well-known DSWM, shown in the figure below, is based on the use of two sampling voltmeters and on computerized evaluation by means of discrete integration (DI) or discrete Fourier transform (DFT).

Similar to others, it consists of two digital sampling voltmeters (DVMs), a precision voltage transformer, an electronically compensated current transformer with a temperature controlled AC shunt resistor, a computer controlled phase-locking device and software. However, the use of the phase-locking unit differs from that of the others to enable the system to operate not only with digitally synthesized power sources but also with analog sources by phase-locking to voltage or current signal.



Block diagram of DSWM

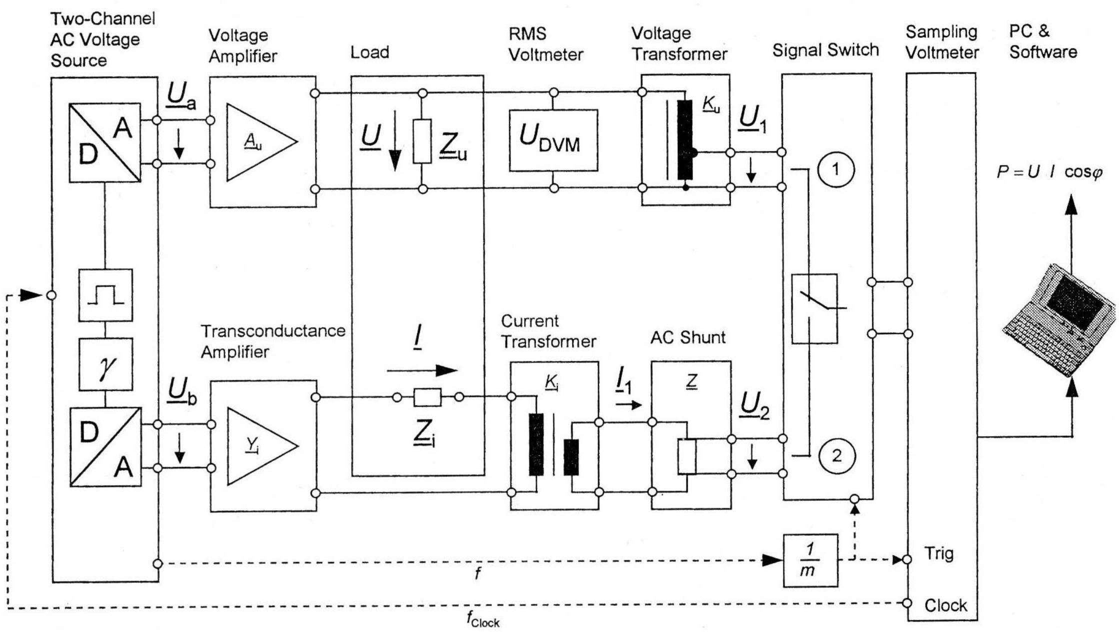
The voltage and current signals of a phantom power source are applied to the input terminals of voltage and current transformers. A regulated voltage from secondary terminals of the voltage transformer and a voltage obtained from the shunt resistor, which is connected to the secondary terminals of the current transformer, are then applied to the DVMs. With the help of the software, DVMs are programmed with the calculated appropriate aperture times for the selected samples per period. Each programmed DVM samples the applied voltage signals with the help of trigger signals generated by the phase-locking unit. The data from both DVMs are then transferred to the computer via IEEE488. The ratio and phase angle errors of the voltage and current transformers were corrected by the software.

The amplitudes of both signals, the phase angles between them and the total power are calculated mainly by using discrete integration. To check for distorted waveforms and to display the harmonic components, DFT is also used on the software. All available calculated results are displayed during the measurements.

2. PTB

The power converter was measured using the primary power standard of PTB. Reference values for the calculation of the relative error were in each case the apparent power calculated from voltage and current applied.

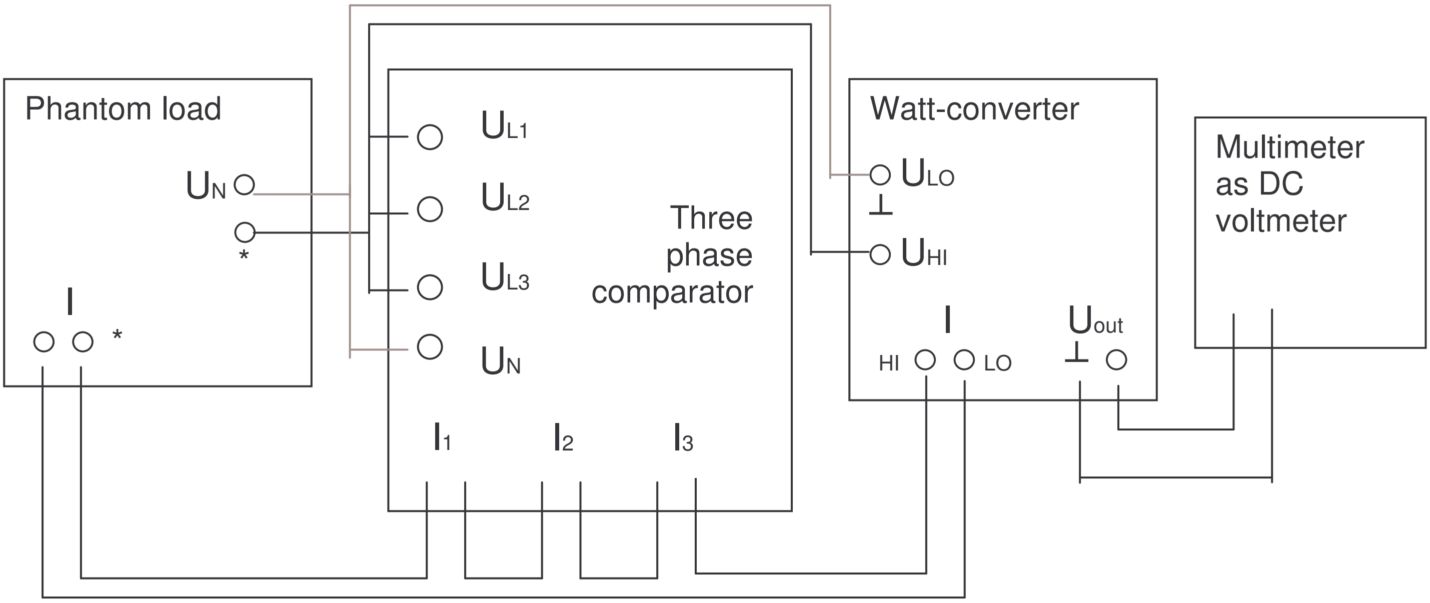
The operating principle is based on synthesized ac voltages, the use of only a single sampling voltmeter, and on computerized evaluation by means of the discrete Fourier transform (DFT). The traceability to the SI units “dc voltage” and “dc resistance” is ensured by the rms voltmeter and the ac shunt with small and well-known frequency characteristics, both calibrated against national standards. The reduction of the measurement uncertainty as compared with the methods previously used is due to the use of a single clock not only for the generation of the required voltages but also for the evaluation of these signals.



3. BIM

The value of measured power is obtained as DC voltage. At the input of the watt-converter is three phase comparator and at the output is DC voltmeter (see fig.).

During the measurements twisted cables for both current and voltage connections with a resistance less than 15 mΩ are used. Configuration of DMM: NPLC 300.



Circuit diagram

<u>Measurement equipment</u>

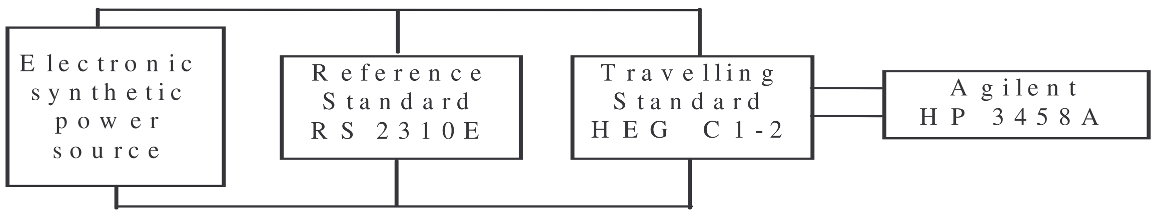
Phantom load, type TU 303, made in Bulgaria-Technical University, Sofia;

Three phase comparator, type COM303, made in Germany-ZERA GmbH, calibration mark 3457 PTB 02;

Digital multimeter (DMM), type 3458A, made in USA-Hewlett Packard, calibration certificate no. 044-EMM/29.03.2004, National Centre of Metrology

4. SMU

The method used in comparison was the direct comparison of the travelling standard AC power under the test with the reference standard AC power. The block diagram is shown in the following figure.



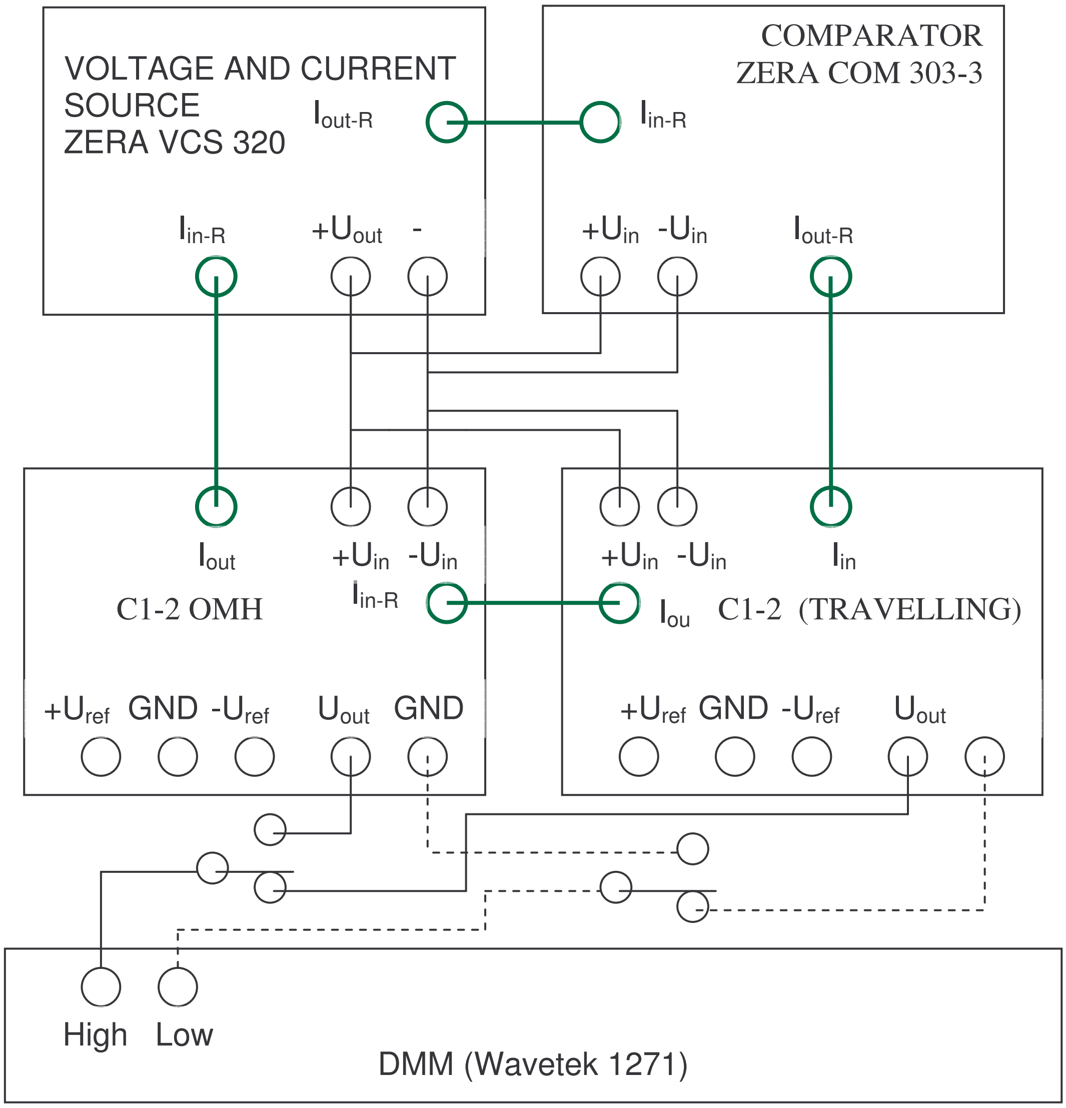
The DC output voltage of the travelling standard is measured using the digital voltmeter Agilent-HP 3458A, which has been calibrated with dc voltage standard immediately before the test.

The AC power standard was calibrated maintaining traceability to national standards of SI units. The calibration was performed using transfer standards of DC electric voltage, AC/DC transfer, electric resistance and phase angle for harmonic signal. The applied transfer standards are traceable to national standards.

5. OMH

The two power converters were supplied with the same voltage and current, their DC-output voltages were measured with a high resolution voltage-meter in sequence, one output after the other. Circuit diagram of the measurement setup is on the figure.

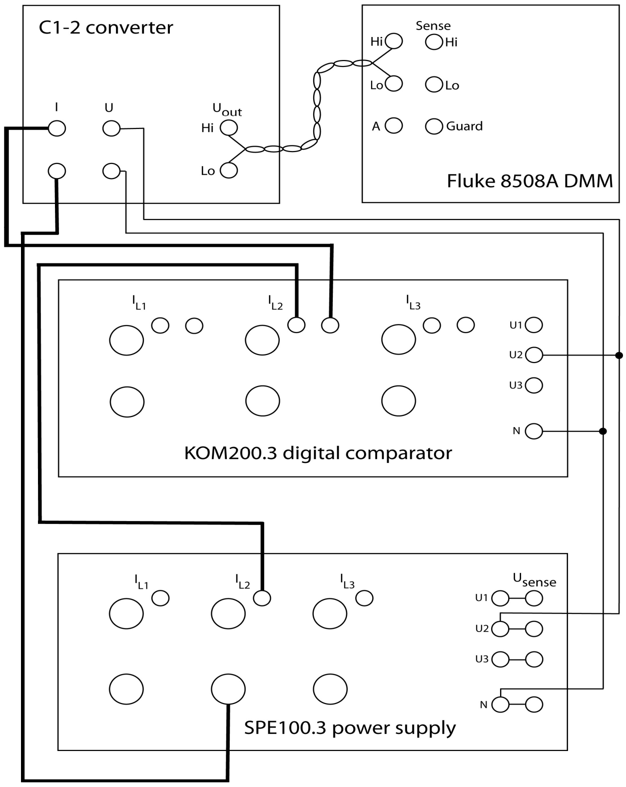
The temperature and the humidity were held within the limits given in the technical protocol ((23 ± 1) ºC, and (30-60)%). The reference DC-outputs of each device were registered before and after the DC-output voltage measurements. The nominal values of the voltage (120 V) and current (5 A) were within the limits (0,2%) given in Technical Protocol. The “0” power factor was actually 0,0096 for inductive and 0,0106 for capacitive load. The frequency of the power supply was 52,6 Hz.



Circuit diagram

6. INM

The specified values for voltage, current and power corresponding to each measurement point were supplied from a static power source SPE 100.3, serial No. 18733, manufactured by EMH Energie-Messtechnik GmbH, Brackel. This source is controlled by a computer, via the CAMCAL software, version V3.3 GB.



Block diagram of the calibration set-up.

The measurements were performed, as shown in figure, by using the scheme with separate circuits for the AC currents and AC voltages. To compare the travelling standard C1-2 against the reference standard KOM 200.3, the both devices were supplied simultaneously, from the static power source SPE 100.3. The output voltage of the C1-2 power converter was measured using the high resolution digital multimeter Fluke 8508. This voltage, multiplied by the converting factor k = 60 W/V, gave the value of power, that was compared with the value measured and displayed by the digital comparator KOM 200.3.

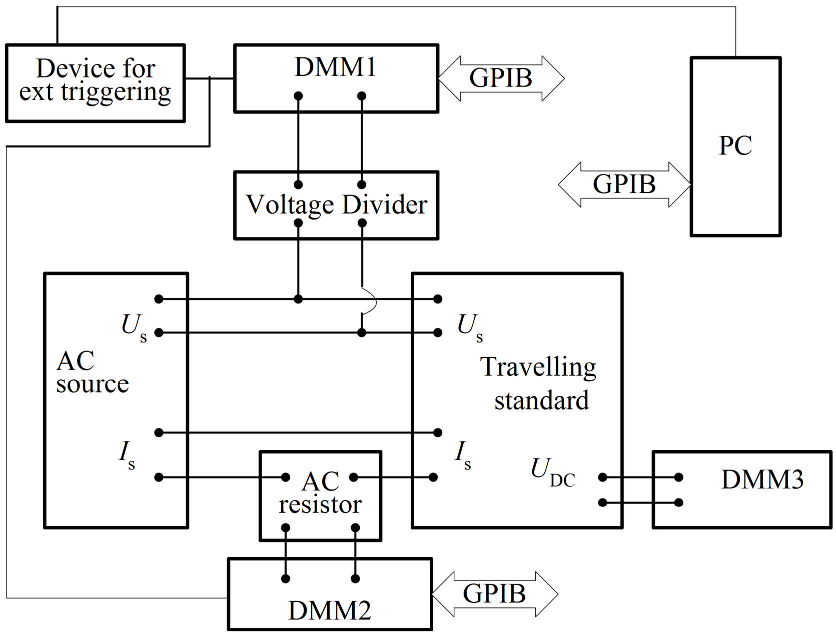
The measurement results are given as mean values of the relative errors between the values measured by the travelling standard and the reference standard of the laboratory reported to the apparent power S [VA]:

$$E\ [\mu W / VA] = \frac{P_{C1-2} - P_{KOM}}{S} \times 1000000\ [\mu W / VA]$$

considering the corrections derived from the corresponding calibration certificates of the measurement instruments. For each point, the measurements were repeated 10 times/day, during 4 consecutive days and the mean value is reported as the measurement result.

7. DMDM

Block diagram of the main measurement setup is given on the following figure.



Block diagram of the main measurement setup

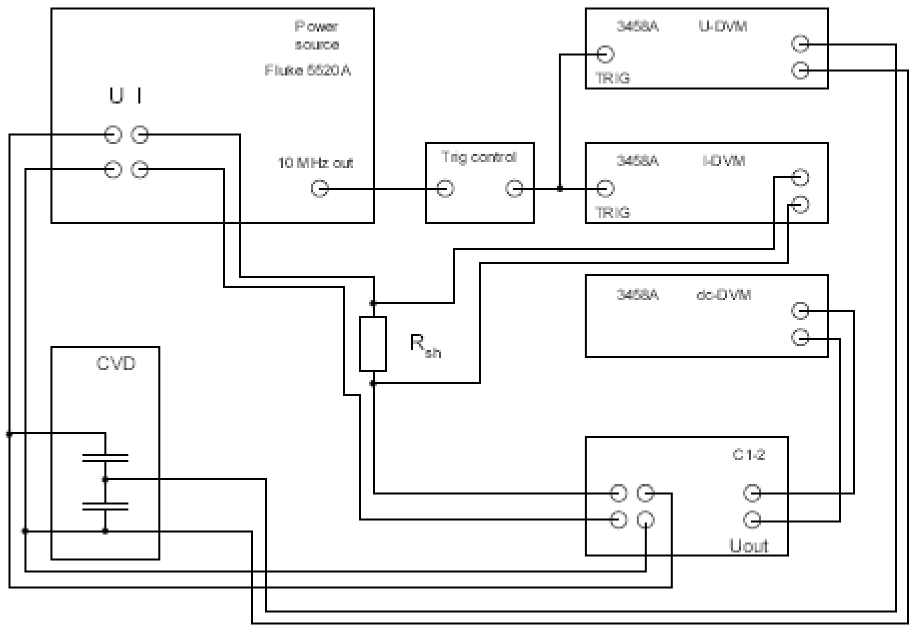
The test voltage is scaled to low level voltage using voltage divider and than applied to a sampling digital multimeter (DMM1). The test current is converted to a low-level voltage using AC resistor before application to the second sampling digital multimeter (DMM2). The samples from these multimeters are fed to the System controller via HPIB cables. From these samples we retrieved voltage and current amplitude as well as the phase angle between them using Four parameter sine fitting technique.

At the same time, DC voltage at output of travelling standard was measured with DMM3.

Method of sampling: External electric device for simultaneous external triggering of both multimeters (DMM1 and DMM2) was applied. DC sampling mode on DMM1 and DMM2 has been choosen.

8. MIKES

The power converter was compared to the digital sampling power standard of MIKES. A simplified diagram of the measurement setup is shown in the following figure. The main components of the MIKES standard are two sampling voltmeters (Agilent/Hewlett Packard 3458A, U-dvm and I-dvm), a capacitive divider (CVD) and a coaxial shunt resistor (R_{sh}). A third Agilent 3458A voltmeter (dc-dvm) was used to measure the output voltage of the power converter. The integration time for this meter was set to 250 NPLC, which equals to 269 periods of the measuring frequency.



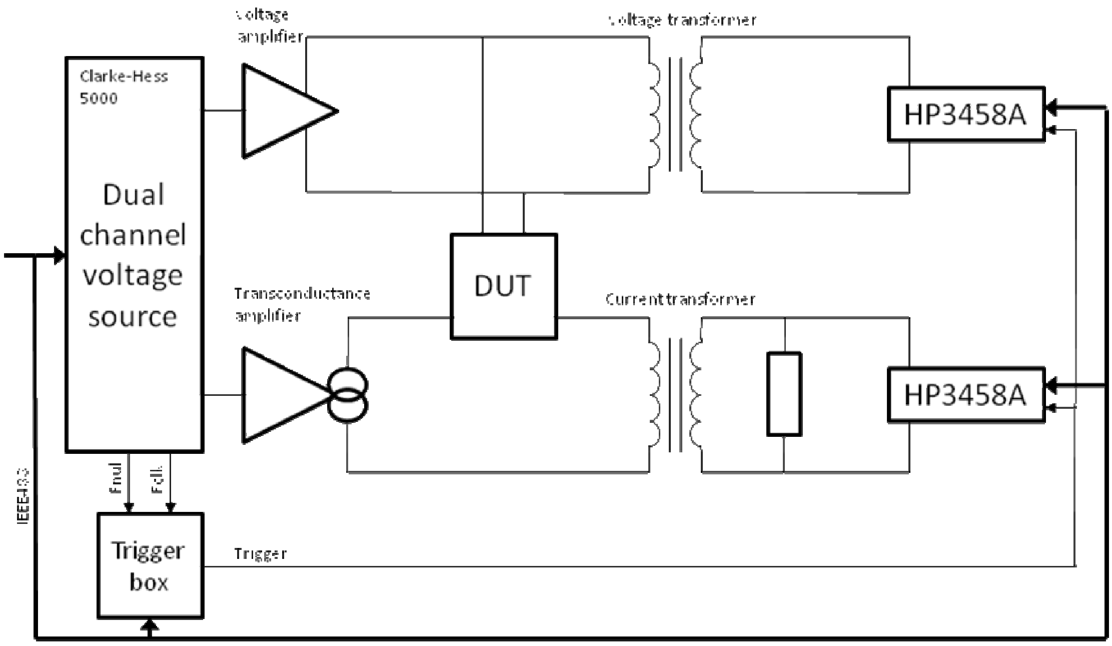
Measurement Setup Diagram

9. VSL

The travelling standard HEG C1-2 was calibrated directly against a Pupin wattmeter, which on its turn was calibrated against the VSL sampling wattmeter.

The generator used in our setup is a commercial Clarke-Hess 5000 phase standard. The signals are amplified with a Fluke 5205A precision power amplifier to get a 120 V test voltage and a Fluke 5220A transconductance amplifier to make the nominal 5 A test current. The resulting voltage and current signals are then fed to the Pupin and the HEG wattmeters in parallel and in series, respectively, via two isolation transformers. The dc voltage output of the wattmeters is read by an Agilent 3458A digital voltmeter. The absolute values of the voltage and current were within 0.1 % of the nominal values, whereas the phase angle could be set to within 0.01 º. The total distortion of the voltage and current signals was less than 0.1 %.

For calibrations with the VSL sampling wattmeter, the nominal test voltage of 120 V is first transformed to 0.8 V level, whereas the nominal test current of 5 A is transformed to 10 mA and fed into a 80 Ω resistor with negligible ac error. The sampling of the two signals is then performed by two Agilent 3458A digital voltmeters in their 1 V ranges in DC mode with a nominal aperture of 26 µs. Each measurement consists of 512 samples per period during 18 periods. The measurement frequency is 52.941 Hz, such that 18 periods coincide with 17 periods of the 50 Hz net such that the influence of mains interference signals is minimized. A schematic overview of the setup is given in the figure below. A more elaborate description of this setup is given in L. Jol and G. Rietveld, "Improved sampling wattmeter for low frequencies (45 Hz – 55 Hz)", Conf. Digest CPEM 2004, London, UK, pp. 297-298 (2004).

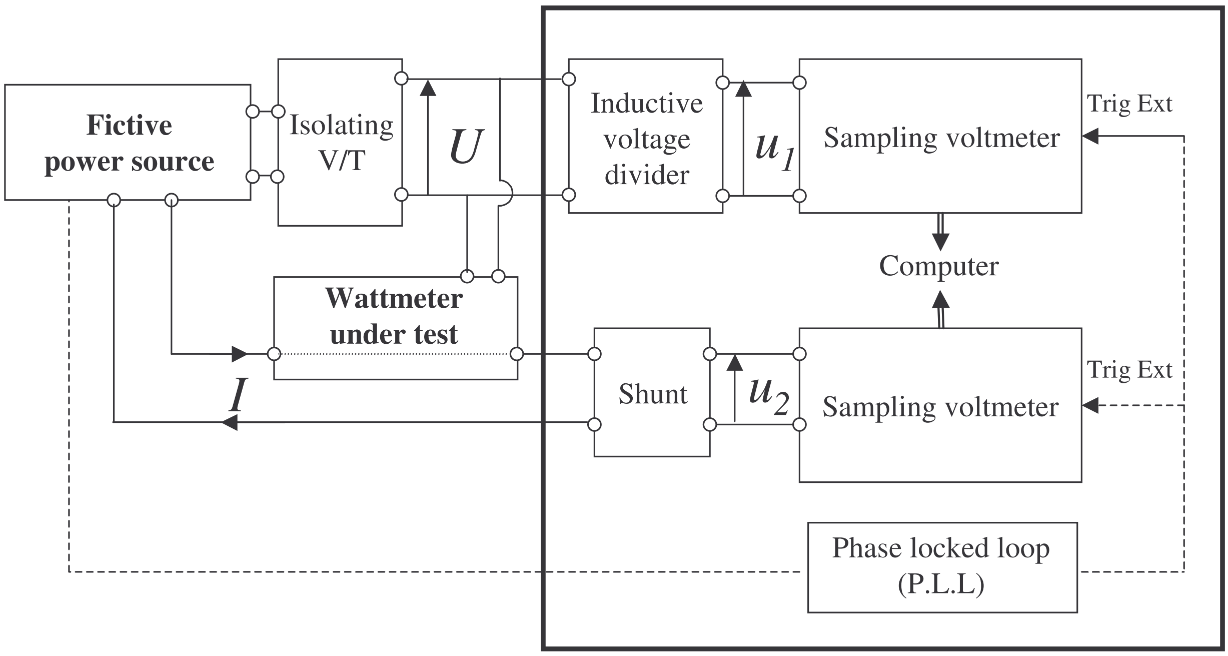


10. NPLI

All the measurements were taken under the condition specified by the Guidelines. The power source was MTS 340 from ZERA Konigswinter, Germany. For measurement of power at different power factors our single phase thermal power standard instrument ILM 03-3, Sl. No. 90 556 10 has been used which was calibrated by PTB, Germany. The correction factors as per the errors given by PTB have been used while the uncertainties are taken directly in power measurement instead of voltage and current and accordingly the uncertainty budgets have been prepared. The final values are given in the form of mean error with uncertainties in terms of apparent power. Resolution in power measurement has been taken as 1ppm, wherever it is 1 or less than 1 ppm. As the thermal power standard ILM 03-3 was calibrated in September ’2004, the drift has been assumed as 25 ppm per year.

11. LNE

The experimental set-up is shown in the following figure. A fictive power source provides voltages up to 1000 V and currents up to 20 A with a total harmonic distortion smaller than 0.02%. Voltage *U* and current *I* are applied simultaneously to the wattmeter under test (travelling standard) and to the LNE Digital Sampling Wattmeter (DSWM) as primary standard.



Digital Sampling Wattmeter

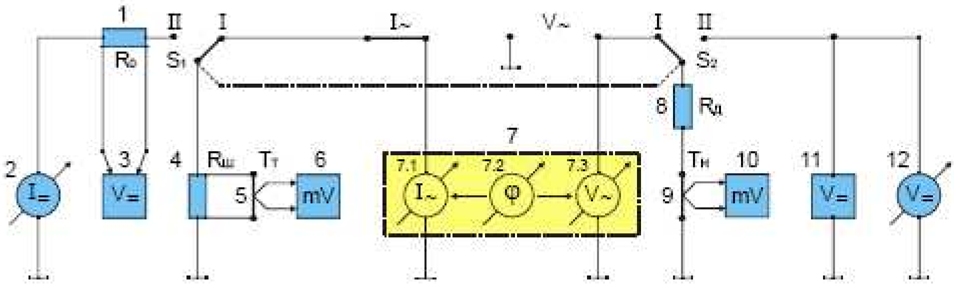
DC output voltage of the travelling standard is measured using a digital voltmeter of high resolution (Agilent-HP 3458A).

The basic measuring principle of the DSWM is to take simultaneous samples of the voltage and current inputs at equally spaced discrete instants covering an integer number of periods of the input waveforms. The total power is then calculated by discrete Fourier transform (DFT) of the sampled signals.

The DSWM is composed of two high precision sampling voltmeters with ADC-capability (Agilent-HP 3458A) which are used in the DCV sampling mode to digitize the signals. A shunt is used to transform the current into a 0.8 V voltage signal and a separately excited three-stage inductive voltage divider (IVD) has been added to the voltage circuit to divide the test voltage, usually up to 1000V, to a low-level signal that could be measured with better accuracy at the 1 V range. A voltage isolation transformer is used to prevent the IVD cores to be magnetized. To control the sampling process, a phase-lock circuit is used. The power source generating the sinusoidal waveforms provides a “sample reference” (TTL) to trigger the multimeters. The TTL reference signal is a harmonic of the phase reference signal and is phase locked to it. Thus, the frequency of the power source and the sampling rate are synchronised, in order to sample an integer number of periods of the input waveforms.

12. UMTS

The base of State Standard of electrical power is precision comparator of electrical power COM 303 that is used for storage, measurements and transfer of the electrical power unit to other devices. The correction factors of comparator COM 303 are determined during electrical power unit reproduction procedure. The structural scheme of State Standard in the regime of electrical power unit reproduction procedure is presented on the following figure.



On the scheme above:

1 – precision shunt;
2 – highly stable generator of direct current;
3, 11 – precision digital voltmeters of direct voltage “AGILENT 3458A”;
4 – precision current shunt;
5, 9 – precision thermo-electric converters;
6, 10 – precision digital nano-voltmeters “AGILENT 34420A”;
7 – highly stable generator of alternate voltage and current;
8 – precision resistor voltage divider;
12 – highly stable generator of direct voltage.

The reproduction procedure is conducted as follows:

- the switches S1 and S2 are switched to position I;
- with assistance of highly stable generator of alternate voltage and current (7) the desired voltage V~, current I~ and phase shift angle are formed;
- the values of voltage V~, current I~ and phase shift angle measured by precision comparator COM 303 are recorded;
- the measurement results of precision digital nanovoltmeters VI (6) and VV (10) are recorded;
- the switches S1 and S2 are switched to position II;
- with assistance of highly stable generator of direct current adjust the current threw precision current shunt (4) until on precision digital nano-voltmeters (6) settles the same voltage VI;
- the value of voltage VDC, measured by precision digital voltmeter of direct voltage (3) is recorded;
- with assistance of highly stable generator of direct voltage adjust the voltage on precision resistor voltage divider (8) until on precision digital nanovoltmeters (9) settles the same voltage VV;
- the value of voltage VDC, measured by precision digital voltmeter of direct voltage (11) is recorded.

APPENDIX A2. Uncertainty Budgets

1. UME

Source of uncertainty (At power factor 1 ± 0,002)	Standard uncertainty (μW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (μW/VA)
Digital Sampling Wattmeter				
Voltage measurement	5,0	normal	1	5,0
Current measurement	7,5	normal	1	7,5
Phase measurement	7,5	normal	0	0,0
Measurement setup	2,5	rectangular	1	2,5
Std uncertainty of meas.	2,5	normal	1	2,5
Standard uncertainty (k=1)				**9,7**

Source of uncertainty (At power factor 0,5 ± 0,002)	Standard uncertainty (μW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (μW/VA)
Digital Sampling Wattmeter				
Voltage measurement	5,0	normal	0,5	2,5
Current measurement	7,5	normal	0,5	3,8
Phase measurement	7,5	normal	0,87	6,5
Measurement setup	2,5	rectangular	1	2,5
Std uncertainty of meas.	2,5	normal	1	2,5
Standard uncertainty (k=1)				**8,7**

Source of uncertainty (At power factor 0,0 ± 0,002)	Standard uncertainty (μW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (μW/VA)
Digital Sampling Wattmeter				
Voltage measurement	5,0	normal	0	0,0
Current measurement	7,5	normal	0	0,0
Phase measurement	7,5	normal	1	7,5
Measurement setup	2,5	rectangular	1	2,5
Std uncertainty of meas.	2,5	normal	1	2,5
Standard uncertainty (k=1)				**8,3**

The expanded uncertainty for any power factor is rounded to 20 μW/VA relative to the apparent power (k=2).

2. PTB

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
δPx	31,750 µWatt/VA	0,648 µWatt/VA	7	normal	1,0	0,65	1,8 %
δPs	0,0 µWatt/VA	2,50 µWatt/VA	50	normal	1,0	2,5	27,2 %
δPxdrift	0,0 µWatt/VA	4,04 µWatt/VA	infinity	rectangular	1,0	4,0	71,0 %
y	31,75	4,80	660				

Quantity	Value	Expanded Uncertainty	Coverage Factor	Coverage
y	31,8	9,6	2,00	95% (t-table 95,45%)

		PF =1	PF = 0,5c	PF = 0,5i	PF = 0,0c	PF = 0,0i
Type A	Standard deviation of mean of polynomial fit	0,6	0,4	0,3	0,2	0,0

3. BIM

Uncertainty Budget: at power factor cos φ = 1							
i	Quantity (unit)	Distrib.	xi	u(xi)	ν_i	ci	ui(y)
1	Travelling standard observations (indicated power)	Normal	599,97 W	0,0086 W	309	0,00167 1/VA	1,434E-05 W/VA
2	Error of the observations (error of the indicated power)	Normal	0,0028 W	0,0003 W	infinity	-0,00167 1/VA	-5E-07 W/VA
3	AC active power (applied power)	Normal	599,96 W	0,0087 W	61	-0,00167 1/VA	-1,45E-05 W/VA
4	Error of the AC power (error of the applied power)	Normal	-0,0033 W	0,018 W	infinity	0,00167 1/VA	3E-05 W/VA
5	Apparent power	Normal	599,96 VA	0,0087 VA	61	-2,6E-08 W/(VA*VA)	-2,24E-10 W/VA
6	Error of the apparent power	Normal	-0,0033 VA	0,018 VA	infinity	2,578E-08 W/(VA*VA)	4,64E-10 W/VA
y	ERROR	Normal	1,5E-05 W/VA	3,6E-05 W/VA	infinity		
Confidence level =		95,50 %		k =	2,0047		
Result =		0,000015 W/VA		U =	0,000073 W/VA		

Uncertainty Budget: at power factor cos φ = 0,5c							
i	Quantity (unit)	Distrib.	xi	u(xi)	ν_i	ci	ui(y)
1	Travelling standard observations (indicated power)	Normal	299,946 W	0,0158 W	309	0,00167 1/VA	2,6E-05 W/VA
2	Error of the observations (error of the indicated power)	Normal	0,00138 W	0,0002 W	infinity	-0,00167 1/VA	-2,5E-07 W/VA
3	AC active power (applied power)	Normal	299,925 W	0,0154 W	61	-0,00167 1/VA	-2,6E-05 W/VA
4	Error of the AC power (error of the applied power)	Normal	-0,00469 W	0,018 W	infinity	0,00167 1/VA	3E-05 W/VA
5	Apparent power	Normal	599,960 VA	0,009 VA	61	-4,0E-09 W/(VA*VA)	-3,6E-11 W/VA
6	Error of the apparent power	Normal	-0,0033 VA	0,018 VA	infinity	4,0E-09 W/(VA*VA)	7,2E-10 W/VA
y	ERROR	Normal	2,4E-05 W/VA	4,7E-05 W/VA	infinity		
	Confidence level =	95,50 %		k =	2,0047		
	Result =	0,000024 W/VA		U =	0,000095 W/VA		

Uncertainty Budget: at power factor cos φ = 0,5i							
i	Quantity (unit)	Distrib.	xi	u(xi)	ν_i	ci	ui(y)
1	Travelling standard observations (indicated power)	Normal	299,959 W	0,0161 W	309	0,00167 1/VA	2,7E-05 W/VA
2	Error of the observations (error of the indicated power)	Normal	0,00138 W	0,0002 W	infinity	-0,00167 1/VA	-2,5E-07 W/VA
3	AC active power (applied power)	Normal	299,966 W	0,0166 W	61	-0,00167 1/VA	-2,8E-05 W/VA
4	Error of the AC power (error of the applied power)	Normal	0,00517 W	0,018 W	infinity	0,00167 1/VA	3E-05 W/VA
5	Apparent power	Normal	599,955 VA	0,008 VA	61	5,8E-09 W/(VA*VA)	4,8E-11 W/VA
6	Error of the apparent power	Normal	-0,0033 VA	0,018 VA	infinity	-5,8E-09 W/(VA*VA)	-1,0E-10 W/VA
y	ERROR	Normal	-3,5E-06 W/VA	4,9E-05 W/VA	infinity		
	Confidence level =	95,50 %		k =	2,0047		
	Result =	-0,000003 W/VA		U =	0,000098 W/VA		

Uncertainty Budget: at power factor cos φ = 0,0c							
i	Quantity (unit)	Distrib.	xi	u(xi)	ν_i	ci	ui(y)
1	Travelling standard observations (indicated power)	Normal	5,896 W	0,0177 W	309	0,00167 1/VA	3,0E-05 W/VA
2	Error of the observations (error of the indicated power)	Normal	0,00003 W	0,0000 W	infinity	-0,00167 1/VA	-6E-08 W/VA
3	AC active power (applied power)	Normal	5,875 W	0,0181 W	61	-0,00167 1/VA	-3E-05 W/VA
4	Error of the AC power (error of the applied power)	Normal	-0,0065 W	0,018 W	infinity	0,00167 1/VA	3E-05 W/VA
5	Apparent power	Normal	599,967 VA	0,009 VA	61	-3,8E-08 W/(VA*VA)	-3,4E-10 W/VA
6	Error of the apparent power	Normal	-0,0033 VA	0,018 VA	infinity	2,8E-08 W/(VA*VA)	6,9E-10 W/VA
y	ERROR	Normal	2,3E-05 W/VA	5,2E-05 W/VA	infinity		
Confidence level =		95,50 %		k =	2,0047		
Result =		0,000023 W/VA		U =	0,00010 W/VA		

Uncertainty Budget: at power factor cos φ = 0,0i							
i	Quantity (unit)	Distrib.	xi	u(xi)	ν_i	ci	ui(y)
1	Travelling standard observations (indicated power)	Normal	5,668 W	0,0177 W	309	0,00167 1/VA	2,9E-05 W/VA
2	Error of the observations (error of the indicated power)	Normal	0,00003 W	0,0000 W	infinity	-0,00167 1/VA	-6E-08 W/VA
3	AC active power (applied power)	Normal	5,685 W	0,0177 W	61	-0,00167 1/VA	-3E-05 W/VA
4	Error of the AC power (error of the applied power)	Normal	0,0093 W	0,018 W	infinity	0,00167 1/VA	3E-05 W/VA
5	Apparent power	Normal	599,963 VA	0,009 VA	61	2,1E-08 W/(VA*VA)	1,8E-10 W/VA
6	Error of the apparent power	Normal	-0,0033 VA	0,018 VA	infinity	-2,1E-08 W/(VA*VA)	3,8E-10 W/VA
y	ERROR	Normal	-1,3E-05 W/VA	5,1E-05 W/VA	infinity		
Confidence level =		95,50 %		k =	2,0047		
Result =		-0,000013 W/VA		U =	0,000010 W/VA		

4. SMU

Source of uncertainty PF=1	Standard uncertainty (µW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (µW/VA)
SMU Voltage meas.	12	normal	1	12
SMU Current meas.	19	normal	1	19
SMU Phase meas.	26	normal	0	0
Measurement	30	rectangular	1	17
Std uncertainty of meas.	4	normal	1	4
Standard uncertainty (k = 1)				**28,5**
Standard uncertainty (k = 2)				**57**

Source of uncertainty PF=0,5	Standard uncertainty (µW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (µW/VA)
SMU Voltage meas.	12	normal	0,5	6
SMU Current meas.	19	normal	0,5	8,5
SMU Phase meas.	26	normal	0,87	22.6
Measurement	30	rectangular	1	17
Std uncertainty of meas.	4	normal	1	4
Standard uncertainty (k = 1)				**30,4**
Standard uncertainty (k = 2)				**61**

Source of uncertainty PF=0,01	Standard uncertainty (µW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (µW/VA)
SMU Voltage meas.	12	normal	0,01	0,1
SMU Current meas.	19	normal	0,01	0,2
SMU Phase meas.	26	normal	1	26
Measurement	30	rectangular	1	17
Std uncertainty of meas.	4	normal	1	4
Standard uncertainty (k = 1)				**31,3**
Standard uncertainty (k = 2)				**63**

5. OMH

Source of uncertainty PF=1	Estimate	Standard uncertainty	Probability distribution	Sensitivity coefficient	Contribution to the std. unc. (µW/VA)
Calibration of the OMH's std.	600 W	$7{,}5\cdot10^{-6}$	normal	1	7,5
Stability in 1 year	0	$5/\sqrt{3}\cdot10^{-5}$	rectangular	1	28,9
Temperature influence (our standard)	0	$1/\sqrt{3}$ K	rectangular	$5\cdot10^{-6}$ [1/K]	2,9
DC-voltage measurement (DMM)	0	$5\cdot10^{-5}$ V	normal	0,1 [1/V]	5,0
Short term stability of the generator	0	$1/\sqrt{3}\cdot10^{-5}$	rectangular	1	5,8
Uncertainty					**31**

Source of uncertainty PF=0,5	Estimate	Standard uncertainty	Probability distribution	Sensitivity coefficient	Contribution to the std. unc. (µW/VA)
Calibration of the OMH's std.	300 W	$7{,}5\cdot10^{-6}$	normal	1	7,5
Stability in 1 year	0	$5/\sqrt{3}\cdot10^{-5}$	rectangular	1	28,9
Temperature influence (our standard)	0	$1/\sqrt{3}$ K	rectangular	$2{,}5\cdot10^{-6}$ [1/K]	1,4
DC-voltage measurement (DMM)	0	$2{,}5\cdot10^{-5}$V	normal	0,1/V	2,5
Short term stability of the generator	0	$1/\sqrt{3}\cdot10^{-5}$	rectangular	0,5	2,9
Uncertainty					**30**

Source of uncertainty PF=0,01	Estimate	Standard uncertainty	Probability distribution	Sensitivity coefficient	Contribution to the std. unc. (µW/VA)
Calibration of the OMH's std.	6 W	$7{,}5\cdot10^{-6}$	normal	1	7,5
Stability in 1 year	0	$5/\sqrt{3}\cdot10^{-5}$	rectangular	1	28,9
Temperature influence (our standard)	0	$1/\sqrt{3}$ K	rectangular	$1\cdot10^{-6}$ /K	0,6
DC-voltage measurement (DMM)	0	$10\cdot10^{-6}$V	normal	0,1/V	1
Short term stability of the generator	0	$1/\sqrt{3}\cdot10^{-5}$	rectangular	0,01	0,6
Uncertainty					**30**

6. INM

Uncert. evaluation	Parameter	Uncertainty contribution [µW / VA]				
		U=120V;I =5A cos φ=1	U=120V I=5A cos φ=0,5i	U=120V I=5A cos φ=0,5c	U=120V I=5A cos φ=0,01i	U=120V I=5A cos φ=0,01c
Type A	Mean value of the observations of the differences (errors) between the travelling standard and the reference standard	2	0	2	2	1
Type B	Correction (Uncertainty)-of the Fluke 8505 digital multimeter, calibrated before each measurement point, against the calibrator Fluke 5720	0,5	1	1	0,6	0,6
	Correction (Uncertainty) of the KOM 200.3, stated in the PTB calibration certificate	40	40	40	40	40
	Effects (Uncertainty) due to the instability of the power source SPE 100.3	10	10	10	10	10
Combined standard uncertainty		**41,3**	**41,2**	**41,3**	**41,3**	**41,2**
Expanded uncertainty (k=2)		**82,6**	**82,4**	**82,6**	**82,6**	**82,4**

7. DMDM

Type of uncertainty	Source of uncertainty	Power factor			
		1,00	0,50 i/c	0,00 i/c	
		value of uncertainty			unit
Type A (ν=10)	Travelling standard repeated observations	2	3,5	2,5	µW/VA
Type B	DC voltage measurement	1	0,5	3	µV/V
	Voltage divider constant of proporcionality	2,2	2,2	2,2	µV/V
	AC resistor amplitude	2,3	2,3	2,3	µΩ/Ω
	AC voltage amplitude measurement (sampling, fitting)	10	10	10	µV/V
	Voltage divider phase	3	3	3	µrad/rad
	AC resistor phase	4	4	4	µrad/rad
	Phase measurement (sampling, fitting)	10	10	10	µrad/rad
	Stability of power source	18	18	18	µW/VA
Combined (k=1)		**23,2**	**19,3**	**18,2**	µW/VA

8. MIKES

Uncertainty at PF=1

Source of uncertainty		Standard uncertainty	Unit	Probability distribution	Sensitivity coefficient	Contribution to the std. uncert. µW/VA
U_m	dc-DVM reading	3,11E-05	V	normal	1,00E+05	3,1
S_{dft}	ac-DVM rms product	8,88E-06	V^2	normal	-3,51E+05	3,1
ϕ	measured phase angle	1,93E-06	deg	normal	-4,17E+00	8,0E-06
t	shunt temperature	2,52E-03	°C	normal	1,98E-01	5,0E-04
	type A total					0,45
t	shunt temperature	0,012	°C	rectangular	0,198064819	0,0023
U_o	dc-DVM offset	0,50	µV	normal	-0,09999965	-0,050
g	dc-DVM gain error	0,173	ppm	rectangular	-0,99992112	-0,17
r_{CVD}	CVD ratio	0,000113	V/V	rectangular	-47614,23374	-5,39
dR	shunt resistance error	3,00	ppm	rectangular	0,999867742	3,00
α	shunt t_c	0,0215	ppm/°C	normal	5,191413065	0,11
β	shunt second order t_c	0,00090	ppm/°C^2	normal	26,95433454	0,024
d	total ac/dc multiplier	7,2E-06	-	rectangular	2002166,757	14,43
g_U	voltage-DVM gain error	0,58	ppm	rectangular	0,999885624	0,58
g_I	current-DVM gain error	1,15	ppm	rectangular	-0,350829414	-0,41
ϕ_{sh}	shunt phase error	0,30	mdeg	rectangular	-0,004166406	-0,0013
ϕ_{cvd}	CVD phase error	0,58	mdeg	rectangular	0,004166406	0,0024
ϕ_{DVM}	DVM phase difference	0,03	mdeg	rectangular	0,004166406	0,00013
	Standard uncertainty					15,7
	ν_{eff}					1378

Uncertainty at PF=0,5

Source of uncertainty		Standard uncertainty	Unit	Probability distribution	Sensitivity coefficient	Contribution to the std. uncert. µW/VA
U_m	dc-DVM reading	1,43E-05	V	normal	1,00E+05	1,4
S_{dft}	ac-DVM rms product	8,16E-06	V^2	normal	-1,75E+05	1,4
ϕ	measured phase angle	2,73E-06	deg	normal	-1,51E+04	4,1E-02
t	shunt temperature	5,22E-03	°C	normal	9,90E-02	5,2E-04
	type A total					0,23
t	shunt temperature	0,012	°C	rectangular	0,098994927	0,0011
U_o	dc-DVM offset	0,50	µV	normal	-0,09999965	-0,050
g	dc-DVM gain error	0,173	ppm	rectangular	-0,499747374	-0,09
r_{CVD}	CVD ratio	0,000113	V/V	rectangular	-23797,36112	-2,70
dR	shunt resistance error	3,00	ppm	rectangular	0,499729007	1,50
α	shunt t_c	0,0215	ppm/°C	normal	2,595142786	0,06
β	shunt second order t_c	0,00090	ppm/°C^2	normal	13,47683643	0,012
d	total ac/dc multiplier	7,2E-06	-	rectangular	1000673,151	7,21
g_U	voltage-DVM gain error	0,58	ppm	rectangular	0,499737944	0,29
g_I	current-DVM gain error	1,15	ppm	rectangular	-0,175343097	-0,20
ϕ_{sh}	shunt phase error	0,30	mdeg	rectangular	-15,11526878	-4,5385
ϕ_{cvd}	CVD phase error	0,58	mdeg	rectangular	15,11526878	8,8151
ϕ_{DVM}	DVM phase difference	0,03	mdeg	rectangular	15,11526878	0,47916
	Standard uncertainty					12,7
	ν_{eff}					2784

Uncertainty at PF=0

Source of uncertainty		Standard uncertainty	Unit	Probability distribution	Sensitivity coefficient	Contribution to the std. uncert. µW/VA
U_m	dc-DVM reading	6,57E-07	V	normal	1,00E+05	0,1
S_{dft}	ac-DVM rms product	7,76E-06	V^2	normal	3,62E+01	0,0003
ϕ	measured phase angle	3,11E-06	deg	normal	-1,75E+04	5,4E-02
t	shunt temperature	3,05E-02	°C	normal	-2,04E-05	6,2E-07
	type A total					0,08
t	shunt temperature	0,012	°C	rectangular	-2,03734E-05	-0,0000002
U_o	dc-DVM offset	0,30	µV	normal	-0,09999957	-0,030
g	dc-DVM gain error	0,577	ppm	rectangular	0,000114233	0,00007
r_{CVD}	CVD ratio	0,000113	V/V	rectangular	4,919469291	0,00056
dR	shunt resistance error	3,00	ppm	rectangular	-0,000103306	-0,00031
α	shunt t_c	0,0215	ppm/°C	normal	-0,000521766	-0,00001
β	shunt second order t_c	0,00090	ppm/°C^2	normal	-0,002635282	-0,000002
d	total ac/dc multiplier	7,2E-06	-	rectangular	-206,8624674	-0,00149
g_U	voltage-DVM gain error	0,58	ppm	rectangular	-0,000103307	-0,00006
g_I	current-DVM gain error	1,15	ppm	rectangular	3,62477E-05	0,00004
ϕ_{sh}	shunt phase error	0,30	mdeg	rectangular	-17,45116056	-5,2399
ϕ_{cvd}	CVD phase error	0,58	mdeg	rectangular	17,45116056	10,1774
ϕ_{DVM}	DVM phase difference	0,03	mdeg	rectangular	17,45116056	0,55321
	Standard uncertainty					11,5
	ν_{eff}					1502

9. VSL

Uncertainty budget for cosΦ=1:

Note that for cosΦ=1 we have omitted the phase errors, which have sensitivity coefficient equal to zero.

Unit X_i	Value x_i	Standard uncertainty $U(x_i)$	Distri-bution	Sensitivity coefficient c_i	Uncertainty-Value $U_i(y)$
V_V	0,800000 V	1,6 µV	normal	750 W/V	1,2 mW
$Ratio_V$	150,0000	0,0003	normal	4 W	1,2 mW
V_I	0,800000 V	1,6 µV	normal	750 W/V	1,2 mW
$Ratio_I$	500,0000	0,0010	normal	1,2 W	1,2 mW
Resistor	80,0000 Ω	0,16 mΩ	normal	7,5 W	1,2 mW
Aperture correction	1,0000064	$0,28 \cdot 10^{-6}$	normal	600 W	0,17 mW
P_{HEG}	600,0122 W	1,2 mW	normal	1	1,2 mW
Stability Pupin	1,000000	$2 \cdot 10^{-6}$	normal	600 W	1,2 mW
Power difference	8,4 mW			Combined Uncertainty	3,2 mW

For cosΦ=1, the error with expanded uncertainty (k=2) is equal to (8,4±6,4) mW or (14±11) µW/VA.

Uncertainty budget for cosΦ=0,5:

Unit X_i	Value x_i	Standard uncertainty $U(x_i)$	Distri-bution	Sensitivity coefficient c_i	Uncertainty-Value $U_i(y)$
V_V	0,800000 V	1,6 µV	normal	750 W/V	1,2 mW
$Ratio_V$	150,0000	0,0003	normal	4 W	1,2 mW
	0 º	0,0003 º	square	9,1 W/º	1,6 mW
V_I	0,800000 V	1,6 µV	normal	750 W/V	1,2 mW
$Ratio_I$	500,0000	0,0010	normal	1,2 W	1,2 mW
	0 º	0,0005 º	square	9,1 W/º	2,6 mW
Resistor	80,0000 Ω	0,16 mΩ	normal	7,5 W	1,2 mW
	0 º	0,0005 º	square	9,1 W/º	2,6 mW
Aperture correction	1,0000064	$0,28 \cdot 10^{-6}$	normal	600 W	0,17 mW
P_{HEG}	600,0032 W	1,2 mW	normal	1	1,2 mW
Stability Pupin	1,000000	$2 \cdot 10^{-6}$	normal	600 W	1,2 mW
Power difference	-0,6 mW			Combined Uncertainty	5,1 mW

For cosΦ=0,5 c, the error with expanded uncertainty (k=2) is equal to (-0,6±10,2) mW or (-1±17) µW/VA.

Uncertainty budget for cosΦ=0:

Unit X_i	Value x_i	Standard uncertainty $U(x_i)$	Distri-bution	Sensitivity coefficient c_i	Uncertainty-Value $U_i(y)$
V_V	0,800000 V	1,6 µV	normal	750 W/V	1,2 mW
$Ratio_V$	150,0000	0,0003	normal	4 W	1,2 mW
	0 º	0,0003 º	square	10,5 W/º	1,8 mW
V_I	0,800000 V	1,6 µV	normal	750 W/V	1,2 mW
$Ratio_I$	500,0000	0,0010	normal	1,2 W	1,2 mW
	0 º	0,0005 º	square	10,5 W/º	3,0 mW
Resistor	80,0000 Ω	0,16 mΩ	normal	7,5 W	1,2 mW
	0 º	0,0005 º	square	10,5 W/º	3,0 mW
Aperture correction	1,0000064	$0,28 \cdot 10^{-6}$	normal	600 W	0,17 mW
P_{HEG}	600,0080 W	1,2 mW	normal	1	1,2 mW
Stability Pupin	1,000000	$2 \cdot 10^{-6}$	normal	600 W	1,2 mW
Power difference	4,2 mW			Combined Uncertainty	5,6 mW

For cosΦ=0 c, the error with expanded uncertainty (k=2) is equal to (4,2±11,3) mW or (7±19) µW/VA.

10. NPLI

Uncertainty at power factor= 1 ± 0,002

Source of uncertainty X_i	Estimates x_i	Limits $\pm\Delta x_i$	-Probability -distribution -Type A or B -factor	Standard uncertainty $u(x_i)$ ppm	Sensitivity Coefficient c_i	Uncertainty contribution $u_i(y)$ ppm	Degree of freedom v_i
Reference Power Standard	120V 5 A UPF	60 µW/W	-Normal -Type B -2	30	1	30	∞
Reference voltmeter	10V	3ppm	Normal -Type B -2	1,5	1	1,5	∞
Measurement Resolution		1 ppm	Rectangular -Type-B $\sqrt{3}$	0,57735	1	0,5774	∞
Drift of the Reference standard		25µW/W per year	Rectangular -Type-B $\sqrt{3}$	14,434	1,75	25,26	∞
Temperature Variation		10 ppm	-Rectangular -Type B - $\sqrt{3}$	5,774	1	5,774	9
Repeatability (power measurement)			-Normal -Type A			4,8	15
Repeatability (DC voltage measurement)			-Normal -Type A			0,23	15
Combined standard uncertainty uc(ηeff)			k=1			39,964	
Effective degree of freedom							(16053) taken as ∞ (hence k=2)
Expanded uncertainty U((ηeff)			k=2			79,93 <80	

Uncertainty at power factor = 0,5i ± 0,002

Source of uncertainty X_i	Estimates x_i	Limits $\pm\Delta x_i$	-Probability -distribution -Type A or B -factor	Standard uncertainty $u(x_i)$ ppm	Sensitivity Coefficient c_i	Uncertainty contribution $u_i(y)$ ppm	Degree of freedom v_i
Reference Power Standard	120V, 5 A 0,5lag PF	60*2µW /W	-Normal -Type B -2	60	1	60	∞
Reference voltmeter	10V	3ppm	Normal -Type B -2	1,5	1	1,5	∞
Measurement Resolution		1 ppm	Rectangular -Type-B $\sqrt{3}$	0,57735	1	0,5774	∞
Drift of the Reference standard		25µW/ W	Rectangular -Type-B $\sqrt{3}$	14,434	1,75	25,26	∞
Temperature Variation		10 ppm	-Rectangular -Type B - $\sqrt{3}$	5,774	1	5,774	9
Repeatability (power measurement)			-Normal -Type A			5,6	15
Repeatability (DC voltage measurement)			-Normal -Type A			0,62	15
Combined standard uncertainty uc(ηeff)			k=1			65,62	
Effective degree of freedom							(98053) taken as ∞ (hence k=2)
Expanded uncertainty U((ηeff)			k=2			131,24 (<66 µW/VA)	

Uncertainty at power factor = 0,5c ± 0,002

Source of uncertainty X_i	Estimates x_i	Limits $\pm\Delta x_i$	-Probability -distribution -Type A or B -factor	Standard uncertainty $u(x_i)$ ppm	Sensitivity Coefficient c_i	Uncertainty contribution $u_i(y)$ ppm	Degree of freedom v_i
Reference Power Standard	120V, 5 A 0,5le--ad PF	60*2µW /W	-Normal -Type B -2	60	1	60	∞
Reference voltmeter	10V	3ppm	Normal -Type B -2	1,5	1	1,5	∞
Measurement Resolution		1 ppm	Rectangular -Type-B $\sqrt{3}$	0,57735	1	0,5774	∞
Drift of the Reference standard		25µW/ W	Rectangular -Type-B $\sqrt{3}$	14,434	1,75	25,26	∞
Temperature Variation		10 ppm	-Rectangular -Type B - $\sqrt{3}$	5,774	1	5,774	9
Repeatability (power measurement)			-Normal -Type A			5,15	15
Repeatability (DC voltage measurement)			-Normal -Type A			0,97	15
Combined standard uncertainty uc(ηeff)			k=1			65,585	
Effective degree of freedom							(108545) taken as ∞ (hence k=2)
Expanded uncertainty U((ηeff)			k=2			131,17 (<66 µW/VA)	

Uncertainty at power factor = 0,01i ± 0,002

Source of uncertainty X_i	Estimates x_i	Limits $\pm\Delta x_i$	-Probability -distribution -Type A or B -factor	Standard uncertainty $u(x_i)$ ppm	Sensitivity Coefficient c_i	Uncertainty contribution $u_i(y)$ ppm	Degree of freedom v_i
Reference Power Standard	120V, 5 A 0 lag PF	60*100 µW/W	-Normal -Type B -2	3000	1	3000	∞
Reference voltmeter	100mV	7ppm	Normal -Type B -2	3,5	1	3,5	∞
Measurement Resolution		8,33 ppm	Rectangular -Type-B $\sqrt{3}$	4,81	1	4,81	∞
Drift of the Reference standard		25µW/W	Rectangular -Type-B $\sqrt{3}$	14,434	1,75	25,26	∞
Temperature Variation		20 ppm	-Rectangular -Type B -$\sqrt{3}$	11,547	1	11,547	9
Repeatability (power measurement)			-Normal -Type A			90	15
Repeatability (DC voltage measurement)			-Normal -Type A			14	15
Combined standard uncertainty uc(ηeff)			k=1			3001,517	
Effective degree of freedom							(18536779) taken as ∞ (hence k=2)
Expanded uncertainty U((ηeff)			k=2			6003,03 (<61 µW/VA)	

Uncertainty at power factor = 0,01c ± 0,002

Source of uncertainty X_i	Estimates x_i	Limits $\pm\Delta x_i$	-Probability -distribution -Type A or B -factor	Standard uncertainty $u(x_i)$ ppm	Sensitivity Coefficient c_i	Uncertainty contribution $u_i(y)$ ppm	Degree of freedom v_i
Reference Power Standard	120V, 5 A 0 lead PF	60*100 µW/W	-Normal -Type B -2	3000	1	3000	∞
Reference voltmeter	100mV	7ppm	Normal -Type B -2	3,5	1	3,5	∞
Measurement Resolution		8,33 ppm	Rectangular -Type-B $\sqrt{3}$	4,81	1	4,81	∞
Drift of the Reference standard		25µW/W	Rectangular -Type-B $\sqrt{3}$	14,434	1,75	25,26	∞
Temperature Variation		20 ppm	-Rectangular -Type B -$\sqrt{3}$	11,547	1	11,547	9
Repeatability (power measurement)			-Normal -Type A			117	15
Repeatability (DC voltage measurement)			-Normal -Type A			19	15
Combined standard uncertainty uc(ηeff)			k=1			3002,475	
Effective degree of freedom							(6499723) taken as ∞ (hence k=2)
Expanded uncertainty U((ηeff)			k=2			6004,95 (<61 µW/VA)	

11. LNE

Source of uncertainty PF=1	Standard uncertainty (µW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (µW/VA)
DSWM voltage	5,8	Normal	1	5,8
DSWM current	11,8	Normal	1	11,8
DSWM phase	5,2	Normal	0	0
Measurement setup	3	Normal	1	3
Standard uncertainty (k = 1)				**13.5**

Source of uncertainty PF=0,5	Standard uncertainty (µW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (µW/VA)
DSWM voltage	5,8	Normal	0,5	2,9
DSWM current	11,8	Normal	0,5	5,9
DSWM phase	5,2	Normal	0,87	4,5
Measurement setup	3	Normal	1	3
Standard uncertainty (k = 1)				**8,5**

Source of uncertainty PF=0,5	Standard uncertainty (µW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (µW/VA)
DSWM voltage	5,8	Normal	0	0
DSWM current	11,8	Normal	0	0
DSWM phase	5,2	Normal	1	5,2
Measurement setup	3	Normal	1	3
Standard uncertainty (k = 1)				**6,0**

The expanded uncertainty at power factor 1 is 27 µW/VA relative the apparent power.
The expanded uncertainty at power factor 0.5 is 17 µW/VA relative the apparent power.
The expanded uncertainty at power factor 0 is 12 µW/VA relative the apparent power.

12. UMTS

Uncertainty Evaluation	Parameter	Power Factor ($c_i \times 10^{-6}$)				
		1.0	0,5i	0,5c	0i	0c
Type A (ν=19)	Standard deviation of the mean of travelling standard (C1-2) tests	1×2	1×3	1×1	1×57	1×51
Type A (ν=13)	Standard deviation of the mean of voltage reproduction	1×4	0,5×4	0,5×4	0×4	0×4
Type A (ν=11)	Standard deviation of the mean of current reproduction	1×4	0,5×4	0,5×4	0×4	0×4
Type B (ν→∞)	Voltage measurement on 100V range	1×8	0,5×8	0,5×8	0×8	0×8
Type B (ν→∞)	Voltage measurement on 1V range	1×7	0,5×7	0,5×7	0×7	0×7
Type B (ν→∞)	Resistance	1×5	0,5×5	0,5×5	0×5	0×5
Type B (ν→∞)	Thermal converter AC-DC difference (voltage channel)	1×5	0,5×5	0,5×5	0×5	0×5
Type B (ν→∞)	Thermal converter AC-DC difference (current channel)	1×5	0,5×5	0,5×5	0×5	0×5
Type B (ν→∞)	Phase measurement	0×52	0,87×52	0,87×52	1×52	1×52
Combined standard uncertainty:		15 ppm	46 ppm	46 ppm	77 ppm	73 ppm
Expanded uncertainty (k=2):		30 ppm	92 ppm	92 ppm	154 ppm	146 ppm

APPENDIX A3. Comparison Protocol

EUROMET Key Comparison Supplementing CCEM-K5
"Comparison of AC Power at 50 Hz"
Technical Protocol

Hüseyin Çaycı
Electricity Division

Ulusal Metroloji Enstitüsü (UME)
(National Metrology Institute of Turkey)
P.O.Box: 54, 41470 Gebze, Kocaeli
TURKEY
November 2006

1. Introduction

In 2002, a EUROMET Key Comparison of 50 Hz electric power was organised to be a follow up of the previous EUROMET Key Comparison (Project no:385). The National Metrology Institute of Turkey (UME) was selected as the pilot laboratory, which is responsible for providing the travelling standard, coordinating the schedule, collecting and analyzing the comparison data, and preparing the draft report.

2. The travelling standard

2.1. General requirements

The selected travelling standard is a HEG C1-2, based on a time-division-multiplication scheme. The instrument is configured as an ac power-to-dc voltage transducer, with a nominal full-scale dc output of 10 V.

Although UME has such a travelling standard, the instrument of PTB was selected since it had been used in the previous EUROMET Key Comparison. However, the travelling standard will not have the same value since it has been modified.

2.2. Description of the standard

The travelling standard has separate (electrically isolated) voltage and current inputs on the front panel with the voltage range of 120 V and the current range of 5 A. The input frequency capability of the instrument is between 45 Hz to 65 Hz. The internal dc reference voltages (nominally +7.044... V and –7.044... V) can be monitored at the front panel. The nominal full-scale dc output of 10 V is also available on the front panel (Volt OUT). It has also nominal full-scale frequency outputs of 10 kHz and 10 Hz which are available with BNC connectors on the front panel (f OUT).

More details about the travelling standard

Manufacturer : HEG – Hamburger Elektronik Gesellschaft MBH
Model : C1-2
Serial number : 46043

Power supply voltage : 220 - 240 V at 50 Hz.

Accuracy Class : 0.005% (10 VDC Output)
0.01% (10 Hz or 10 kHz Frequency Outputs)

Figure 1. Front panel of the travelling standard C1-2.

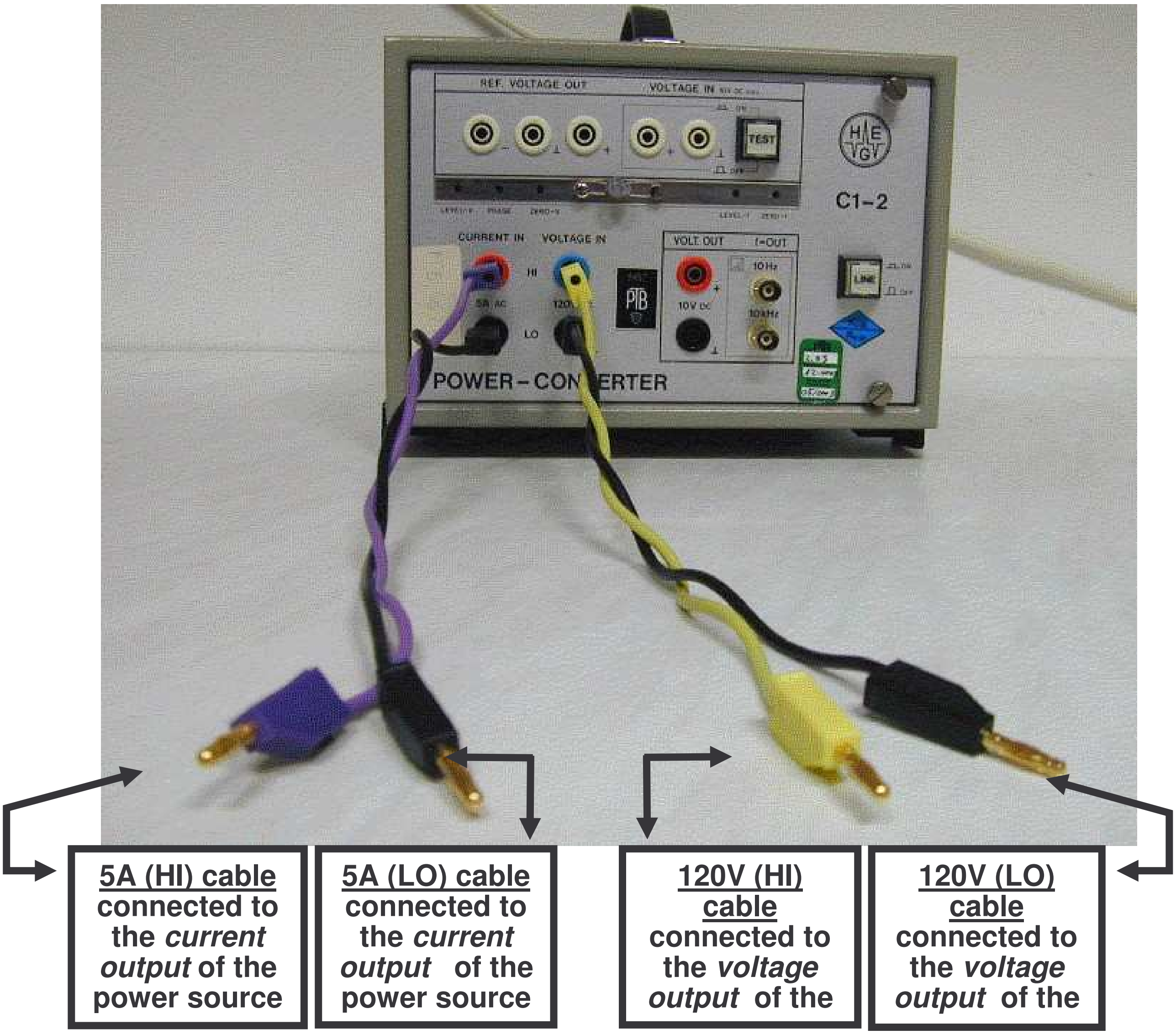


Figure 2. Current and voltage input connections of the travelling standard.

Participants shall use twisted cables for both current and voltage input connections.

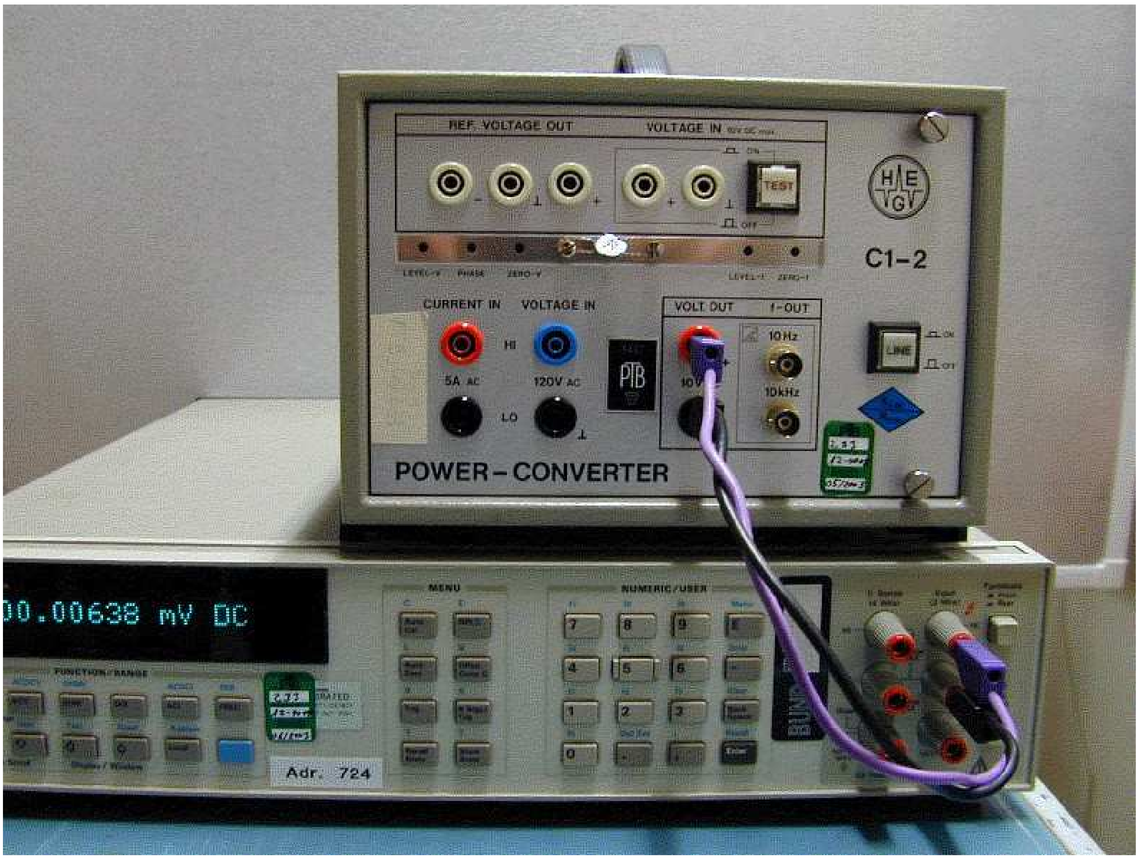


Figure 3. Connections and DC voltage measurement from the voltage output (VOLT.OUT) of the travelling standard.

A digital multimeter with a high input impedance shall be used to measure the DC voltage. An Agilent (HP) 3458A digital multimeter is given in the Figure 3, to show a sample connection for the measurement of DC voltage values from the travelling standard. Voltage and current input connections are not shown in the figure.

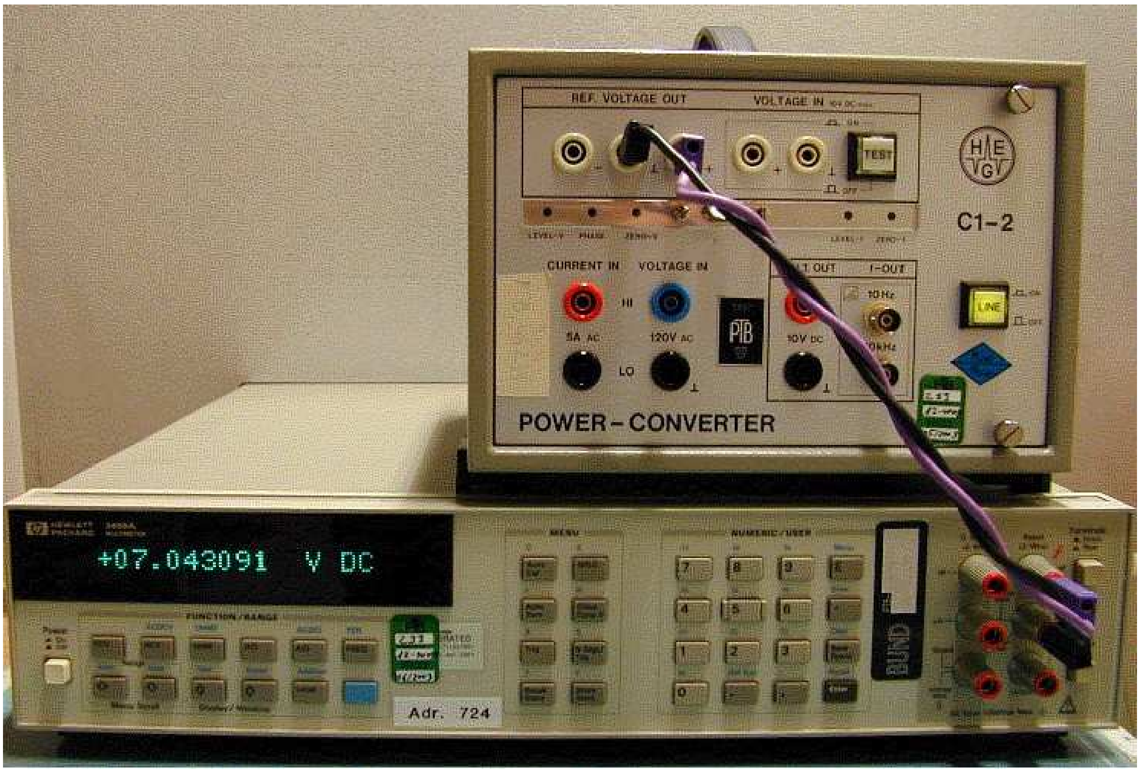


Figure 4. DC reference voltage measurements from the reference voltage output (REF. VOLTAGE OUT) of the travelling standard by means of a digital multimeter.

Only positive output connection is given in the Figure 4. Negative reference voltage can be measured by removing the cable used for HI connection and reconnecting it to the next banana connector which is signed with (-) negative

The multimeter shall be programmed to measure the DC reference values with the best resolution and accuracy.

During the measurement of DC reference voltages, no AC signal shall be connected to the travelling standard.

2.3. Quantities to be measured

Main measurements (nominal test power) shall be performed at:

Voltage	: 120 V
Current	: 5 A
Power Factor	: 1; 0,5i/c; 0i/c (i: inductive, c: capacitive)
Frequency	: 53 Hz (slightly aside from 50 Hz)

DC output voltage of the travelling standard (10 V nominal at the rated input) shall be measured from the VOLT.OUT sockets (10 V DC). The DC output voltage is measured using a digital voltmeter of high resolution (e.g. Agilent-HP 3458A), which is calibrated with a dc voltage standard immediately before the test. The integration time of the multimeter shall be selected long enough to eliminate the travelling standard's input frequency dependence. **Example:** The integration time is set to a multiple integer of the period of the second harmonic of the measuring frequency. The integration time T_i is then 11.4 s (570 NPLC at 50 Hz).

Additional measurements (with no test power applied) shall be performed at the following three "no power" conditions:

Voltage: 120 V	Current: 0 A
Voltage: 0 V (input shorted)	Current: 5 A
Voltage: 0 V (input shorted)	Current: 0 A

With no voltage or current applied, there will be a small DC offset at the output. Participants shall record the mean output offset voltage, but will not correct for the offset.

DC reference voltage measurements (+7.044...V and -7.044...V) shall be performed from the REF.VOLTAGE OUT sockets. The mean DC ref voltages shall be recorded during the measurements.

Particular requirements for ambient conditions:

The power-converter shall not be exposed to draught of cold or hot air (e.g. fan-output of neighbouring power amplifier).

Measurements shall be made at the temperature of 23°C.

2.4. Method of computation of KCRV

KCRV will be computed referring to the Final Report of "CCEM-K5 Comparison of 50/60 Hz Power" by Nile Oldham and Thomas Nelson.

3. Organization

3.1. Co-ordinator and review committee

Co-ordinator

Name	:	Hüseyin ÇAYCI
Organization	:	UME (National Metrology Institute of Turkey)
Mail address	:	TÜBİTAK-UME Ulusal Metroloji Enstitüsü P.O.Box: 54, 41470 Gebze/Kocaeli TURKEY
Telephone	:	+90 262 679 5000 (Ext. 4450)
Fax	:	+90 262 679 5001
e-mail	:	huseyin.cayci@ume.tubitak.gov.tr

Review Committee

1) Name	:	Andreas JAKAB
Organization	:	National Office of Measures (OMH)
Mail address	:	National Office of Measures (OMH) Országos Mérésügyi Hivatal Pf 919 HU - 1535 Budapest Hungary
Telephone	:	+36 1 458 58 40
Fax	:	+36 1 458 59 37
e-mail	:	a.jakab@omh.hu

2) Name	:	Peter RAETHER
Organization	:	Physikalisch-Technische Bundesanstalt (PTB)
Mail address	:	Physikalisch-Technische Bundesanstalt (PTB) Bundesallee 1000 38116 Braunschweig Germany
Telephone	:	+49 531 592 2339
Fax	:	+49 531 592 7188
e-mail	:	peter.raether@ptb.de

3.2. Participants

Table 1. List of participants, contact names, e-mails, phone and fax numbers.

Laboratory address	**Contact name, e-mail, tel & fax**
TÜBİTAK-UME, Ulusal Metroloji Enstitüsü PO Box 54 Gebze 41470 Kocaeli/TURKEY	Hüseyin ÇAYCI huseyin.cayci@ume.tubitak.gov.tr Tel: +90 262 679 5000 (Ext:4450) Fax: +90 262 679 5001
Physikalisch-Technische Bundesanstalt (PTB) PTB Labor 2.33, Elektrizitaetszaehler Bundesallee 100 D-38116 Braunschweig/GERMANY	Peter RAETHER Peter.raether@ptb.de Tel: +49 531 592 2339 Fax: +49 531 592 7188
Slovenian Institute of Quality (SIQ) and Metrology Trzaska 2, SI - 1000 Ljubljana/SLOVENIA	Zoran SVETIK zoran.svetik@siq.si Tel: +386 1 477 8301 Fax: +386 1 477 8303
National Centre of Metrology (NCM) 52-B G. M. Dimitrov Str. 1797 Sofia/BULGARIA	Petya ALADZHEM ncm@sasm.orbitel.bg Tel: (+359 2) 710 237 Fax: (+359 2) 717 050
National Office of Measures (OMH) Országos Mérésügyi Hivatal Pf 919 HU - 1535 Budapest/HUNGARY	György HEGYI g.hegyi@omh.hu Tel: +36 1 458 59 17 Fax: +36 1 458 59 49
Slovak Institute of Metrolgy (SMU) Karloveská 63 SK - 842 55 Bratislava/SLOVAK REPUBLIC	Ján HANÁK hanak@smu.gov.sk Tel: +421 2 602 94 491 Fax: +421 2 654 29 592
National Institute of Metrology (INM) 11, Sos. Vitan-Bârzesti RO - 75669 Bucharest 4/ROMANIA	Ioana Izabela ODOR odor@inm.ro Tel: +40 1 334 55 20 Fax: +40 1 334 53 45
Federal Bureau of Measures and Precious Metals (SZMDM) Mike Alasa 14 YU - 11 000 Belgrad/Yugoslavıa	Jelena Pantelic-BABIC electro@szmdm.sv.gov.yu Tel: +381 11 622 365 Fax: +381 11 181 668
Centre for Metrology and Accreditation (MIKES) Otakaari 7B FI - 02150 Espoo/FINLAND	Pekka IMMONEN pekka.immonen@mikes.fi Tel: +358 10 605 4407 Fax: +358 9 4554 875
NMi Van Swinden Laboratorium B.V.(NMi-VSL) Schoemakerstraat 97 P.O. Box 654 NL - 2600 AR Delft/THE NETHERLANDS	Leendert JOL ljol@nmi.nl Tel: +31 15 269 16 21 Fax: +31 15 261 29 71
National Physical Laboratory Dr. K.S.Krishnan Road New Delhi – 110012, INDIA	M. K. MITTAL mkmittal@mail.nplindia.ernet.in Tel: +91 11 25742610 Fax: +91 11 25726938
State Enterprise "Ukrmetrteststandard" (UKRCSM) 4, Metrologichna St. Kyiv-143, 03143, UKRAINE	Oleh VELYCHKO velychko@ukrcsm.kiev.ua Tel./Fax: + 38 (044) 526 0335
Laboratoire National de Métrologie et d'Essais 29, avenue Roger Hennequin - 78197 Trappes Cedex	Dr Alexandre BOUNOUH alexandre.bounouh@lne.fr Tel: +33(0)1 30 692151 Fax: +33(0)1 30 162841

3.3. Time Schedule

Table 2. List of the participants and measurement dates

Laboratory	**Measurement Dates**
New period of measurements is started after the repair of the travelling standard C1-2.	
PTB - Germany	December 2003
UME- Turkey	January 2004
SIQ - Slovenia	February 2004
NCM - Bulgaria	March 2004
UME - Turkey	April 2004
New ATA Carnet	
PTB - Germany	May 2004 - June 2004
SMU - Slovakia	July 2004
OMH - Hungary	August 2004
PTB - Germany	September 2004
UME - Turkey	October 2004
INM - Romania	November 2004 - May 2005
New ATA Carnet (ATA Carnet was lost in Customs of Romania)	
FBMPM - Yugoslavia	June 2005
PTB - Germany	July 2005 - August 2005
MIKES - Finland	September 2005
UME - Turkey	October 2005
NMi-VSL - The Netherlands	December 2005 - April 2006
NPL - India	May 2006 - July 2006
New ATA Carnet	
PTB - Germany	August 2006 - November 2006
UME - Turkey	December 2006 - January 2007
LNE - France	February 2007
PTB - Germany	March 2007
UKRCSM - Ukraine	April 2007 (without ATA Carnet)
PTB - Germany	May 2007
UME - Turkey	June 2007
PTB - Germany	July 2007

One month has been allowed for each participant and includes transportation time to the next participant. Suggested term for the measurements is 2 weeks, so the travelling standard could be sent to the next recipient within expected time.

If there will be an unexpected delay, then the co-ordinator and the next recipient shall be informed by fax or e-mail.

3.4. Transportation

Participants will be responsible for arranging transportation to the next participant.

An ATA Carnet is required for some of the countries so one will accompany the travelling standard. The ATA Carnet document **must always** travel with the equipment, so please ensure that the correct paperwork accompanies the travelling standard. It will be up to the freight companies at each stage of the journey to ensure customs declaration at each relevant stage. Endorsements by customs will be required at departure from Germany, entry to and departure from each country and finally on return to Germany.

Participants shall inform the pilot laboratory by e-mail or fax when the travelling standard has arrived by filling the following form given in Figure 5.

Confirmation Note For Receipt		
Date of Arrival		
NMI		
Name of Responsible Person		
Travelling standard	Damaged	Not Damaged
ATA Carnet	Received	Not Received
Declaration of ATA Carnet	Customs Declared	No Declaration
Additional Notes:		

Figure 5. Sample form for the information of arrival of the travelling standard.

Participants shall also inform the next recipient and the pilot laboratory by e-mail or fax about the shipment of the travelling standard by filling the following form.

Confirmation Note For Dispatch		
Date of Shipment		
NMI		
Name of Responsible Person		
Shipment Information (company name etc.)		
ATA Carnet	Enclosed	
Declaration of ATA Carnet	Customs Declared	No Declaration
Additional Notes:		

Figure 6. Sample form for the information of dispatch of the travelling standard.

3.5. Unpacking, Handling, Packing

The travelling standard will be circulated within a bag, which is well furnished for the safety of the travelling standard. Upon receipt, participants shall check the container to determine if all parts on the list are present. At the end of the test, the travelling standard shall be carefully re-packed in the container in which it arrived.

If this container was damaged, the travelling standard shall be re-packed in a new container that will provide adequate protection during shipment.

3.6. Failure of the travelling standard

If any failure of the travelling standard is noted, then the pilot laboratory and PTB shall be informed immediately by e-mail or fax. If the travelling standard shall be repaired, then the participant will send it to PTB.

3.7. Financial Aspects, Insurance

Participants will be responsible for the costs of shipment to the next recipient (transportation and customs formalities).

4. Measurement Instructions

4.1. Tests before measurements

The voltmeter shall be calibrated with a DC voltage standard immediately before measurements.

4.2. Measurement performance

Warm-up time of the travelling standard (C1-2 Power-Converter)

The travelling standard shall be plugged to the mains supply for 24 hours and signal voltage and current shall be connected to the instrument for at least 2 hours before starting the measurements. After these procedures have been performed, one may find out that the travelling standard will remain extremely stable even if the voltage and current input signals are shut down for a moment. Particularly, if the power supply of the travelling standard will be shut down in any time, then the warm-up time procedure shall be performed once more.

Ranges of applied values

Tests should be performed under the following conditions:

Voltage	: 120V ± 0.2%
Current	: 5A ± 0.2%
Power Factor	: 1, 0.5i/c, and 0.0i/c ± 0.002 of the nominal values
Frequency	: 53Hz ± 0.2%
Temperature	: 23°C ± 1°C
Relative Humidity	: Between 30% and 60%

Participants shall inform the pilot laboratory if these conditions can not be met.

4.3. Method of measurement

Description of the measurement methods shall be given to the pilot laboratory within the measurement reports.

5. Uncertainty of measurement

The uncertainty must be calculated following the GUM: standard uncertainties, degrees of freedom, correlations, scheme for the evaluation of uncertainty (Annex A5).

Main uncertainty components and example schemes to report the uncertainty budget when the NMI reference system is based on the measurement of voltage, current and phase angle:

Table A. Uncertainty at power factor = 1 ± 0.002

Source of uncertainty	Standard uncertainty (μW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (μW/VA)
NMI voltage measurement	X_1	normal	1	X_1
NMI current measurement	X_2	normal	1	X_2
NMI phase measurement	X_3	normal	0	0
Measurement	X_4	rectangular	1	X_4
Std uncertainty of measurement	X_5	normal	1	X_5
Standard uncertainty				$\sqrt{X_1^2 + ... + X_5^2}$

Table B. Uncertainty at power factor = 0.5 ± 0.002

Source of uncertainty	Standard uncertainty (μW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the std uncertainty (μW/VA)
NMI voltage measurement	X_1	normal	0.5	0.5 X_1
NMI current measurement	X_2	normal	0.5	0.5 X_2
NMI phase measurement	X_3	normal	0.87	0.87 X_3
Measurement	X_4	rectangular	1	X_4
Std uncert of measurement	X_5	normal	1	X_5
Standard uncertainty				$\sqrt{(0.5X_1)^2 + ... + X_5^2}$

Table C. Uncertainty at power factor = 0.0 ± 0.002

Source of uncertainty	Standard uncertainty (μW/VA)	Probability distribution	Sensitivity coefficient	Contribution to the standard uncertainty (μW/VA)
NMI voltage measurement	X_1	normal	0	0
NMI current measurement	X_2	normal	0	0
NMI phase angle measurement	X_3	normal	1	X_3
Measurement	X_4	rectangular	1	X_4
Std uncertainty of measurement	X_5	normal	1	X_5
Standard uncertainty				$\sqrt{X_3^2 + X_4^2 + X_5^2}$

6. Measurement Report

Participants shall report the mean errors and uncertainties in terms of apparent power.

The report shall be sent to the pilot laboratory within 6 weeks after completing the measurements. In addition to the results, the report shall contain a brief description of the measurement technique, circuit diagram of the measurement setup and all relevant defining conditions such as temperature and date of measurement.

The report shall contain an uncertainty budget and statement. The uncertainty calculations shall comply with the requirements of the GUM for the calculation of the uncertainty of measurement. On the uncertainty, the report shall include the coverage factor (k=1 or k=2) and the complete budget of uncertainty.

7. Report of the Comparison

Draft A will be prepared by the pilot laboratory after the completion of the measurements and agreed by the participants. Draft B will be submitted to the support group. Reference value will be computed referring to the Final Report of “CCEM-K5 Comparison of 50/60 Hz Power” by Nile Oldham and Thomas Nelson.

References

1. “Key comparisons and mutual recognition arrangement,” BIPM website: http://www.bipm.fr/enus/8_Key_Comparisons/key_comparisons.html

2. P. Miljanić et al., “The development of a high precision time-division power meter,” in CPEM 84 Dig., Delft, the Netherlands, pp 67-68, 1984.

3. N. Oldham, Thomas Nelson, Nien Fan Zhang, and Hung-kung Liu, “Final Report of CCEM-K5 Comparison of 50/60 Hz Power,” June 2002.