Final Report

EUROMET.EM-K5 Comparison of 50/60 Hz Power
(EUROMET Project 385)

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Abstract
At 17 National Metrology Institutes (NMI) of EUROMET member states, electrical standards of low-frequency (50/60 Hz) power were compared to establish the relationship between the electrical unit of AC power at these laboratories. The results of this comparison are described. The differences between most laboratory's values and the reference values were within the expanded measurement uncertainties at a coverage factor k=2.

1. Introduction

To support mutual recognition agreements between members of the European Community, it was agreed at a meeting of EUROMET AC power experts at the Swedish National Testing and Research Institute (SP) in May 1994, to perform a EUROMET comparison of 50/60 Hz electric power [1]. The Physikalisch-Technische Bundesanstalt (PTB) was proposed as the *pilot laboratory*, which is responsible for providing the travelling standard, co-ordinating the schedule, collecting and analysing the comparison data, and preparing the draft report. All of the EUROMET laboratories were invited to participate, and the comparison began in November 1996. A previous international comparison of electric power had been conducted independently between eleven European NMIs during 1981 to 1984 and was sponsored by the Commission of the European Communities [2].

While the EUROMET comparison was being conducted, one world wide CCEM [3] and two other regional power comparisons were ongoing in NORAMET (NRC – pilot) and APMP (CSIRO-NML – pilot). To better link the EUROMET to the CCEM comparison, CCEM measurements were performed at IEN (now INRIM) in April 1997, at NPL in March 1997, at PTB in August 1996 and May 1999, and at SP in September 1996 and October 2000.

2. Participants

At the start, 12 NMIs had agreed to participate. During the comparison, one NMI (BNM/LCIE in France) withdrew from participation, but during 1997 to 1998 six additional NMIs (Arepa in Denmark, CEM in Spain, CMI in the Czech Republic, GUM in Poland, OMH in Hungary, and UME in Turkey) asked for inclusion in the comparison, and the EUROMET TCEM granted an extension. Of the 17 participants at the end of the comparison, three requested a repetition of their tests, thus the measurements period for the comparison took more than four years. The final NMI results were received in May 2001.

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

Laboratory	Measurement Date
PTB, Physikalisch-Technische Bundesanstalt, Germany	Nov 1996 – Apr 2001
NPL, National Physical Laboratory, UK	Feb/Mar 1997
IEN, Istituto Elettrotecnico Nazionale, Italy (now INRIM)	Apr/May 1997
SP, Swedish National Research and Testing Institute, Sweden	May/Jun 1997
AREPA, Arepa Test & Kalibrering A/S, Denmark	Jun 97
NMi/VSL, Nederlands Meetinstituut NV, The Netherlands	Aug 1997 and Jan/Jun 2000
INETI/DEE, Instituto Nacional de Engenharia e Tecnologia Industrial, Portugal	Sep/Oct 1997
BMS, Belgian Metrology Service, Belgium	Nov/Dec 1997
BEV, Bundesamt für Eich- und Vermessungswesen, Austria	Jan/Feb 1998
METAS, Swiss Federal Office of Metrology and Accreditation, Switzerland	Mar 1998
MIKES, Centre for Metrology and Accreditation, Finland	Apr/May 1998 and Nov/Dec 1999
CMI, Czech Metrology Institute, Czech Republic	May/Jun 1998
OMH, National Office of Measures, Hungary	Jun/Jul 1998
Justervesenet, Norwegian Metrology and Accreditation Service, Norway	Aug 1998
UME, Ulusal Metroloji Enstitüsü, Turkey	Sep/Oct 1998 and Jul 2000/Jan2001
CEM, Centro Espanol de Metrologia, Spain	Nov/Dec1998
GUM, Central Office of Measures, Poland	Jan/Feb 1999

Travelling Standard

During the initialising meeting at SP in 1994 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 [4]. 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 regularly monitored for several years in the power and energy laboratory in the Electricity Division at PTB. Measurements of the standard between 0 ºC and 40 ºC indicated a temperature coefficient of $4.5 \cdot 10^{-6}$ K^{-1} in this range. 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 normalisation procedure described below, thus the measured voltages were not directly used in the analysis of the comparison reference values and the degree of equivalence of measurements.*

4. Test Points

During the meeting at SP in 1994, the participants 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 comparison. Instructions to the participants were as follows:

1. The comparison of AC Power Measurement Systems shall be performed at:

Voltage	120 V
Current	5 A
Power factor	1 ; 0.5 ; 0 (inductive and capacitive)
Frequency	53 Hz (slightly aside from power supply frequency).

The response of the Power-Converter type C1-2 is a DC voltage (10 V nominal at rated input), which is measured at the VOLT. OUT sockets (10 V DC).
(At PTB a DVM HP3458A is used for the DC voltage measurements).

2. Appreciated are also measurement values of the output voltage for 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

and measurement values for the DC REF. VOLTAGE (+7.044...V and -7.044...V).

3. All data relevant to the derivation of the reported results should accompany the report and also a short description and circuit diagram of the measurement set-up.

4. Any relevant environmental data (e.g. temperature) should be included in the report of the results.

5. Based on ISO 'Guide to the Expression of Uncertainty in Measurement' an estimate of the uncertainty shall be stated together with the results. For the expanded uncertainty a 95% coverage probability should be used and the coverage factor employed in calculating the uncertainty should be reported.

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 three times cycled through two and in one case through three 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.

5. Results

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

Table 2. Relative deviations from nominal and standard uncertainties (*k*=1) in µW/VA

$x_{i,j}$ =	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**
	µW/VA	µW/VA	µW/VA	µW/VA	µW/VA	µW/VA	µW/VA	µW/VA	µW/VA	µW/VA	**Date**
PTB	-61	11	-23	10	-40	10	13	10	-8	10	Nov 96
PTB	-57	11	-21	10	-42	10	12	10	-12	10	Feb 97
NPL	-51	16	-22	14	-30	14	5	14	-3	14	Mar 97
PTB	-42	11	-12	10	-33	10	13	10	-10	10	Apr 97
IEN	-47	15	-11	15	-37	15	21	15	-10	15	Apr 97
PTB	-59	11	-24	10	-43	10	9	10	-14	10	May 97
SP	-79	15	-30	10	-54	10	18	8	-13	8	Jun 97
Arepa	-49	47	-38	50	-35	50	-13	70	-14	70	Jun 97
PTB	-53	11	-21	10	-43	10	5	10	-20	10	Jul 97
NMi/ VSL*	84		15		-5		-120		15		Aug 97
INETI	-49	36	-26	76	-30	97	-208	241	4	148	Oct 97
BMS	9	19	4	19	1	19	17	14	9	14	Dec 97
PTB	-49	11	-17	10	-39	10	10	10	-17	10	Dec 97
BEV	-104	35	-34	35	-45	35	11	110	-3	110	Feb 98
PTB	-47	11	-16	10	-38	10	9	10	-19	10	Feb 98
EAM/ METAS	-59	27	-3	24	-52	24	31	23	-24	23	Mar 98
PTB	-41	11	-15	10	-35	10	7	10	-16	10	Mar 98
VTT*											Apr 98
PTB	-35	11	-10	10	-33	10	8	10	-14	10	May 98
CMI	-40	35	-35	30	-50	30	-50	25	-130	25	Jun 98
OMH	0	85	-35	85	28	85	45	85	-37	85	Jun 98
PTB	-47	11	-14	10	-37	10	14	10	-14	10	Jul 98
Juster- vesenet	-18	35	-2	35	-12	35	6	35	-13	35	Aug 98
PTB	-54	11	-15	10	-39	10	13	10	-13	10	Sep 98
UME*											Oct 98
PTB	-50	11	-18	10	-35	10	10	10	-10	10	Nov 98
CEM	-50	33	-68	33	36	33					Dec 98
PTB	-59	11	-20	10	-41	10	12	10	-8	10	Jan 99
GUM	-26	38	-9	37	-23	37	16	37	7	37	Feb 99
PTB	-61	11	-20	10	-45	10	12	10	-8	10	Feb 99
PTB	-44	11	-17	10	-28	10	8	10	2	10	Oct 99

VTT/ MIKES	-9	17	-8	10	-7	10	-3	6	-1	6	Dec 99
PTB	-48	11	-17	10	-28	10	8	10	-1	10	Dec 99
NMi/ VSL	-30	5	-30	25	-5	25	-10	85	12	85	Apr 00
UME	-24	36	29	36	-55	36	10	36	-15	36	Nov 00
PTB	-32	11	-9	10	-18	10	16	10	12	10	Mar 01
PTB	-28	11	4	10	-12	10	20	10	16	10	Apr 01

Values (if any) of participants marked with an asterisk were not used in the final results. The NMIs concerned discovered errors in their measurement systems, and therefore asked for repetition of their measurements. The first tests made by these three NMIs were not used in the final results.

Data from Table 2 are also 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)

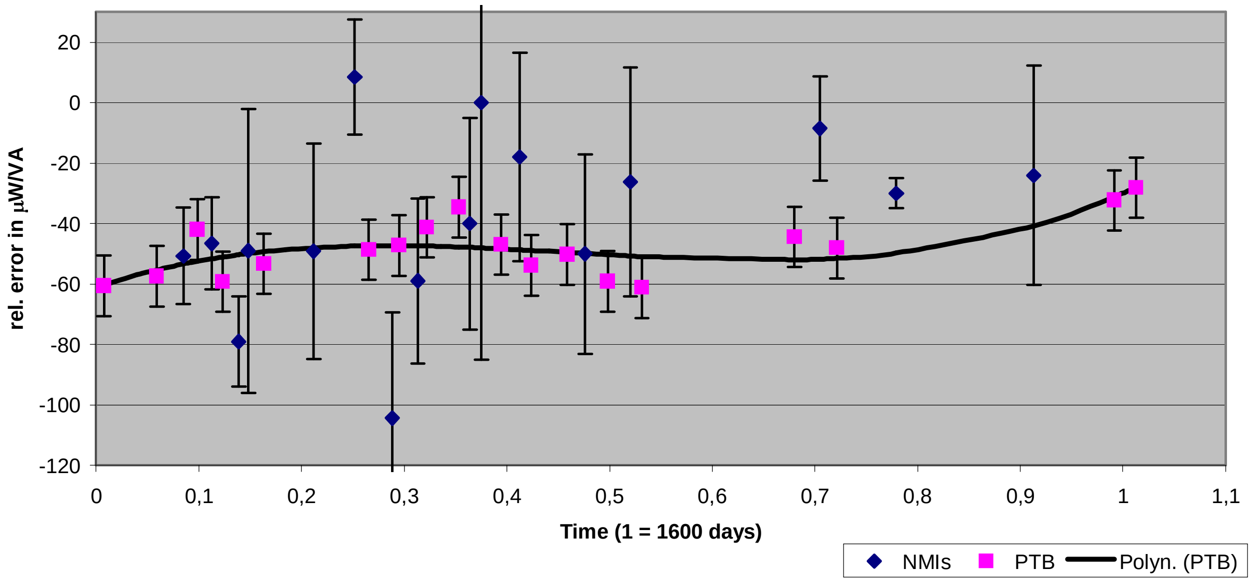


Figure 2. Reported results, 120 V, 5 A, PF = 0.5 Lead (cap) (*k* = 1)

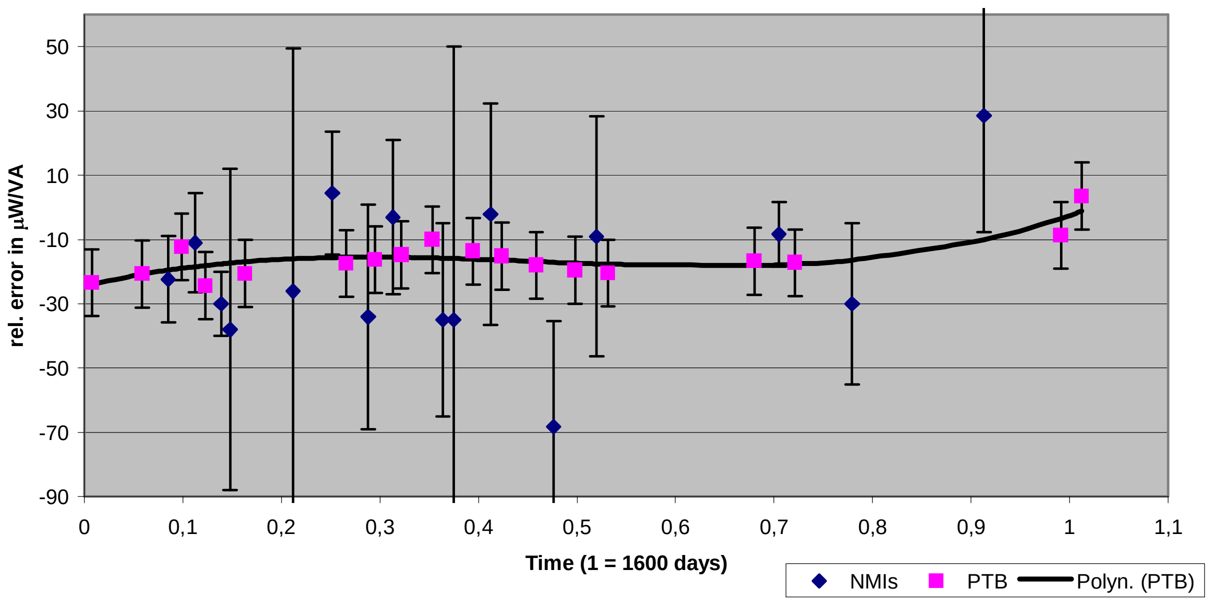


Figure 3. Reported results, 120 V, 5 A, PF = 0.5 Lag (ind) (*k* = 1)

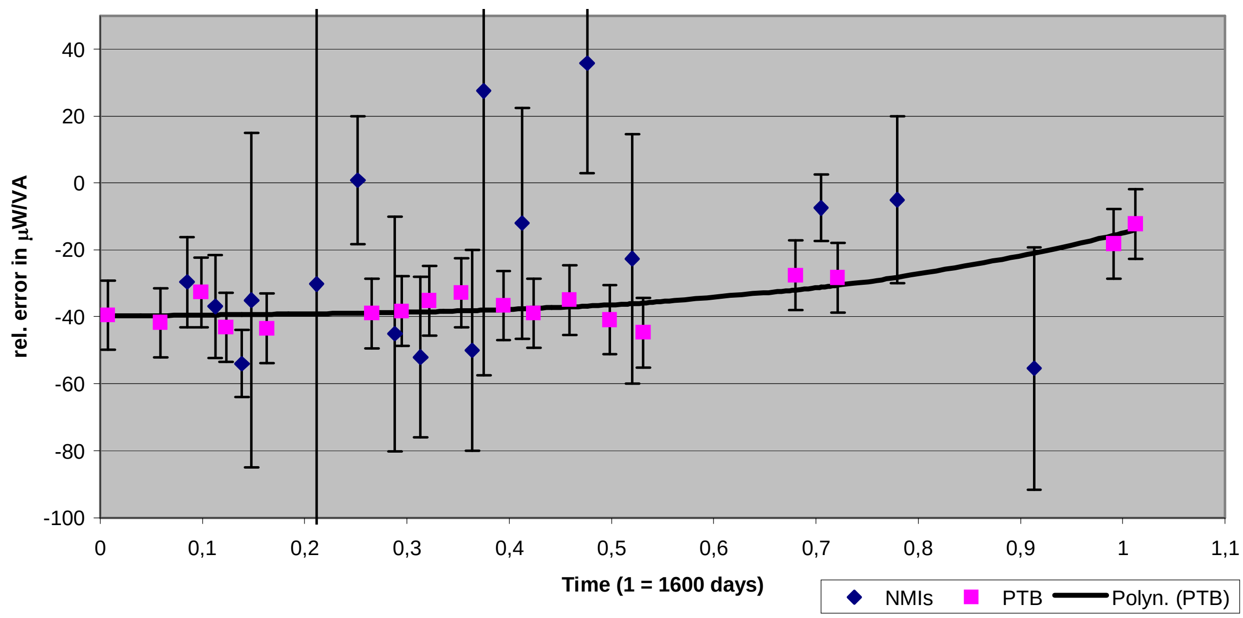


Figure 4. Reported results, 120 V, 5 A, PF = 0.0 Lead (cap) (*k* = 1)

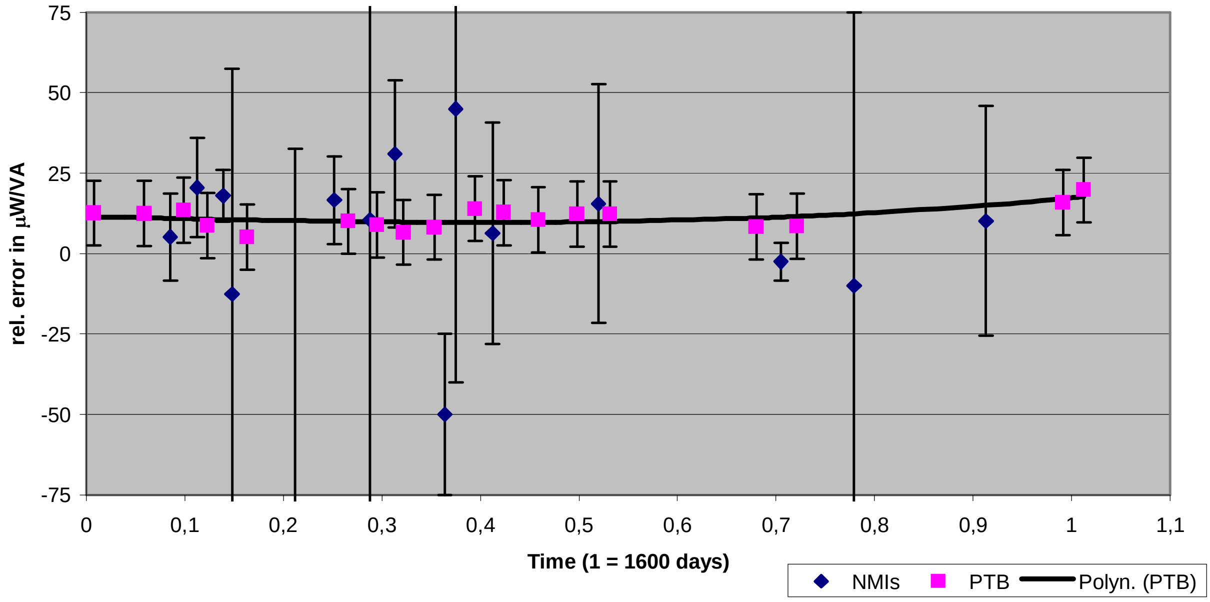
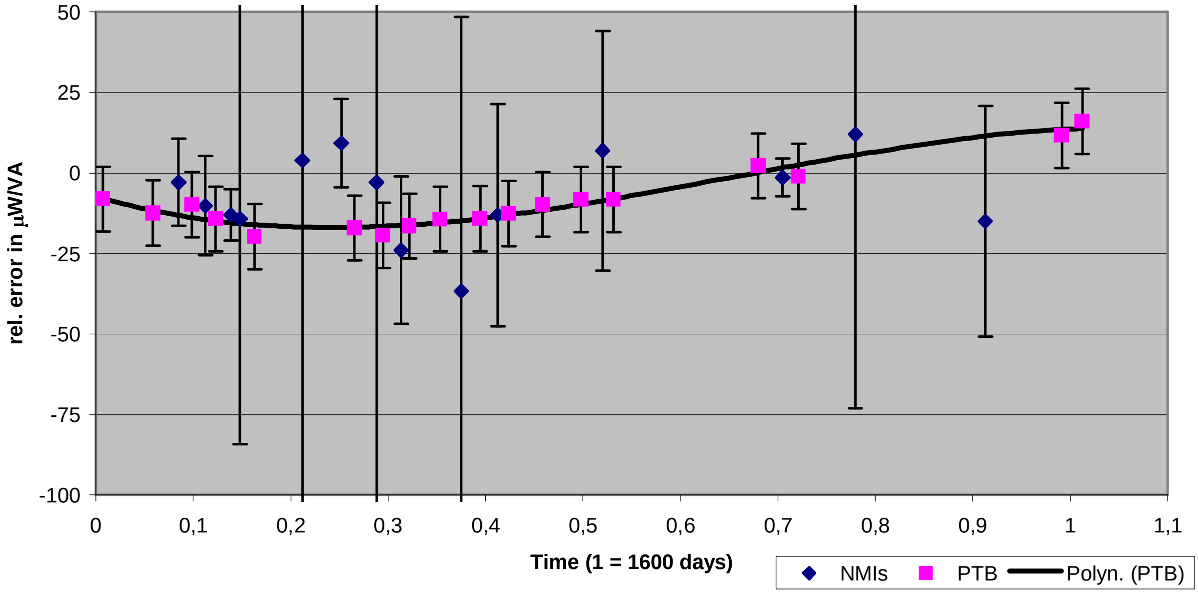


Figure 5. Reported results, 120 V, 5 A, PF = 0.0 Lag (ind) (*k* = 1)



The Drift Effect

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

$$x_{PTB,1}(k) = -60.975 + 112.09 \times t_{PTB}(k) - 282.43 \times t_{PTB}^2(k) + 201.51 \times t_{PTB}^3(k) + \varepsilon_1(k)$$

$$x_{PTB,2}(k) = -24.490 + 73.145 \times t_{PTB}(k) - 183.95 \times t_{PTB}^2(k) + 132.76 \times t_{PTB}^3(k) + \varepsilon_2(k)$$

$$x_{PTB,3}(k) = -39.834 + 4.8936 \times t_{PTB}(k) - 12.181 \times t_{PTB}^2(k) + 32.214 \times t_{PTB}^3(k) + \varepsilon_3(k)$$

$$x_{PTB,4}(k) = +11.469 - 6.6946 \times t_{PTB}(k) + 1.2149 \times t_{PTB}^2(k) + 11.350 \times t_{PTB}^3(k) + \varepsilon_4(k)$$

$$x_{PTB,5}(k) = -7.3022 - 86.786 \times t_{PTB}(k) + 220.40 \times t_{PTB}^2(k) - 112.64 \times t_{PTB}^3(k) + \varepsilon_5(k)$$

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 days/1600) from the beginning of the comparison when PTB made the measurements, k = 1,2,...,18 , $\varepsilon_j(k)$ = 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:
$s_r(1) = 6.379$, $s_r(2) = 3.510$, $s_r(3) = 3.936$, $s_r(4) = 2.629$, and $s_r(5) = 2.036$,
which are estimates of $\sigma_r(j)$ for j = 1,2,3,4,5.

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 $\vec{X}_{PTB,j} = (x_{PTB,j}(1),...,x_{PTB,j}(18))'$ is a column vector, $\vec{\beta}(j)$ is the 4 by 1 column vector of the regression parameters, and T_{PTB} is a 18 by 4 matrix with the elements of the first column being 1's and other (k,n) elements (for $k = 1,2,...,18$ and $n = 2,3,4$) being $t_{PTB}^{n-1}(k)$. For a matrix A or a vector, A' is the transpose of A.

For all the 17 NMIs, the difference $D_i(j)$ $(i = 1,2,...,17)$ 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, which is the pilot NMI, 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 $k = 1,2,...,18$. Namely,

$$AVE[D_{PTB}(j)] = \frac{\sum_{k=1}^{18}[x_{PTB,j}(k) - xp_{PTB,j}(k)]}{18}$$

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. The variance of $D_i(j)$ is given by

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

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 pilot NMI. (Note: The influence of the term for the correction of the measurement date is in the largest case not larger than

0,9 µW/VA). When the i^{th} NMI is PTB, the corresponding variance for $AVE[D_{PTB}(j)]$ is given by

$$u^2_{AVE[D_{PTB}(j)]} = u^2_{B,PTB}(j) + \frac{u^2_{A,PTB}(j)}{18}$$

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.

Reference Values

Comparison reference values $X_{CRV}(j)$ for each of the five test points were calculated as the weighted mean of $D_i(j)$ from 11 NMIs including PTB as the first NMI. Not included are those six NMIs who refer their national reference values to a calibration at the pilot laboratory.
That is,

$$X_{CRV}(j) = \sum_{i=1}^{11} w_i(j) \times D_i(j)$$

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

$$w_i(j) = \frac{\dfrac{1}{u^2_{D_i(j)}}}{\sum\limits_{k=1}^{11} \dfrac{1}{u^2_{D_k(j)}}}$$

Note that $D_1(j) = AVE[D_{PTB}(j)] \equiv 0$ and $u_{D_1(j)} = u_{AVE[D_{PTB}(j)]}$ for PTB. Note also that while each NMI measurement is realised 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

$$u^2_{CRV}(j) = \frac{1}{\sum\limits_{i=1}^{11} \dfrac{1}{u^2_{D_i(j)}}} + \frac{2s_r^2(j)}{(\sum\limits_{i=1}^{11} \dfrac{1}{u^2_{D_i(j)}})^2} \times \sum_{i>k,i=2}^{11} \sum_{k=2}^{11} \frac{\vec{t}_i (T'_{PTB} T_{PTB})^{-1} \vec{t}_k^{\,'}}{u^2_{D_i(j)} \times u^2_{D_k(j)}}$$

Note: The contribution of the right hand part of this equation to $u_{CRV}(j)$ is not larger than some 0.01 µW/VA.

The weighted mean can be influenced if one or more NMIs have differences $D_i(j)$ significantly larger than their corresponding $u_{D_i(j)}$. Three NMIs identified and corrected errors in their power standards after making measurements. These labs requested follow-up tests and it was decided to use the results of these follow-up tests (rather than their initial results and uncertainties) to compute the reference value. The reference values and their uncertainties are given in Table 3.

Table 3. Reference Values and Uncertainties

Power Factor	$\boldsymbol{X_{CRV}}$	$\boldsymbol{u_{CRV}}$
	in µW/VA	in µW/VA
1.0	10.9	5.2
0.5 Lead	-0.4	4.9
0.5 Lag	7.7	4.9
0.0 Lead	-2.2	4.0
0.0 Lag	2.3	3.9

<u>Equivalence</u>

The differences between each of the NMI values and the predicted value (based on 18 independent measurements performed at the Pilot NMI) were adjusted by the reference values to generate $D_{i,CRV}(j)$ the NMI- Reference differences:

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

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

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

Note: The contribution of the right hand part of this equation to $u_{D_{i,CRV}}(j)$ is in all cases less than 0.5 µW/(VA).

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

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

and its uncertainty is given by

$$u^2_{D_{PTB,CRV}}(j) = [1-2w_1(j)]\times(u^2_{B,PTB}(j)+\frac{u^2_{A,PTB}(j)}{18}) + u^2_{CRV}(j)$$

where w_1 is the corresponding weight for PTB. The differences and the expanded uncertainty (using a coverage factor of *k*=2) denoted by $U_{D_{i,CRV}}$ 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 the pilot NMI is given by

$$u^2_{i,k}(j) = u^2_i(j) + u^2_k(j) + s^2_r(j)[2 + \vec{t}_i(T'_{PTB}T_{PTB})^{-1}\vec{t}_i^{\,'} + \vec{t}_k(T'_{PTB}T_{PTB})^{-1}\vec{t}_k^{\,'} - 2\times\vec{t}_i(T'_{PTB}T_{PTB})^{-1}\vec{t}_k^{\,'}]$$

When one NMI is the pilot NMI, 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

$$u^2_{1,k}(j) = u^2_{PTB,k}(j) = u^2_{B,PTB}(j) + \frac{u^2_{A,PTB}(j)}{18} + u^2_k(j) + s^2_r(j)[1 + \vec{t}_k(T'_{PTB}T_{PTB})^{-1}\vec{t}_k^{\,'}]$$

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

Table 4. Differences and Expanded Uncertainties in µW/VA

$D_{i,CRV}$	Differences										
$U_{Di,CRV}$	Expanded uncertainties of $D_{i,CRV}$ (k=2)										
i		**1.0 pf**		**0.5 Lead**		**0.5 Lag**		**0.0 Lead**		**0.0 Lag**	
	NMI	$D_{i,CRV}$	$U_{Di,CRV}$	$D_{i,CRV}$	$U_{Di,CRV}$	$D_{i,CRV}$	$U_{Di,CRV}$	$D_{i,CRV}$	$U_{Di,CRV}$	$D_{i,CRV}$	$U_{Di,CRV}$
1	**PTB (AVE)**	-10.9	21.5	0.4	19.1	-7.7	19.3	2.2	18.9	-2.3	19.4
2	**NPL**	-8.2	33.6	-2.4	26.6	2.1	26.8	-3.5	26.5	8.0	26.3
3	**IEN**	-5.8	32.0	7.8	30.4	-5.2	30.6	11.9	30.4	2.0	30.2
4	**SP**	-39.6	31.6	-12.1	19.4	-22.4	19.8	9.6	15.2	0.1	14.9
5	**Arepa**	-10.0	94.5	-20.3	99.9	-3.5	99.9	-21.0	139.9	-0.8	139.9
6	**INETI**	-12.1	72.0	-9.7	150.9	1.1	194.0	-216.4	482.0	18.4	294.9
7	**BMS**	45.1	39.6	20.4	37.9	31.9	38.1	8.7	27.0	24.0	26.8
8	**BEV**	-67.9	70.7	-18.2	69.8	-14.2	69.9	2.8	219.9	11.5	219.9
9	**EAM/METAS**	-22.5	55.4	13.0	47.9	-21.2	48.0	23.3	45.5	-10.0	45.4
10	**CMI**	-3.0	70.7	-18.8	59.8	-19.6	59.9	-57.6	49.7	-117.1	49.6
11	**OMH**	37.2	170.3	-18.7	169.9	57.8	170.0	37.5	169.9	-24.2	169.9
12	**JV**	19.8	69.6	14.6	68.8	17.9	68.9	-1.2	68.8	-1.8	68.7
13	**CEM**	-11.0	66.6	-50.9	65.8	64.9	65.9	n.a.	n.a.	n.a.	n.a.
14	**GUM**	13.6	76.2	8.9	74.4	5.7	74.5	7.8	74.0	13.3	74.0
15	**VTT/MIKES**	32.3	36.0	9.8	19.8	16.0	20.2	-11.6	10.8	-5.3	10.2
16	**NMi/VSL**	8.9	15.5	-13.2	49.9	15.4	50.0	-20.2	169.9	4.1	169.9
17	**UME**	5.8	73.3	39.0	72.4	-42.1	72.5	-2.6	71.3	-28.7	71.3

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

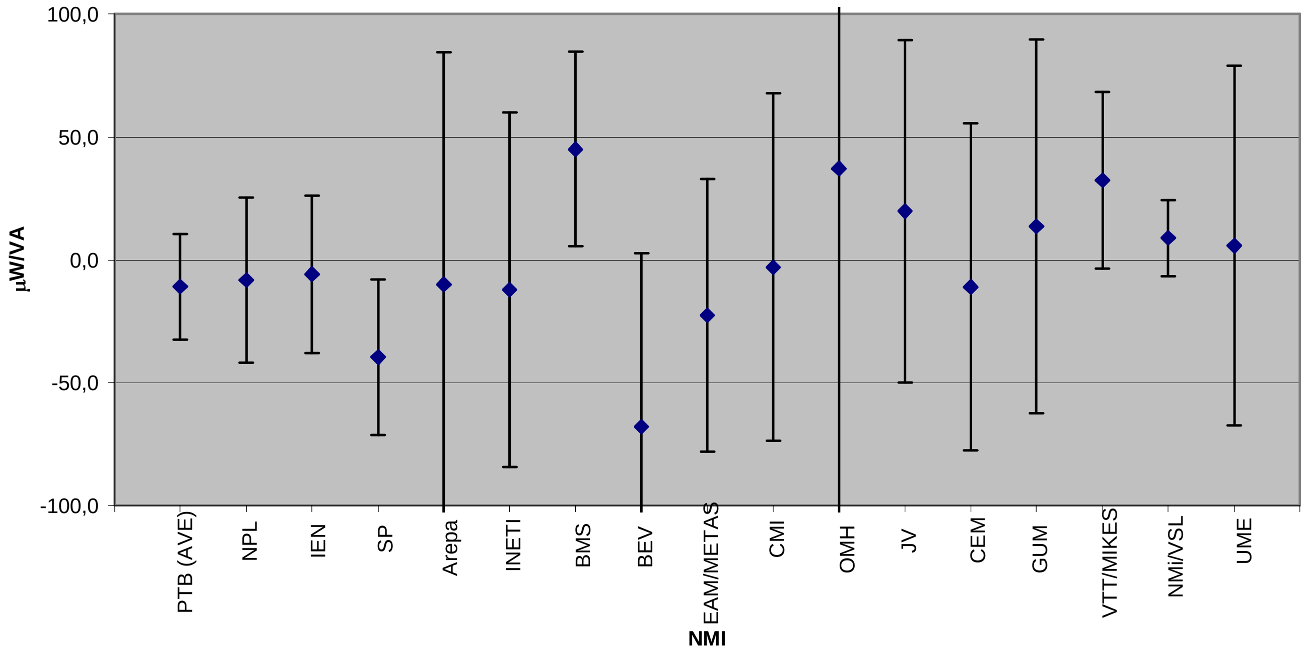


Figure 7. Deviation from Reference Value 120 V, 5 A, PF 0.5 Lead (*k* =2)

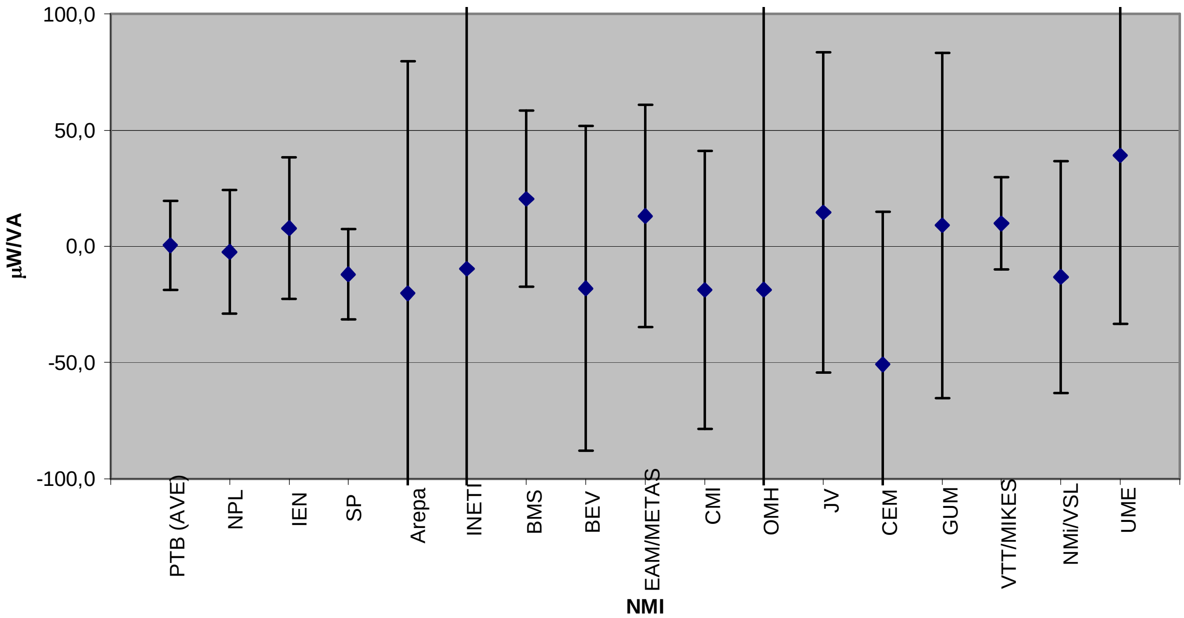


Figure 8. Deviation from Reference Value 120 V, 5 A, PF 0.5 Lag (*k* =2)

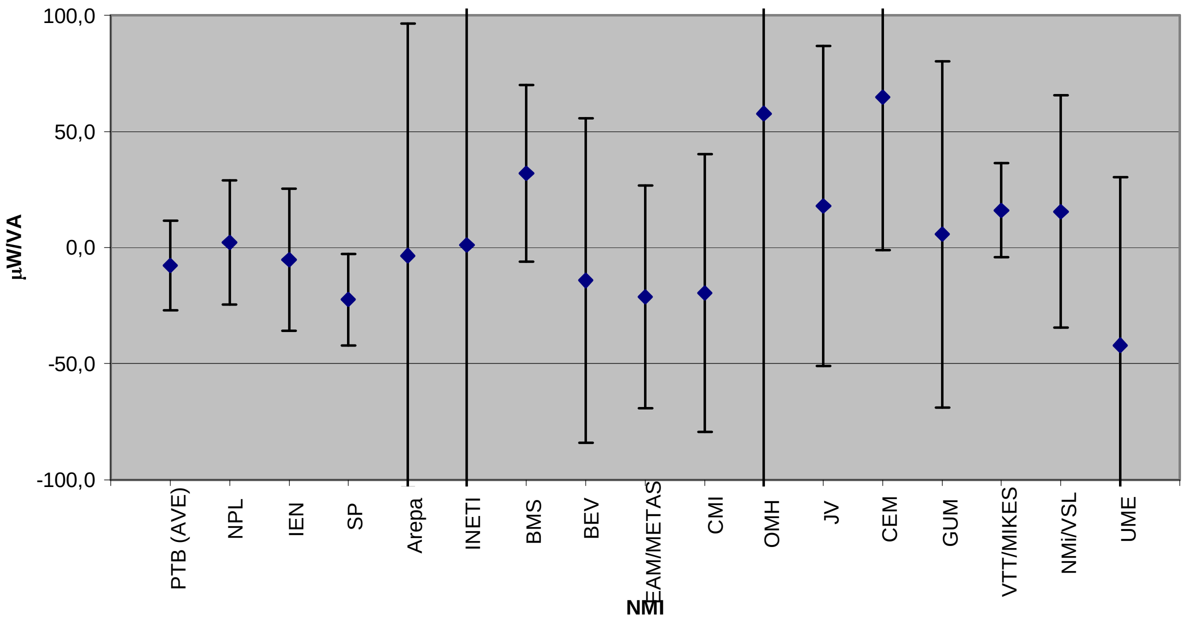


Figure 9. Deviation from Reference Value 120 V, 5 A, PF 0.0 Lead (*k* =2)

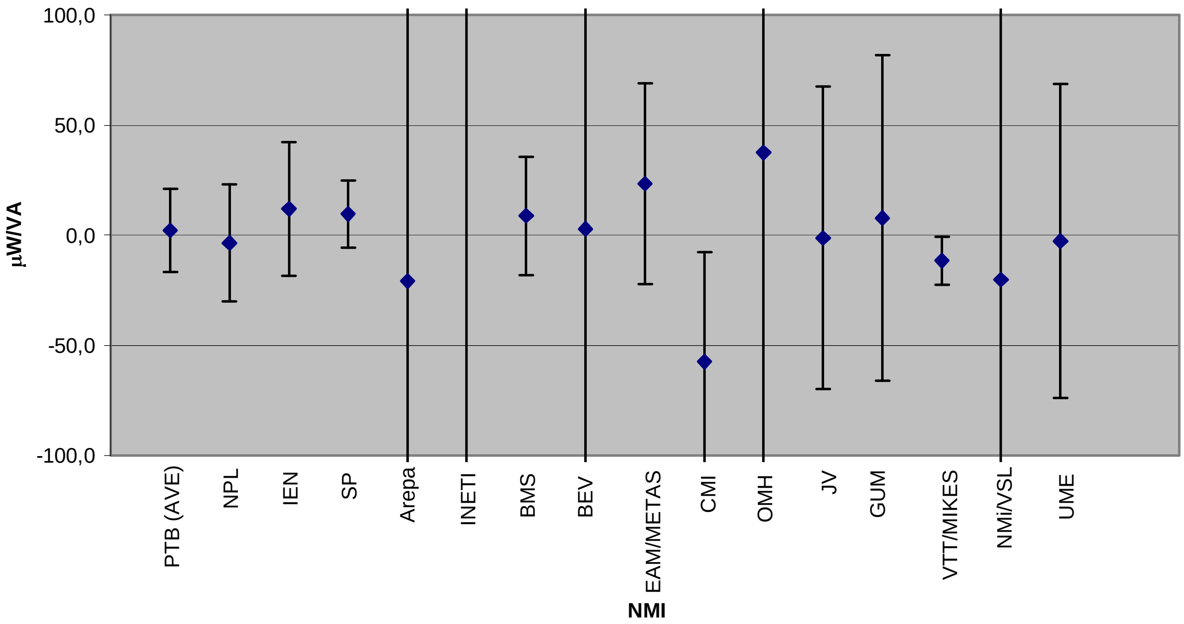


Figure 10. Deviation from Reference Value 120 V, 5 A, PF 0.0 Lag (*k* =2)

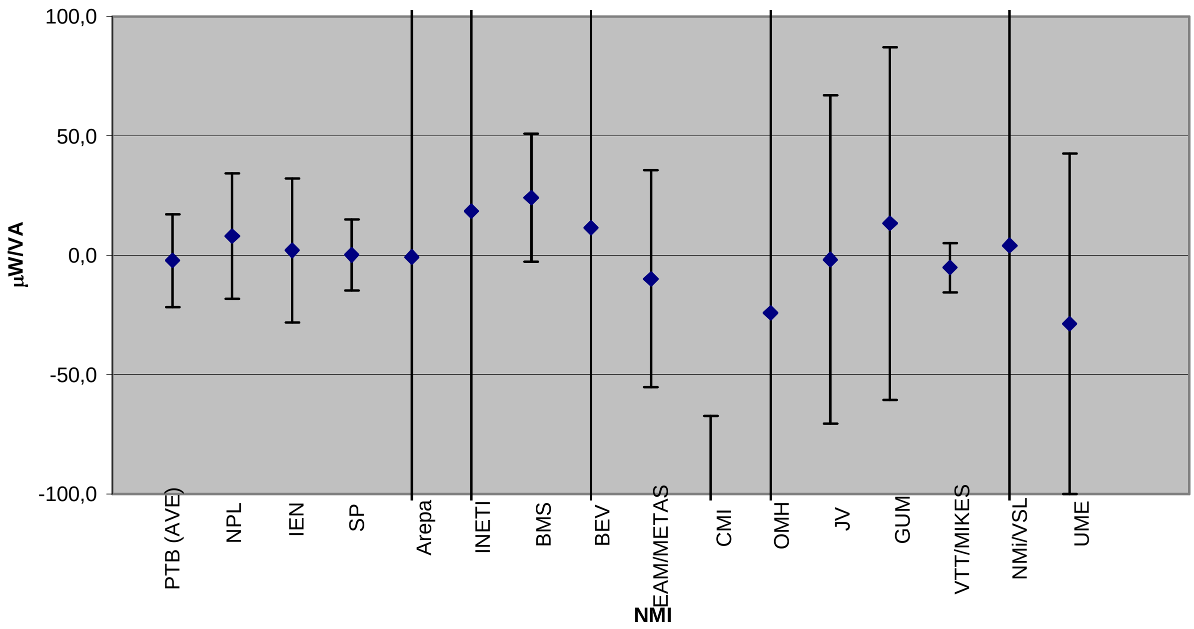


Table 5. Equivalence at 1.0 Power Factor

	PTB	NPL	IEN	SP	Arepa	INETI	BMS	BEV	METAS	CMI	OMH	JV	CEM	GUM	MIKES	NMi/VSL	UME
PTB	-	-3 ± 42	-5 ± 41	29 ± 40	-1 ± 98	1 ± 76	-56 ± 47	57 ± 75	12 ± 61	-8 ± 75	-48 ± 172	-31 ± 74	0 ± 71	-25 ± 80	-43 ± 44	-20 ± 29	-17 ± 78
NPL	3 ± 42	-	-2 ± 48	31 ± 48	2 ± 101	4 ± 80	-53 ± 53	60 ± 79	14 ± 66	-5 ± 79	-45 ± 174	-28 ± 78	3 ± 76	-22 ± 84	-41 ± 51	-17 ± 39	-14 ± 82
IEN	5 ± 41	2 ± 48	-	34 ± 46	4 ± 100	6 ± 80	-51 ± 52	62 ± 79	17 ± 65	-3 ± 79	-43 ± 174	-26 ± 78	5 ± 75	-19 ± 84	-38 ± 50	-15 ± 38	-12 ± 81
SP	-29 ± 40	-31 ± 48	-34 ± 46	-	-30 ± 100	-27 ± 79	-85 ± 52	28 ± 78	-17 ± 65	-37 ± 78	-77 ± 174	-59 ± 78	-29 ± 75	-53 ± 84	-72 ± 50	-48 ± 38	-45 ± 81
Arepa	1 ± 98	-2 ± 101	-4 ± 100	30 ± 100	-	2 ± 119	-55 ± 103	58 ± 119	13 ± 110	-7 ± 119	-47 ± 195	-30 ± 118	1 ± 116	-24 ± 122	-42 ± 102	-19 ± 97	-16 ± 120
INETI	-1 ± 76	-4 ± 80	-6 ± 80	27 ± 79	-2 ± 119	-	-57 ± 83	56 ± 102	10 ± 92	-9 ± 102	-49 ± 185	-32 ± 101	-1 ± 99	-26 ± 106	-44 ± 82	-21 ± 75	-18 ± 104
BMS	56 ± 47	53 ± 53	51 ± 52	85 ± 52	55 ± 103	57 ± 83	-	113 ± 82	68 ± 69	48 ± 82	8 ± 175	25 ± 81	56 ± 79	31 ± 87	13 ± 55	36 ± 45	39 ± 85
BEV	-57 ± 75	-60 ± 79	-62 ± 79	-28 ± 78	-58 ± 119	-56 ± 102	-113 ± 82	-	-45 ± 91	-65 ± 101	-105 ± 185	-88 ± 100	-57 ± 98	-82 ± 105	-100 ± 81	-77 ± 74	-74 ± 103
METAS	-12 ± 61	-14 ± 66	-17 ± 65	17 ± 65	-13 ± 110	-10 ± 92	-68 ± 69	45 ± 91	-	-19 ± 91	-60 ± 179	-42 ± 90	-12 ± 88	-36 ± 95	-55 ± 68	-31 ± 59	-28 ± 93
CMI	8 ± 75	5 ± 79	3 ± 79	37 ± 78	7 ± 119	9 ± 102	-48 ± 82	65 ± 101	19 ± 91	-	-40 ± 185	-23 ± 100	8 ± 98	-17 ± 105	-35 ± 81	-12 ± 74	-9 ± 103
OMH	48 ± 172	45 ± 174	43 ± 174	77 ± 174	47 ± 195	49 ± 185	-8 ± 175	105 ± 185	60 ± 179	40 ± 185	-	17 ± 184	48 ± 183	24 ± 187	5 ± 175	28 ± 171	31 ± 186
JV	31 ± 74	28 ± 78	26 ± 78	59 ± 78	30 ± 118	32 ± 101	-25 ± 81	88 ± 100	42 ± 90	23 ± 100	-17 ± 184	-	31 ± 97	6 ± 104	-13 ± 80	11 ± 73	14 ± 102
CEM	0 ± 71	-3 ± 76	-5 ± 75	29 ± 75	-1 ± 116	1 ± 99	-56 ± 79	57 ± 98	12 ± 88	-8 ± 98	-48 ± 183	-31 ± 97	-	-25 ± 102	-43 ± 77	-20 ± 69	-17 ± 100
GUM	25 ± 80	22 ± 84	19 ± 84	53 ± 84	24 ± 122	26 ± 106	-31 ± 87	82 ± 105	36 ± 95	17 ± 105	-24 ± 187	-6 ± 104	25 ± 102	-	-19 ± 85	5 ± 79	8 ± 107
MIKES	43 ± 44	41 ± 51	38 ± 50	72 ± 50	42 ± 102	44 ± 82	-13 ± 55	100 ± 81	55 ± 68	35 ± 81	-5 ± 175	13 ± 80	43 ± 77	19 ± 85	-	23 ± 40	27 ± 82
NMi/VSL	20 ± 29	17 ± 39	15 ± 38	48 ± 38	19 ± 97	21 ± 75	-36 ± 45	77 ± 74	31 ± 59	12 ± 74	-28 ± 171	-11 ± 73	20 ± 69	-5 ± 79	-23 ± 40	-	3 ± 76
UME	17 ± 78	14 ± 82	12 ± 81	45 ± 81	16 ± 120	18 ± 104	-39 ± 85	74 ± 103	28 ± 93	9 ± 103	-31 ± 186	-14 ± 102	17 ± 100	-8 ± 107	-27 ± 82	-3 ± 76	-

Table 6. Equivalence at 0.5 Lead (capacitive)

	PTB	NPL	IEN	SP	Arepa	INETI	BMS	BEV	METAS	CMI	OMH	JV	CEM	GUM	MIKES	NMi/VSL	UME
PTB	-	3 ± 35	-7 ± 38	12 ± 30	21 ± 102	10 ± 153	-20 ± 44	19 ± 73	-13 ± 53	19 ± 64	19 ± 171	-14 ± 73	51 ± 70	-9 ± 78	-9 ± 30	14 ± 55	-39 ± 76
NPL	-3 ± 35	-	-10 ± 42	10 ± 35	18 ± 104	7 ± 154	-23 ± 48	16 ± 76	-15 ± 56	16 ± 67	16 ± 172	-17 ± 75	49 ± 72	-11 ± 80	-12 ± 35	11 ± 58	-41 ± 78
IEN	7 ± 38	10 ± 42	-	20 ± 38	28 ± 105	18 ± 154	-13 ± 50	26 ± 77	-5 ± 58	27 ± 68	26 ± 173	-7 ± 76	59 ± 74	-1 ± 81	-2 ± 38	21 ± 60	-31 ± 80
SP	-12 ± 30	-10 ± 35	-20 ± 38	-	8 ± 102	-2 ± 153	-32 ± 44	6 ± 74	-25 ± 53	7 ± 64	7 ± 171	-27 ± 73	39 ± 70	-21 ± 78	-22 ± 30	1 ± 55	-51 ± 76
Arepa	-21 ± 102	-18 ± 104	-28 ± 105	-8 ± 102	-	-11 ± 181	-41 ± 108	-2 ± 122	-33 ± 111	-2 ± 117	-2 ± 197	-35 ± 122	31 ± 120	-29 ± 125	-30 ± 103	-7 ± 112	-59 ± 124
INETI	-10 ± 153	-7 ± 154	-18 ± 154	2 ± 153	11 ± 181	-	-30 ± 156	8 ± 167	-23 ± 159	9 ± 163	9 ± 228	-24 ± 166	41 ± 165	-19 ± 169	-20 ± 153	4 ± 159	-49 ± 168
BMS	20 ± 44	23 ± 48	13 ± 50	32 ± 44	41 ± 108	30 ± 156	-	39 ± 80	7 ± 62	39 ± 72	39 ± 175	6 ± 80	71 ± 77	11 ± 84	11 ± 45	34 ± 64	-19 ± 83
BEV	-19 ± 73	-16 ± 76	-26 ± 77	-6 ± 74	2 ± 122	-8 ± 167	-39 ± 80	-	-31 ± 86	1 ± 93	0 ± 184	-33 ± 99	33 ± 97	-27 ± 103	-28 ± 74	-5 ± 87	-57 ± 101
METAS	13 ± 53	15 ± 56	5 ± 58	25 ± 53	33 ± 111	23 ± 159	-7 ± 62	31 ± 86	-	32 ± 78	32 ± 177	-2 ± 85	64 ± 82	4 ± 89	3 ± 53	26 ± 70	-26 ± 88
CMI	-19 ± 64	-16 ± 67	-27 ± 68	-7 ± 64	2 ± 117	-9 ± 163	-39 ± 72	-1 ± 93	-32 ± 78	-	0 ± 181	-33 ± 92	32 ± 90	-28 ± 96	-29 ± 64	-6 ± 79	-58 ± 95
OMH	-19 ± 171	-16 ± 172	-26 ± 173	-7 ± 171	2 ± 197	-9 ± 228	-39 ± 175	0 ± 184	-32 ± 177	0 ± 181	-	-33 ± 184	32 ± 183	-28 ± 186	-29 ± 172	-5 ± 178	-58 ± 185
JV	14 ± 73	17 ± 75	7 ± 76	27 ± 73	35 ± 122	24 ± 166	-6 ± 80	33 ± 99	2 ± 85	33 ± 92	33 ± 184	-	65 ± 96	6 ± 102	5 ± 73	28 ± 86	-24 ± 101
CEM	-51 ± 70	-49 ± 72	-59 ± 74	-39 ± 70	-31 ± 120	-41 ± 165	-71 ± 77	-33 ± 97	-64 ± 82	-32 ± 90	-32 ± 183	-65 ± 96	-	-60 ± 100	-61 ± 70	-38 ± 83	-90 ± 99
GUM	9 ± 78	11 ± 80	1 ± 81	21 ± 78	29 ± 125	19 ± 169	-11 ± 84	27 ± 103	-4 ± 89	28 ± 96	28 ± 186	-6 ± 102	60 ± 100	-	-1 ± 78	22 ± 90	-30 ± 105
MIKES	9 ± 30	12 ± 35	2 ± 38	22 ± 30	30 ± 103	20 ± 153	-11 ± 45	28 ± 74	-3 ± 53	29 ± 64	29 ± 172	-5 ± 73	61 ± 70	1 ± 78	-	23 ± 55	-29 ± 76
NMi/VSL	-14 ± 55	-11 ± 58	-21 ± 60	-1 ± 55	7 ± 112	-4 ± 159	-34 ± 64	5 ± 87	-26 ± 70	6 ± 79	5 ± 178	-28 ± 86	38 ± 83	-22 ± 90	-23 ± 55	-	-52 ± 89
UME	39 ± 76	41 ± 78	31 ± 80	51 ± 76	59 ± 124	49 ± 168	19 ± 83	57 ± 101	26 ± 88	58 ± 95	58 ± 185	24 ± 101	90 ± 99	30 ± 105	29 ± 76	52 ± 89	-

Table 7. Equivalence at 0.5 Lag (inductive)

	PTB	NPL	IEN	SP	Arepa	INETI	BMS	BEV	METAS	CMI	OMH	JV	CEM	GUM	MIKES	NMi/VSL	UME
PTB	-	-10 ± 35	-2 ± 38	15 ± 30	-4 ± 103	-9 ± 195	-40 ± 44	6 ± 74	13 ± 53	12 ± 64	-66 ± 172	-26 ± 73	-73 ± 70	-13 ± 78	-24 ± 31	-23 ± 55	34 ± 76
NPL	10 ± 35	-	7 ± 42	25 ± 35	6 ± 104	1 ± 196	-30 ± 48	16 ± 76	23 ± 56	22 ± 67	-56 ± 173	-16 ± 75	-63 ± 72	-4 ± 80	-14 ± 36	-13 ± 58	44 ± 78
IEN	2 ± 38	-7 ± 42	-	17 ± 38	-2 ± 105	-6 ± 197	-37 ± 50	9 ± 77	16 ± 58	14 ± 68	-63 ± 173	-23 ± 76	-70 ± 74	-11 ± 82	-21 ± 39	-21 ± 60	37 ± 80
SP	-15 ± 30	-25 ± 35	-17 ± 38	-	-19 ± 103	-24 ± 195	-54 ± 45	-8 ± 74	-1 ± 53	-3 ± 64	-80 ± 172	-40 ± 73	-87 ± 70	-28 ± 78	-38 ± 31	-38 ± 55	20 ± 76
Arepa	4 ± 103	-6 ± 104	2 ± 105	19 ± 103	-	-5 ± 219	-35 ± 108	11 ± 123	18 ± 112	16 ± 117	-61 ± 198	-21 ± 122	-68 ± 120	-9 ± 125	-19 ± 103	-19 ± 113	39 ± 124
INETI	9 ± 195	-1 ± 196	6 ± 197	24 ± 195	5 ± 219	-	-31 ± 198	15 ± 207	22 ± 200	21 ± 203	-57 ± 258	-17 ± 206	-64 ± 205	-5 ± 208	-15 ± 195	-14 ± 201	43 ± 208
BMS	40 ± 44	30 ± 48	37 ± 50	54 ± 45	35 ± 108	31 ± 198	-	46 ± 81	53 ± 62	52 ± 72	-26 ± 175	14 ± 80	-33 ± 77	26 ± 85	16 ± 45	16 ± 64	74 ± 83
BEV	-6 ± 74	-16 ± 76	-9 ± 77	8 ± 74	-11 ± 123	-15 ± 207	-46 ± 81	-	7 ± 86	5 ± 93	-72 ± 184	-32 ± 99	-79 ± 97	-20 ± 103	-30 ± 74	-30 ± 87	28 ± 102
METAS	-13 ± 53	-23 ± 56	-16 ± 58	1 ± 53	-18 ± 112	-22 ± 200	-53 ± 62	-7 ± 86	-	-2 ± 78	-79 ± 177	-39 ± 85	-86 ± 82	-27 ± 90	-37 ± 54	-37 ± 71	21 ± 88
CMI	-12 ± 64	-22 ± 67	-14 ± 68	3 ± 64	-16 ± 117	-21 ± 203	-52 ± 72	-5 ± 93	2 ± 78	-	-77 ± 181	-38 ± 92	-85 ± 90	-25 ± 96	-36 ± 64	-35 ± 79	23 ± 95
OMH	66 ± 172	56 ± 173	63 ± 173	80 ± 172	61 ± 198	57 ± 258	26 ± 175	72 ± 184	79 ± 177	77 ± 181	-	40 ± 184	-7 ± 183	52 ± 186	42 ± 172	42 ± 178	100 ± 185
JV	26 ± 73	16 ± 75	23 ± 76	40 ± 73	21 ± 122	17 ± 206	-14 ± 80	32 ± 99	39 ± 85	38 ± 92	-40 ± 184	-	-47 ± 96	12 ± 102	2 ± 73	2 ± 86	60 ± 101
CEM	73 ± 70	63 ± 72	70 ± 74	87 ± 70	68 ± 120	64 ± 205	33 ± 77	79 ± 97	86 ± 82	85 ± 90	7 ± 183	47 ± 96	-	59 ± 100	49 ± 70	49 ± 84	107 ± 99
GUM	13 ± 78	4 ± 80	11 ± 82	28 ± 78	9 ± 125	5 ± 208	-26 ± 85	20 ± 103	27 ± 90	25 ± 96	-52 ± 186	-12 ± 102	-59 ± 100	-	-10 ± 78	-10 ± 91	48 ± 105
MIKES	24 ± 31	14 ± 36	21 ± 39	38 ± 31	19 ± 103	15 ± 195	-16 ± 45	30 ± 74	37 ± 54	36 ± 64	-42 ± 172	-2 ± 73	-49 ± 70	10 ± 78	-	1 ± 55	58 ± 76
NMi/VSL	23 ± 55	13 ± 58	21 ± 60	38 ± 55	19 ± 113	14 ± 201	-16 ± 64	30 ± 87	37 ± 71	35 ± 79	-42 ± 178	-2 ± 86	-49 ± 84	10 ± 91	-1 ± 55	-	58 ± 89
UME	-34 ± 76	-44 ± 78	-37 ± 80	-20 ± 76	-39 ± 124	-43 ± 208	-74 ± 83	-28 ± 102	-21 ± 88	-23 ± 95	-100 ± 185	-60 ± 101	-107 ± 99	-48 ± 105	-58 ± 76	-58 ± 89	-

Table 8. Equivalence at 0.0 Lead (capacitive)

	PTB	NPL	IEN	SP	Arepa	INETI	BMS	BEV	METAS	CMI	OMH	JV	CEM	GUM	MIKES	NMi/VSL	UME
PTB	-	6 ± 34	-10 ± 37	-7 ± 26	23 ± 142	219 ± 482	-7 ± 35	-1 ± 221	-21 ± 50	60 ± 54	-35 ± 171	3 ± 72	-	-6 ± 77	14 ± 24	22 ± 171	5 ± 75
NPL	-6 ± 34	-	-15 ± 42	-13 ± 32	17 ± 143	213 ± 483	-12 ± 39	-6 ± 222	-27 ± 54	54 ± 57	-41 ± 172	-2 ± 75	-	-11 ± 79	8 ± 31	17 ± 172	-1 ± 77
IEN	10 ± 37	15 ± 42	-	2 ± 35	33 ± 144	228 ± 483	3 ± 42	9 ± 222	-11 ± 56	69 ± 59	-26 ± 173	13 ± 76	-	4 ± 81	24 ± 34	32 ± 173	15 ± 78
SP	7 ± 26	13 ± 32	-2 ± 35	-	31 ± 141	226 ± 482	1 ± 33	7 ± 221	-14 ± 49	67 ± 53	-28 ± 171	11 ± 71	-	2 ± 76	21 ± 22	30 ± 171	12 ± 74
Arepa	-23 ± 142	-17 ± 143	-33 ± 144	-31 ± 141	-	195 ± 502	-30 ± 143	-24 ± 261	-44 ± 147	37 ± 149	-58 ± 220	-20 ± 156	-	-29 ± 159	-9 ± 141	-1 ± 220	-18 ± 157
INETI	-219 ± 482	-213 ± 483	-228 ± 483	-226 ± 482	-195 ± 502	-	-225 ± 483	-219 ± 530	-240 ± 484	-159 ± 485	-254 ± 511	-215 ± 487	-	-224 ± 488	-205 ± 482	-196 ± 511	-214 ± 487
BMS	7 ± 35	12 ± 39	-3 ± 42	-1 ± 33	30 ± 143	225 ± 483	-	6 ± 222	-15 ± 54	66 ± 58	-29 ± 172	10 ± 75	-	1 ± 79	20 ± 31	29 ± 172	11 ± 77
BEV	1 ± 221	6 ± 222	-9 ± 222	-7 ± 221	24 ± 261	219 ± 530	-6 ± 222	-	-21 ± 225	60 ± 226	-35 ± 278	4 ± 231	-	-5 ± 232	14 ± 220	23 ± 278	5 ± 231
METAS	21 ± 50	27 ± 54	11 ± 56	14 ± 49	44 ± 147	240 ± 484	15 ± 54	21 ± 225	-	81 ± 68	-14 ± 176	25 ± 83	-	16 ± 88	35 ± 48	44 ± 176	26 ± 85
CMI	-60 ± 54	-54 ± 57	-69 ± 59	-67 ± 53	-37 ± 149	159 ± 485	-66 ± 58	-60 ± 226	-81 ± 68	-	-95 ± 177	-56 ± 86	-	-65 ± 90	-46 ± 52	-37 ± 177	-55 ± 88
OMH	35 ± 171	41 ± 172	26 ± 173	28 ± 171	58 ± 220	254 ± 511	29 ± 172	35 ± 278	14 ± 176	95 ± 177	-	39 ± 184	-	30 ± 186	49 ± 171	58 ± 241	40 ± 185
JV	-3 ± 72	2 ± 75	-13 ± 76	-11 ± 71	20 ± 156	215 ± 487	-10 ± 75	-4 ± 231	-25 ± 83	56 ± 86	-39 ± 184	-	-	-9 ± 102	10 ± 70	19 ± 184	1 ± 100
CEM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
GUM	6 ± 77	11 ± 79	-4 ± 81	-2 ± 76	29 ± 159	224 ± 488	-1 ± 79	5 ± 232	-16 ± 88	65 ± 90	-30 ± 186	9 ± 102	-	-	19 ± 75	28 ± 186	10 ± 103
MIKES	-14 ± 24	-8 ± 31	-24 ± 34	-21 ± 22	9 ± 141	205 ± 482	-20 ± 31	-14 ± 220	-35 ± 48	46 ± 52	-49 ± 171	-10 ± 70	-	-19 ± 75	-	9 ± 171	-9 ± 73
NMi/VSL	-22 ± 171	-17 ± 172	-32 ± 173	-30 ± 171	1 ± 220	196 ± 511	-29 ± 172	-23 ± 278	-44 ± 176	37 ± 177	-58 ± 241	-19 ± 184	-	-28 ± 186	-9 ± 171	-	-18 ± 185
UME	-5 ± 75	1 ± 77	-15 ± 78	-12 ± 74	18 ± 157	214 ± 487	-11 ± 77	-5 ± 231	-26 ± 85	55 ± 88	-40 ± 185	-1 ± 100	-	-10 ± 103	9 ± 73	18 ± 185	-

Table 9. Equivalence at 0.0 Lag (inductive)

	PTB	NPL	IEN	SP	Arepa	INETI	BMS	BEV	METAS	CMI	OMH	JV	CEM	GUM	MIKES	NMi/VSL	UME
PTB	-	-10 ± 34	-4 ± 37	-2 ± 27	-1 ± 142	-21 ± 296	-26 ± 35	-14 ± 221	8 ± 50	115 ± 54	22 ± 171	-1 ± 72	-	-16 ± 77	3 ± 24	-6 ± 171	26 ± 75
NPL	10 ± 34	-	6 ± 41	8 ± 32	9 ± 143	-10 ± 296	-16 ± 39	-4 ± 222	18 ± 54	125 ± 57	32 ± 172	10 ± 74	-	-5 ± 79	13 ± 30	4 ± 172	37 ± 77
IEN	4 ± 37	-6 ± 41	-	2 ± 35	3 ± 143	-16 ± 297	-22 ± 42	-10 ± 222	12 ± 56	119 ± 59	26 ± 173	4 ± 76	-	-11 ± 81	7 ± 34	-2 ± 173	31 ± 78
SP	2 ± 27	-8 ± 32	-2 ± 35	-	1 ± 141	-18 ± 295	-24 ± 32	-11 ± 221	10 ± 49	117 ± 53	24 ± 171	2 ± 71	-	-13 ± 76	5 ± 21	-4 ± 171	29 ± 74
Arepa	1 ± 142	-9 ± 143	-3 ± 143	-1 ± 141	-	-19 ± 327	-25 ± 143	-12 ± 261	9 ± 147	116 ± 149	23 ± 220	1 ± 156	-	-14 ± 159	4 ± 141	-5 ± 220	28 ± 157
INETI	21 ± 296	10 ± 296	16 ± 297	18 ± 295	19 ± 327	-	-6 ± 296	7 ± 368	28 ± 299	136 ± 299	43 ± 341	20 ± 303	-	5 ± 304	24 ± 295	14 ± 341	47 ± 304
BMS	26 ± 35	16 ± 39	22 ± 42	24 ± 32	25 ± 143	6 ± 296	-	12 ± 222	34 ± 54	141 ± 57	48 ± 172	26 ± 74	-	11 ± 79	29 ± 30	20 ± 172	53 ± 77
BEV	14 ± 221	4 ± 222	10 ± 222	11 ± 221	12 ± 261	-7 ± 368	-12 ± 222	-	21 ± 225	129 ± 226	36 ± 278	13 ± 231	-	-2 ± 232	17 ± 220	7 ± 278	40 ± 231
METAS	-8 ± 50	-18 ± 54	-12 ± 56	-10 ± 49	-9 ± 147	-28 ± 299	-34 ± 54	-21 ± 225	-	107 ± 68	14 ± 176	-8 ± 83	-	-23 ± 87	-5 ± 48	-14 ± 176	19 ± 85
CMI	-115 ± 54	-125 ± 57	-119 ± 59	-117 ± 53	-116 ± 149	-136 ± 299	-141 ± 57	-129 ± 226	-107 ± 68	-	-93 ± 177	-115 ± 85	-	-130 ± 90	-112 ± 52	-121 ± 177	-88 ± 87
OMH	-22 ± 171	-32 ± 172	-26 ± 173	-24 ± 171	-23 ± 220	-43 ± 341	-48 ± 172	-36 ± 278	-14 ± 176	93 ± 177	-	-22 ± 184	-	-37 ± 186	-19 ± 171	-28 ± 241	5 ± 185
JV	1 ± 72	-10 ± 74	-4 ± 76	-2 ± 71	-1 ± 156	-20 ± 303	-26 ± 74	-13 ± 231	8 ± 83	115 ± 85	22 ± 184	-	-	-15 ± 101	3 ± 70	-6 ± 184	27 ± 100
CEM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
GUM	16 ± 77	5 ± 79	11 ± 81	13 ± 76	14 ± 159	-5 ± 304	-11 ± 79	2 ± 232	23 ± 87	130 ± 90	37 ± 186	15 ± 101	-	-	19 ± 75	9 ± 186	42 ± 103
MIKES	-3 ± 24	-13 ± 30	-7 ± 34	-5 ± 21	-4 ± 141	-24 ± 295	-29 ± 30	-17 ± 220	5 ± 48	112 ± 52	19 ± 171	-3 ± 70	-	-19 ± 75	-	-9 ± 170	23 ± 73
NMi/VSL	6 ± 171	-4 ± 172	2 ± 173	4 ± 171	5 ± 220	-14 ± 341	-20 ± 172	-7 ± 278	14 ± 176	121 ± 177	28 ± 241	6 ± 184	-	-9 ± 186	9 ± 170	-	33 ± 185
UME	-26 ± 75	-37 ± 77	-31 ± 78	-29 ± 74	-28 ± 157	-47 ± 304	-53 ± 77	-40 ± 231	-19 ± 85	88 ± 87	-5 ± 185	-27 ± 100	-	-42 ± 103	-23 ± 73	-33 ± 185	-

Uncertainty budgets for each participant are given in the Appendix.

6. Conclusions

The EUROMET.EM-K5 Comparison of 50/60 Hz Power began in November 1996 and was completed in April 2001. Of the 17 NMIs that performed tests during the comparison, 17 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 85 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 uncertainties. In more general terms, most of the NMIs' measurements agreed with the reference values to within 25 µW/VA, which is about five times larger than the recognised state-of-the-art for sinusoidal power and about 40 times better than the best commercial measurements made for revenue purposes.

Nevertheless one or the other NMI may be willing to improve its capabilities for ac power measurements and its measurement uncertainties or has already done this.

At the end of this comparison some more European countries showed their interest in a participation in the measurements. It was decided to start a new comparison at the same measurement points and using the same kind of travelling standard. The pilot laboratory for this new EUROMET Project 687 is UME in Turkey.

7. References

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8. Acknowledgments

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Appendix A – Uncertainty Budgets

1. PTB

Nr.	Parameter	Powerfactor	Nominal Value	Relative Standarddeviation (10^{-6}) s_i (Category A)	u_i (Category B)	Comments
1	N_u	don' t care	110 V / 7 V = 15,714		3/√3 = 1,73	same figure for amplitude and phase uncertainty
2	N_i	"	5 A / 0,01 A = 500		3/√3 = 1,73	same figure for amplitude and phase uncertainty
3	R_b	"	700 Ω	0,3	1,8/√3 = 1,04	dc measurement
					2/√3 =1,16	estimated ac uncertainty, same value for amplitude and phase
4	R_Σ/R_N	"	280 Ω/20 Ω= 14	0,3	8,1/√3 = 4.68	uncertainty of dc ratio (used for covariance calculation, too)
	or R_Δ/R_N	"			3/√3 = 1,73	estimated ac uncertainty
						individual components:
5	U_Σ	cos phi = 1	1,045 V	0,3	0,5/√3 = 0,29	Standard cell (also used for covariance calculation at cos φ = 0)
	"	cos phi = 0,5	0,905 V		1/√3 = 0,58	Thermal convertor (" " ")
	"	cos phi = 0	0,740 V		1/√3 = 0,58	DVM-linearity (" " ")
	U_Δ	cos phi = 1	0,045 V		3/√3 = 1,73	DVM-stability
	"	cos phi = 0,5	0,524 V			
	"	cos phi = 0	0,740 V	0,5		stability of dc current source
					2,024	combined $U_{\Sigma/\Delta}$ uncertainty for variance calculation
					0,92	combined $U_{\Sigma/\Delta}$ uncertainty for covariance calculation at cos φ = 0
6	F	cos phi = 1 cos phi = 0,5 cos phi = 0	213,8 V^2 106,9 V^2 0		10,82 9,48 9,05	calculated from 4 and 5 and related to the apparent power
7	P	cos phi = 1 cos phi = 0,5 cos phi = 0	600 W 300 W 0		11,38 10,38 10,08	calculated from 1, 2, 3, and 6 and related to the apparent power

With the active power

$$P = \frac{N_u \cdot N_i}{4 \cdot R_b} \cdot F$$

with

$$F = \left\{ V_\Sigma{}^2 \cdot U_{\Sigma DC}{}^2 - V_\Delta{}^2 \cdot U_{\Delta DC}{}^2 \right\},$$

$$V_\Sigma = \frac{R_\Sigma}{R_N}, \qquad V_\Delta = \frac{R_\Delta}{R_N}$$

2. NPL

Uncertainty Component	*Amplitude (μW/VA)*	*Phase (μW/VA)*
Sampling ADC Heads	10	3
IVD	1	1
CT	11	12
Resistor	4	2
Total NPL System	15	12

Power Factor	*NPL System (μW/VA)*	*DVM (μW/VA)*	*Type A (μW/VA)*	*Total (k=1) (μW/VA)*
UPF	15	4	2	**16**
0.5	13	4	2	**14**
ZPF	12	4	2	**14**

3. IEN

Uncertainty components	Type		Amplitude [10^{-6}]		Phase [µrad]
Voltage at 5 V	B	ru_{U5V}	6.7		-
Ratio 120 V- 5 V	B	ru_{rU}	2.1	$u_{\varphi rU}$	2.1
Ratio 5 V - 0.1 V	B	ru_{rI}	2.2	$u_{\varphi ri}$	2.2
AC resistor	B	ru_R	3		
Ratio of the current transformer	B	ru_{rappl}	5		
Current to voltage converter	B			$u_{\varphi rappl}$	15
Uncertainty of the power measurement (k=1)					
Power factor 1			14.9		
Power factor 0.5			15.2		
Power factor 0			15.3		

Determination of the total uncertainties

		Uncertainties (10^{-6})				
	Type	1.0	0.5 cap.	0 cap.	0.5 ind.	0 ind.
Uncertainties of the calibration	B	14.9	15.2	15.3	15.2	15.3
Stability	B	3	2.5	2	2.5	2
Comparison	A	0.5	0.3	0.4	0.4	0.4
Rounded total uncertainties		**15.2**	**15.4**	**15.4**	**15.4**	**15.4**

4. SP

Source of uncertainty at power factor = 1.0	Standard uncertainty (µW/W)	probability distribution	Sensitivity coefficient	Contribution to the std uncert (µW/W)
DSWM voltage, traceability & stability	10	normal	1	10
DSWM current, traceability & stability	10	normal	1	10
DSWM phase, traceability & stability	7	normal	0	0
Measurement setup	3	rectangular	1	3
Std uncert of measurement	2	normal	1	2
Standard uncertainty, k=1				**14,6**

Source of uncertainty at power factor = 0,5	Standard uncertainty (µW/W)	probability distribution	Sensitivity coefficient	Contribution to the std uncert (µW/W)
DSWM voltage traceability & stability	10	normal	0,5	5
DSWM current traceability & stability	10	normal	0,5	5
DSWM phase traceability & stability	7	normal	0,87	6
Measurement	3	rectangular	1	3
Std uncert of measurement	2	normal	1	2
Standard uncertainty, k=1				**9,9**

Source of uncertainty at power factor = 0	Standard uncertainty (µW/W)	probability distribution	Sensitivity coefficient	Contribution to the std uncert (µW/W)
DSWM voltage traceability & stability	10	Normal	0	0
DSWM current traceability & stability	10	Normal	0	0
DSWM phase traceability & stability	7	Normal	1	7
Measurement	3	rectangular	1	3
Std uncert of measurement	2	Normal	1	2
Standard uncertainty, k=1				**7,9**

The expanded uncertainty at power factor 1 is 30 µW/W relative the apparent power
The expanded uncertainty at power factor 0,5 is 20 µW/W relative the apparent power
The expanded uncertainty at power factor 0 is 16 µW/W relative the apparent power

The reported expanded uncertainty of measurement is stated as a standard uncertainty of measurement multiplied by the coverage factor k=2, which for a normal distribution corresponds to a coverage probability of approximately 95 %.

5. Arepa

Uncertainty budget for 120 V / 5 A, $\varphi = 0°$ (PF = 1):

120 V / 5 A, $\varphi = 0°$					
Contribution u_i	**Type**	**Value**	**Distribution**	**Standard dev.**	ν_{eff}
AC voltage	B	16 ppm	normal	16 ppm	∞
AC current	B	43ppm	normal	43 ppm	∞
Stability of voltage	B	3 ppm	uniform	1.8 ppm	∞
Stability of current	B	10 ppm	uniform	5.8 ppm	∞
Phaseangle	B	0.005° ~ 0.004 ppm	uniform	0.003 ppm	∞
Standard deviation of mean	A	1.1 ppm	normal	1.1 ppm	9
DC Output voltage	B	2 ppm	normal	2 ppm	∞
Total uncertainty u				**47 ppm**	$>10^7$
Total uncertainty at 95%, k = 2				**94 ppm**	

Uncertainty budget for 120 V / 5 A, $\varphi = 60°$ (PF = 0,5 i):

120 V / 5 A, $\varphi = 60°$		relative to 300 W			
Contribution u_i	**Type**	**Value**	**Distribution**	**Standard dev.**	ν_{eff}
AC voltage	B	16 ppm	normal	16 ppm	∞
AC current	B	43 ppm	normal	43 ppm	∞
Stability of voltage	B	3 ppm	uniform	1.8 ppm	∞
Stability of current	B	10 ppm	uniform	5.8 ppm	∞
Phaseangle	B	0.005° ~ 152 ppm	uniform	88 ppm	∞
Standard deviation of mean	A	3.7 ppm	normal	3.7 ppm	9
DC Output voltage	B	2.5 ppm	normal	2.5 ppm	∞
Total uncertainty u				**100 ppm**	$>10^6$
Total uncertainty at 95%, k = 2		**relative to 600 W**		**100 ppm**	

Uncertainty budget for 120 V / 5 A, φ = -60° (PF = 0,5 c):

120 V / 5 A, φ = -60°		**relative to 300 W**			
Contribution u_i	**Type**	**Value**	**Distribution**	**Standard dev.**	ν_{eff}
AC voltage	B	16 ppm	normal	16 ppm	∞
AC current	B	43 ppm	normal	43 ppm	∞
Stability of voltage	B	3 ppm	uniform	1.8 ppm	∞
Stability of current	B	10 ppm	uniform	5.8 ppm	∞
Phaseangle	B	0.005° ~ 152 ppm	uniform	88 ppm	∞
Standard deviation of mean	A	9.6 ppm	normal	9.6 ppm	9
DC Output voltage	B	2.5 ppm	normal	2.5 ppm	∞
Total Uncertainty u				**100 ppm**	$>10^5$
Total uncertainty at 95%,	**k = 2**	**relative to 600 W**		**100 ppm**	

Uncertainty budget for 120 V / 5 A, φ = 90° (PF = 0 i):

120 V / 5 A, φ = 90°		**relative to 600 W**			
Contribution u_i	**Type**	**Value**	**Distribution**	**Standard dev.**	ν_{eff}
AC voltage	B	16 ppm	normal	16 ppm	∞
AC current	B	43 ppm	normal	43 ppm	∞
Stability of voltage	B	3 ppm	uniform	1.8 ppm	∞
Stability of current	B	10 ppm	uniform	5.8 ppm	∞
Phaseangle	B	0.005° ~ 89 ppm	uniform	52 ppm	∞
Standard deviation of mean	A	42 µV ~ 4.2 ppm	normal	4.2 ppm	9
DC Output voltage	B	200 nV ~ 0.02 ppm	normal	0.02 ppm	∞
Total uncertainty u				**70 ppm**	$>10^5$
Total uncertainty at 95%,	**k = 2**	**relative to 600 W**		**140 ppm**	

Uncertainty budget for 120 V / 5 A, φ = -90° (PF = 0 c):

120 V / 5 A, φ = -90°		**relative to 600 W**			
Contribution u_i	**Type**	**Value**	**Distribution**	**Standard dev.**	ν_{eff}
AC voltage	B	16 ppm	normal	16 ppm	∞
AC current	B	43 ppm	normal	43 ppm	∞
Stability of voltage	B	3 ppm	uniform	1.8 ppm	∞
Stability of current	B	10 ppm	uniform	5.8 ppm	∞
Phaseangle	B	0.005° ~ 89 ppm	uniform	52 ppm	∞
Standard deviation of mean	A	45 µV ~ 4.5 ppm	normal	4.5 ppm	9
DC Output voltage	B	200 nV ~ 0.02 ppm	normal	0.02 ppm	∞
Total uncertainty u				**70 ppm**	$>10^5$
Total uncertainty at 95%,	**k = 2**	**relative to 600 W**		**140 ppm**	

6. INETI

Uncertainty budget for measurements at power factor 1

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ in 10^{-6}	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$ in 10^{-6}
P_{C1-2}/S	0,99946615	6,40	normal	1,0	6,40
P_{7200}/S	0,99951264	3,68	normal	-1,0	-3,68
$\Delta P_{7200}/S$	-2,70E-06	30,00	normal	1,0	30,00
$\Delta P_{Voltm.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Temp.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Source}/S$	0	17,32	rectangular	1,0	17,32
$Y=\Delta P_{C1-2}/S$	-4,92E-05				**35,65**

Uncertainty budget for measurements at power factor 0,5c

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ in 10^{-6}	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$ in 10^{-6}
P_{C1-2}/S	0,49628113	38,66	normal	1,0	38,66
P_{7200}/S	0,49634251	40,76	normal	-1,0	-40,76
$\Delta P_{7200}/S$	3,57E-05	30,00	normal	1,0	30,00
$\Delta P_{Voltm.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Temp.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Source}/S$	0	17,32	rectangular	1,0	17,32
$Y=\Delta P_{C1-2}/S$	-2,57E-05				**66,13**

Uncertainty budget for measurements at power factor 0,5i

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ in 10^{-6}	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$ in 10^{-6}
$P_{C1\text{-}2}/S$	0,50204075	54,07	normal	1,0	54,07
P_{7200}/S	0,50204595	55,81	normal	-1,0	-55,81
$\Delta P_{7200}/S$	-2,50E-05	30,00	normal	1,0	30,00
$\Delta P_{Voltm.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Temp.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Source}/S$	0	17,32	rectangular	1,0	17,32
$Y=\Delta P_{C1\text{-}2}/S$	-3,02E-05				**85,18**

Uncertainty budget for measurements at power factor 0c

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ in 10^{-6}	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$ in 10^{-6}
$P_{C1\text{-}2}/S$	0,00336240	151,65	normal	1,0	151,65
P_{7200}/S	0,00358275	142,98	normal	-1,0	-142,98
$\Delta P_{7200}/S$	1,20E-05	30,00	normal	1,0	30,00
$\Delta P_{Voltm.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Temp.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Source}/S$	0	17,32	rectangular	1,0	17,32
$Y=\Delta P_{C1\text{-}2}/S$	-2,08E-04				**211,32**

Uncertainty budget for measurements at power factor 0i

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ in 10^{-6}	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$ in 10^{-6}
$P_{C1\text{-}2}/S$	0,00752665	95,56	normal	1,0	95,56
P_{7200}/S	0,00751682	80,27	normal	-1,0	-80,27
$\Delta P_{7200}/S$	-6,00E-06	30,00	normal	1,0	30,00
$\Delta P_{Voltm.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Temp.}/S$	0	2,89	rectangular	1,0	2,89
$\Delta P_{Source}/S$	0	17,32	rectangular	1,0	17,32
$Y=\Delta P_{C1\text{-}2}/S$	3,82E-06				**129,58**

7. BMS

Source of uncertainty	Probability distribution	Power factor		
		1,0 (µVA/VA)	**0,5** (µVA/VA)	**0,0** (µVA/VA)
Calibration of reference wattmeter	normal	7,3	7,3	7,3
Frequency dependence	rectangular	2,0	2,0	2,0
Uncorrected drift since last calibration	rectangular	30,0	30,0	20,0
Multimeter 1	rectangular	2,0	4,0	1,0
Multimeter 2	rectangular	2,0	4,0	1,0
Type B uncertainty		**18,9**	**19,1**	**13,7**

8. BEV

Measurement of active power

Voltage (V)	Current (A)	cos φ	Dev. from nominal F relative *)	Uncertainty U relative *)
120	5	1	-104,3E-06	70E-06
120	5	0,5 ind.	-45,1E-06	70E-06
120	5	0,5 kap.	-34,1E-6	70E-06
120	5	0 ind.	-2,9E-06	220E-06
120	5	0 kap.	10,5E-06	220E-06

*) relative deviation from nominal referred to the apparent power: F = (P_{C1-2} - P_{K2004})/600 VA
relative uncertainty of measurement referred to the apparent power (k=2)

9. METAS

The uncertainty components are given in parts per million (ppm) of apparent power for different power factors (PF).

Measurement parameters: U=120 V, I=5 A, f=52.5 Hz

Input quantity	Evalua-tion Type	Distri-bution	u-stand (ppm)	Uncertainty contributions (ppm)			
				PF=1.0	PF=0.5	PF=0.2	PF=0.0
AC-Voltage	A	normal	12.5	25.0	12.5	5.0	0.0
Reference resistor	B	normal	10.0	10.0	5.0	2.0	0.0
Reference capacitor; phase defect	B	normal	22.5	0.0	19.5	22.0	22.5
Voltage measurement							
Calibration DVM	A	normal	1.0	1.0	1.0	1.0	1.0
Offset voltage	B	rectang.	2.2	2.2	2.2	2.2	2.2
DUT, Set-up							
Reproducibility	A	normal	2.0	2.0	2.0	2.0	2.0
Current comparator							
Ratio	B	rectang.	1.0	1.0	1.0	1.0	1.0
Feedback	B	rectang.	2.5	2.5	2.5	2.5	2.5
Combined Standard uncertainty				**27.2**	**24.0**	**23.1**	**22.9**
Expanded uncertainty (k=2)				**54.5**	**48.1**	**46.1**	**45.8**

10. CMI

Errors of power converter HEG C1-2, ser.no.46043 at 120 V, 5 A and 53 Hz	
Nominal Power Factor	Δ
1	(-0,004 ± 0,007) %
0,5i	(-0,005 ± 0,006) %
0,5k	(-0,0035 ± 0,006) %
0i	(-0,013 ± 0,005) %
0k	(-0,005 ± 0,005) %

The relative deviations from nominal and the relative uncertainties of measurement are referred to the nominal apparent power.
All reported uncertainties were calculated as the standard uncertainty multiplied by the coverage factor k=2, which corresponds to coverage probability of approximately 95 %.

11. OMH

Estimation of the uncertainty for comparison of the Power Converter

Uncertainties of the measurements were determined according to the "Guide to the Expression of Uncertainty Measurement" from the type A and B component.

The Uncertainties are at a confidence level of not less than 95 %, coverage factor is k=2. The values of Uncertainties are given in the following Table.

Uncertainty estimation of Power measurements:

	type A	type B
ZERA COM 303-1	150 ppm	70 ppm
DATRON Multimeter	20 ppm	20 ppm

The combined uncertainty of measurement at all power factors is 170 ppm (k=2).

12. JV

Results

Measuring point	ε_{PTB} relatively to nominal power	Type A rel. to nominal power 1σ	Standard measurement uncertainty relatively to nominal power (k=2)
120V / 5A cos φ = 1	-18	2	±69
120V / 5A cos φ = 0.5 ind.	-12	3	±69
120V / 5A cos φ = 0.01 ind.	-13	3	±69
120V / 5A cos φ = 0.5 cap.	-2.1	3	±69
120V / 5A cos φ = 0.01 cap.	6.3	1	±69
120V Current in open	-6.8	3	±69
Voltage in shorted 5A	7.5	3	±69
Voltage in shorted Current in open	-2.1	3	±69

13. CEM

The Type A uncertainty of the measurement results has to be combined with the uncertainty related with the calibration of the thermal standard. In the following Table the components of this uncertainty are detailed:

Component	**Type**	**Value (*10 $^{-6}$)**
DC voltage reference	B	0.5
DC reversal	B	1
Std. dev in 6 Vdc measurements	A	1
Std. dev in 6 Vac measurements	A	1
TVC reference	B	15
Std. dev in 120 Vac measurements	A	2
Ref. TCC	B	20
Current build up	A	15
DC current reference	B	15
Combined	A+B	33

Combining the type A uncertainty of all three measurements with the uncertainty due to thermal wattmeter results, for the ratio:

Phase Shift (degrees)	Uncertainty (k = 1)	Uncertainty (k = 2)
0º	33×10^{-6}	66×10^{-6}
-60º	33×10^{-6}	66×10^{-6}
60º	33×10^{-6}	66×10^{-6}

14. GUM

Uncertainty budget (δ_C) (in E-6):

PF = 1

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
δ_K	-84,4	30,0	normal	1,0	30,0
$\Delta\delta_{KT}$	0,0	21,7	rectangular	1,0	21,7
δ_i	98,5	0,6	normal	1,0	0,6
$\Delta\delta_{CT}$	0,0	5,8	rectangular	1,0	5,8
δ_{f_V}	-40,3	4,6	normal	1,0	4,6
δ_C	-26,2				37,8

PF=0,5 capacitive

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
δ_K	-33,6	30,0	normal	1,0	30,0
$\Delta\delta_{KT}$	0,0	21,7	rectangular	1,0	21,7
δ_i	44,9	0,5	normal	1,0	0,5
$\Delta\delta_{CT}$	0,0	3,5	rectangular	1,0	3,5
δ_{f_V}	-20,3	2,4	normal	1,0	2,4
δ_C	-9,0				37,3

PF=0,5 inductive

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
δ_K	-62,3	30,0	normal	1,0	30,0
$\Delta\delta_{KT}$	0,0	21,7	rectangular	1,0	21,7
δ_i	60,7	0,4	normal	1,0	0,4
$\Delta\delta_{CT}$	0,0	3,5	rectangular	1,0	3,5
δ_{f_V}	-21,0	2,4	normal	1,0	2,4
δ_C	-22,6				37,3

PF=0,01 capacitive

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
δ_K	3,6	30,0	normal	1,0	30,0
$\Delta\delta_{KT}$	0,0	21,7	rectangular	1,0	21,7
δ_i	8,8	0,4	normal	1,0	0,4
$\Delta\delta_{CT}$	0,0	1,2	rectangular	1,0	1,2
δ_{f_V}	3,1	2,3	normal	1,0	2,3
δ_C	15,5				37,1

PF=0,01 inductive

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
δ_K	-13,7	30,0	normal	1,0	30,0
$\Delta\delta_{KT}$	0,0	21,7	rectangular	1,0	21,7
δ_i	20,7	0,4	normal	1,0	0,4
$\Delta\delta_{CT}$	0,0	1,2	rectangular	1,0	1,2
δ_{f_V}	-0,1	2,3	normal	1,0	2,3
δ_C	6,9				37,1

15. VTT/MIKES

Power Converter HEG C1-2 (S/N 46043) Results. The uncertainty is presented as expanded uncertainty according to EA-4/Q2 publication.

Power factor [-1		Phase angle [rad]	Applied Power [W]	Measured Voltage M	C1-2 Error [uV]	Calibration uncertainty [uV]
0.000580	cap	-1.571377	-0.3252	-0.005444	-25	116
0.499483	cap	-1.047794	299.7796	4.996243	-84	200
1 .000000		-0.000634	600.1260	10.002015	-85	344
0.500486	ind	1 .046636	300.3410	5.005609	-74	200
0.000583	ind	1.570214	0.3267	0.005431	-14	116

16. NMi/VSL

Uncertainty Budget for NMi/VSL-Measurements:

Measuring Angle in °			**0**	**60 i**	**60 c**	**90 i**	**90 c**
REFERENCE WATTMETER		**Nom. value**					
Voltage							
Sampling error	3 ppm	0	3	3	3	3	3
DC-calibration	1 ppm	1	1	1	1	1	1
Transformer ratio	1 ppm	150	1	1	1	1	1
Transformer angle	0.0005 degrees	0	0	15	15	50	50
Current							
Sampling error	3 ppm	0	3	3	3	3	3
DC-calibration	1 ppm	1	1	1	1	1	1
Transformer ratio	1 ppm	500	1	1	1	1	1
Transformer angle	0.0005 degrees	0	0	15	15	50	50
Shunt Value	1 ppm	100					
Shunt angle	0.0005 degrees	0	0	15	15	50	50
Voltage and Current							
Timing differences	20 ns	0	0	11	11	50	50
Bandwith differences	10%	0					
DUT WATTMETER							
DC-calibration	1 ppm FS	10	1	2	2		
Meter error	10 uV						
Total error (k=1)			5	24	24	87	87
Expanded Uncertainty (k=2)			10	49	49	173	173

17. UME

All the uncertainties were calculated according to ISO “Guide to the Expression of Uncertainty in Measurement” for a coverage factor k=2. The contributions to the uncertainty are:

1) PF=1 and PF=0.5i/c

SOURCE OF UNCERTAINTY	10^{-6}
Calibration Uncertainty of K2004 given by PTB	60
DCV Reading Uncertainty of Multimeter	6
Stability of Power Source	40
Temperature	5
Total Phase Angle Uncertainty	**72.53**

2) PF=0i/c

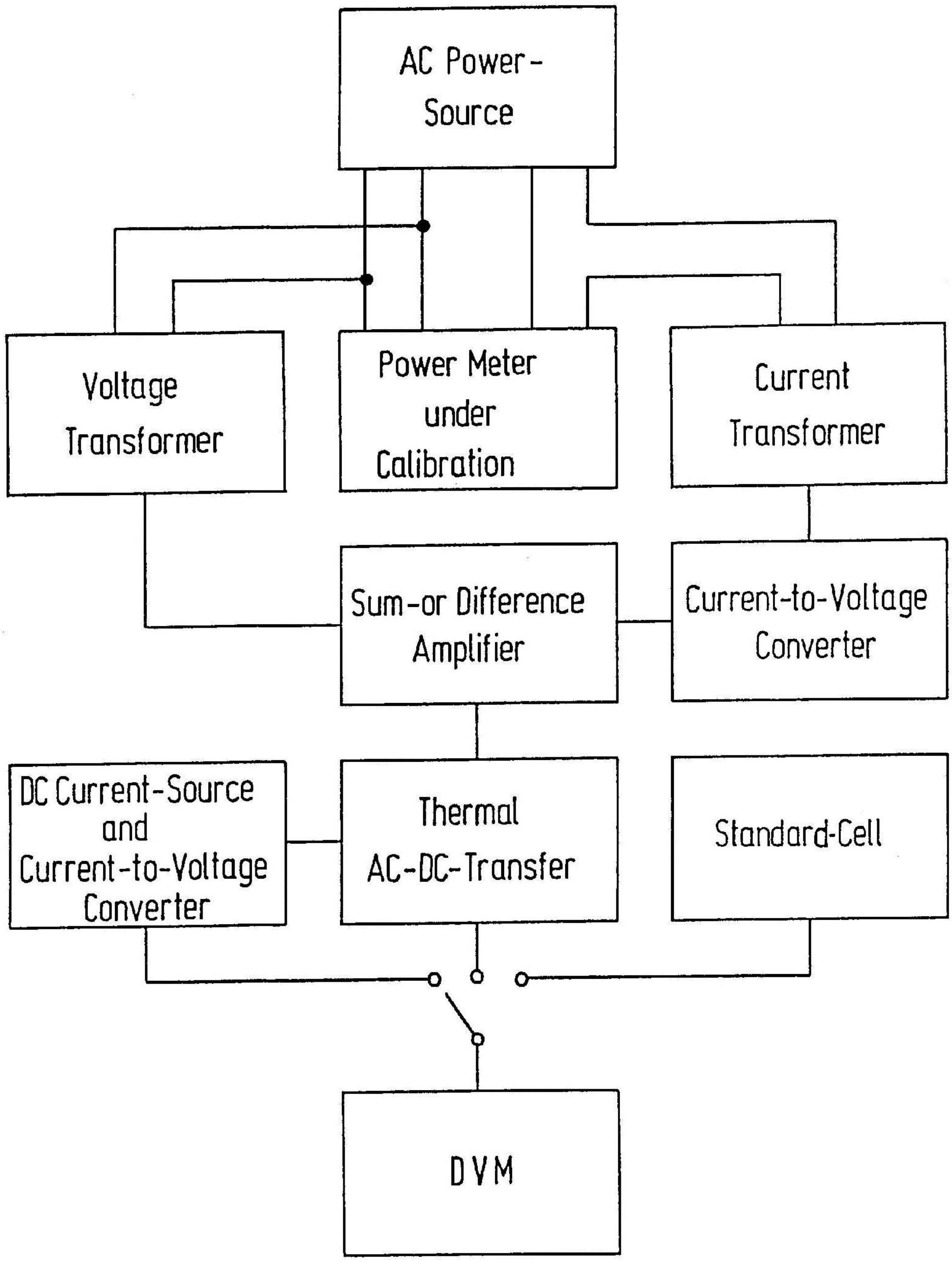
SOURCE OF UNCERTAINTY	10^{-6}	TYPE
Phase Angle Uncertainty of Mutual Inductor	25	Type B
Phase Angle Uncertainty of Inductive Voltage Divider	15	Type B
Uncertainty of Null Detector	25	Type B
Phase Angle Stability of Power Source	60	Type A
DCV Reading Uncertainty of Multimeter	6	Type A
Total Phase Angle Uncertainty	**71.49**	**-**

Appendix B – Measuring systems of participants

1. PTB

The configuration of the PTB equipment is shown in Fig. 1.1. This system is capable of making calibrations of AC voltage, current, and power. Instruments to be calibrated are connected to the system in the usual manner with voltage circuits in parallel and current circuits in series. The AC power source enables two fixed settings of current amplitudes (1 A and 5 A), and two fixed settings of voltage amplitude (120V and 240 V), phase angle between voltage and current (-90°...0°...+90°), and operating frequency (45 Hz to 65 Hz). The calibration system uses an AC-DC transfer principle based on thermal methods. The input to the calibration system consists of two-stage matching transformers for voltage and current. The secondary current of the current transformer is converted to a voltage by means of a burden resistor of well-known value. Sum and difference amplifiers combine the input signals u_u and u_i to
$u_\Sigma = (u_u + u_i)$ and $u_\Delta = (u_u - u_i)$, respectively. These sum and difference signals are consecutively applied to the thermal AC-DC transfer unit (multijunction thermal converter) and compared to equivalent DC currents, which are measured by means of a standard resistor and a high resolution digital voltmeter (DVM). This DVM also monitors the output voltages of the thermal converter at both AC and DC input signals and is itself periodically calibrated against a standard cell. Switching between these different voltage sources and adjustment of the DC current source to the equivalent DC current is accomplished by means of a computer, which also takes the readings from the instrument under calibration (if available) and finally provides a printout of the results. This calibration system involving thermal methods may be used at any power factor, including zero.

Fig 1.1 Schematic diagram of the PTB measuring system.



2. NPL

Measurements were made using the NPL Mk.III Digital Sampling Wattmeter (DSWM). The basis of this Instrument is given in the paper:
Clarke F J J & Stockton J R: "Principles and theory of Wattmeters operating on the basis of regularly spaced samplepairs", J.Phys.E:Sci.Instrum., Vol.15, 645-652, 1982

The DSWM system consists of a voltage channel and the current channel. Each channel has an NPL built analogue to digital converter (ADC) which is used to digitise the respective voltage and current waveforms. The ADCs are battery operated and computer data is transfered using fibre optic links in order to ensure that the ADCs are isolated.

The voltage channel was driven by a Fluke 5700A calibrator set to 120 V rms output voltage, and the current channel was driven by a second Fluke 5700A calibrator and an associated 5220A transconductance amplifier to give a current of 5A rms at 53 Hz.

The phase of the two channels was set to the required nominal values using a controller of NPL design. This device provides the required phase settings by generation of two suitably phase shifted square waves which were applied to the phase lock inputs of the two Fluke calibrators.

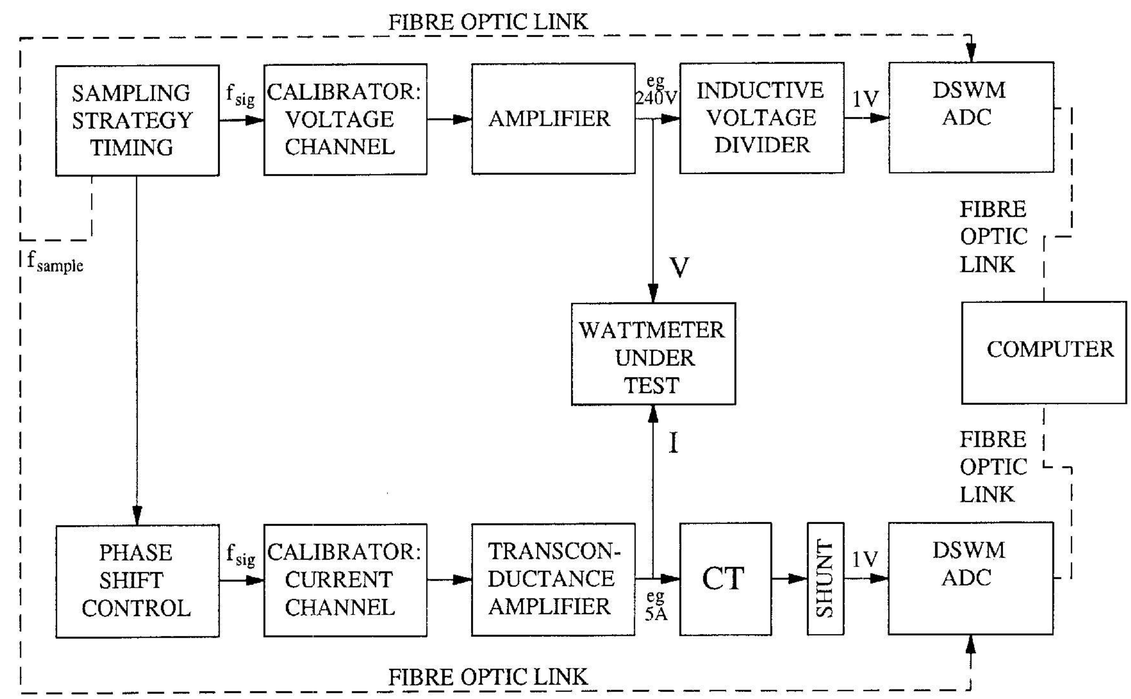


Fig 2.1 Schematic diagram of the NPL measuring system.

3. IEN

The measurement is based on a sampling method already experimented at IEN for the measurements of ac voltages at low frequency.

The whole system, whose basic circuit is represented in Fig. 3.1, consists of a power source, the PWC (C1-2), whose output is read by the voltmeter V (HP mod. 3458A) and the IEN System for power measurement. The whole system is controlled by a computer by means of a IEEE-488 interface.

The power source is a two-phase generator (Clarke-Hess mod. 5500), whose output voltages can be regulated in amplitude from 0.1 V to 120 V and in phase difference from 0° to 360°, in steps of 0.001°. One of the two outputs of this generator produces the voltage that supplies in parallel both the voltage input of the PWC and of the IEN measurement system. The other output is connected to a transconductance amplifier (J. Fluke mod. 5220A) followed by a transformer (TR) to generate the current, supplied in series to the same measurement systems.

The IEN measurement system consists of two identical precision voltmeters (Hewlett Packard mod. 3458A) operating as integrating analog to digital converters (IADC). The voltage signal is acquired directly by one of the voltmeters, while the current is acquired by the other one through an additional current to voltage converter (CVC). This converter consists of a precision 1 Ωanti-inductive resistor (Tinsley mod. 5685) connected to a double stage current transformer in a coaxial arrangement.

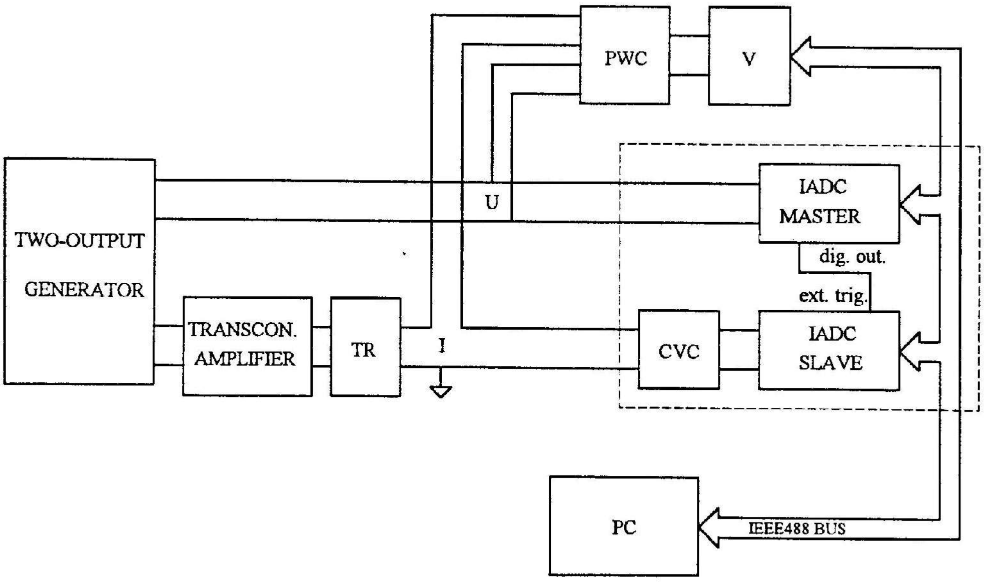


Fig 3.1 Schematic diagram of the IEN measuring system.

4. SP

The measuring principle of the DSWM is the equally-spaced simultaneous sampling of voltage and current during an exact number of periods. From a set of samples the total power is calculated by discrete integration. From the set of samples it is also possible to determine the magnitude and phase angle of each harmonic of the power by using discrete Fourier transform. The DSWM is composed of two sampling DVMs, an inductive voltage divider (IVD), coaxial shunts and a PC for control and data processing. The measured voltage is divided by the IVD to 8V and the output of the current shunt is 0,8V.

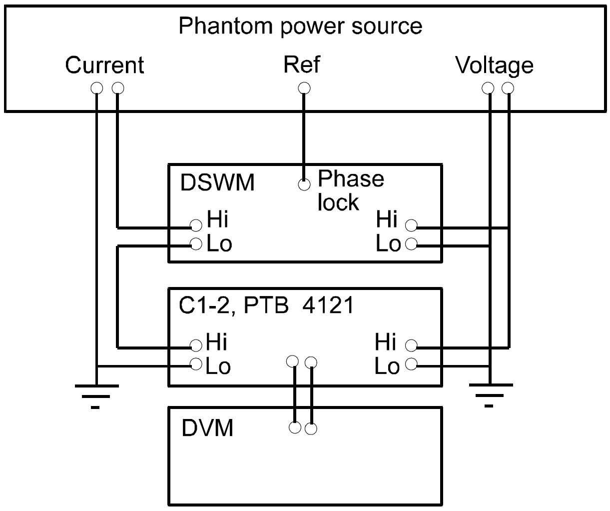


Fig 4.1 Schematic diagram of the SP measuring system.

5. Arepa

The basic measurement set-up used by Arepa is shown schematically in Fig. 5.1.

A Fluke 5500A calibrator was used as the generator of both AC voltage and AC current at the required power factors. During the measurements the phase angle was measured with an A V Power SD 1000 phasemeter. The DC output voltage of the Cl-2 Power Converter and the reference voltage was measured by a Datron 1281 digital multimeter.

Prior to these measurements the Fluke 5500A was calibrated repeatedly at 120 V, 53 Hz and 5 A, 53 Hz against a Fluke 792A AC-DC transfer standard, using a Fluke A40A-10A shunt for the current calibration. In addition to this the output of the Fluke 5500A calibrator was frequently monitored by a HEG K2005 comparator in order to get an estimation of the stability of the output. The phasemeter was calibrated using a homemade RC circuit.

The Fluke 792A and the Fluke A40A current shunt are traceable to PTB, whereas the measurements of the resistance and capacitance of the RC circuit are traceable to NPL.

The current shunt shown in Fig. 5.1 is necessary since the phasemeter requires two voltage inputs . Measurements without the shunt and the phasemeter were also conducted, in order to determine any influence on the phaseangle, but no significant difference in the output voltage of the CI-2 was detected.

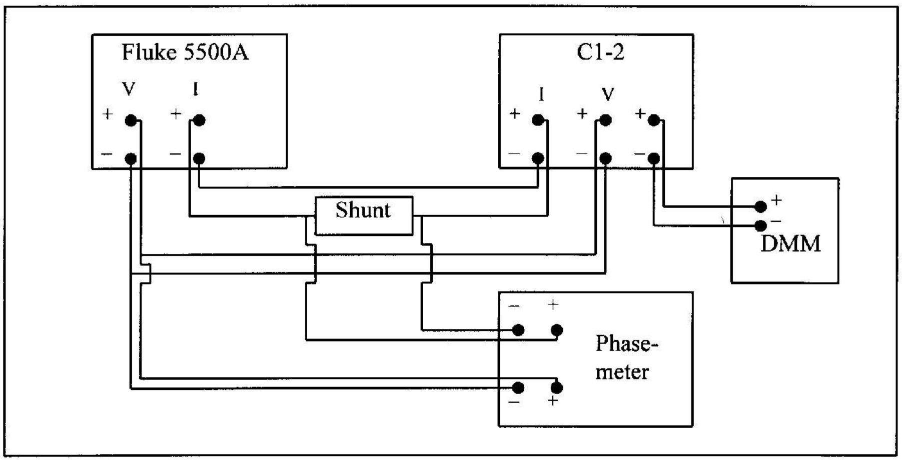
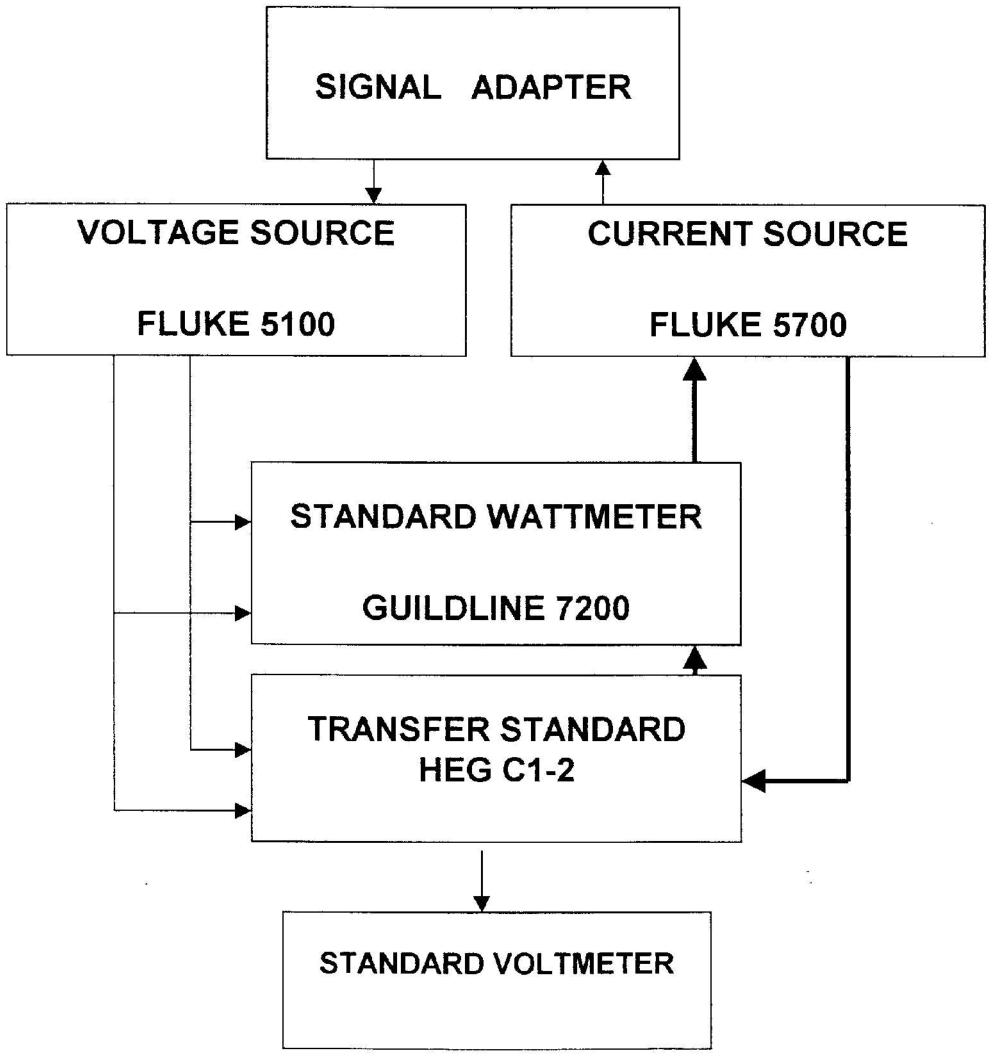


Fig 5.1 Schematic diagram of the Arepa measuring system.

6. INETI

At INETI, the C1-2 power converter was compared to a Guildline 7200 standard wattmeter, which is used as the national power standard. Both were supplied by a Fluke 5100 voltage source and a Fluke 5700 current source, the phase angle between voltage and current was adjusted by using a signal adapter. A standard voltmeter was used to measure the C1-2 output voltage.
Fig 6.1 Schematic diagram of the INETI measuring system.



7. BMS

During this comparison, the decision has been taken to make mainly the work with an automatic Calibration System based on the following instruments (see Fig 7.1):

- one Digital Phase Standard ranging from 1 Hz to 200 kHz for the frequency and from 50 mV to 120 V for both voltage outputs. The displayed phase angle resolution is 0.001° in the same ranges (Clarke-Hess model 5500-2).
- one Precision Current Source fitted with the 5 A and 0,5 A ranges and operating easily from 1 Hz to 10 kHz (Clarke-Hess model 5050).
- one Watt Converter(HEG Cl-1) or one Watt Transducer(MIL 2010M).
- two Multimeters(HP 3458A).
- one Instrument Controller (HP R/332).

The total harmonic distortion at 53 Hz of the reference output of the Digital Phase Standard at the 120 V level was found less than 0,02 % and less than 0,04 % for the Precision Current Source at the 5 A level.

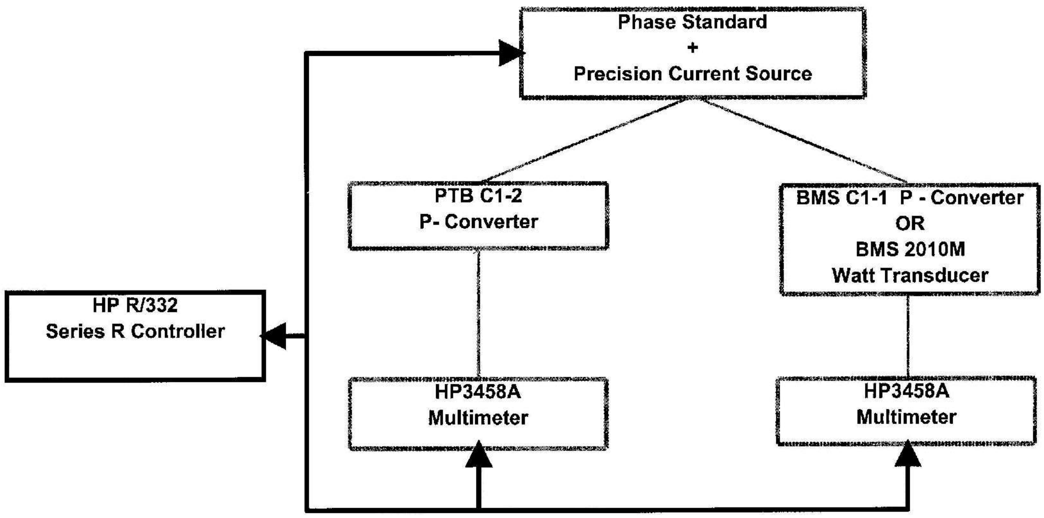


Fig 7.1 Schematic diagram of the BMS measuring system.

8. BEV

The C1-2 Power Converter was calibrated by comparison with Austrian standards of the BEV. The national power standard was a Thermal Comparator K2004 from the manufacturer HEG, the power was supplied by a combined voltage and current source SWE 104-1.2 made by ZERA, and the C1-2 output voltage was measured using a DATRON 1281 as DC voltmeter.

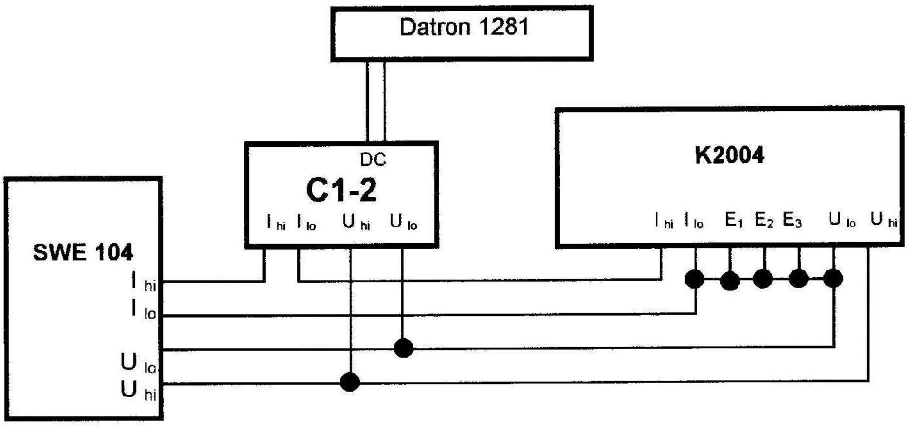


Fig 8.1 Schematic diagram of the BEV measuring system.

9. METAS

The power converter C1-2 under test was directly compared with the power standard of the METAS. The measurement set-up is shown in Fig. 9.1. It is based on a current comparator which compares the current in the power converter under test with currents derived from the test voltage through a reference resistor and a reference capacitor. The current comparator is maintained in balance by a feedback circuit to the current source. The test voltage for both the power meter under test and the power reference Standard is derived from a static AC voltage source.

A HP3458 digital multimeter was used to measure the output voltage of the C1-2 power converter.

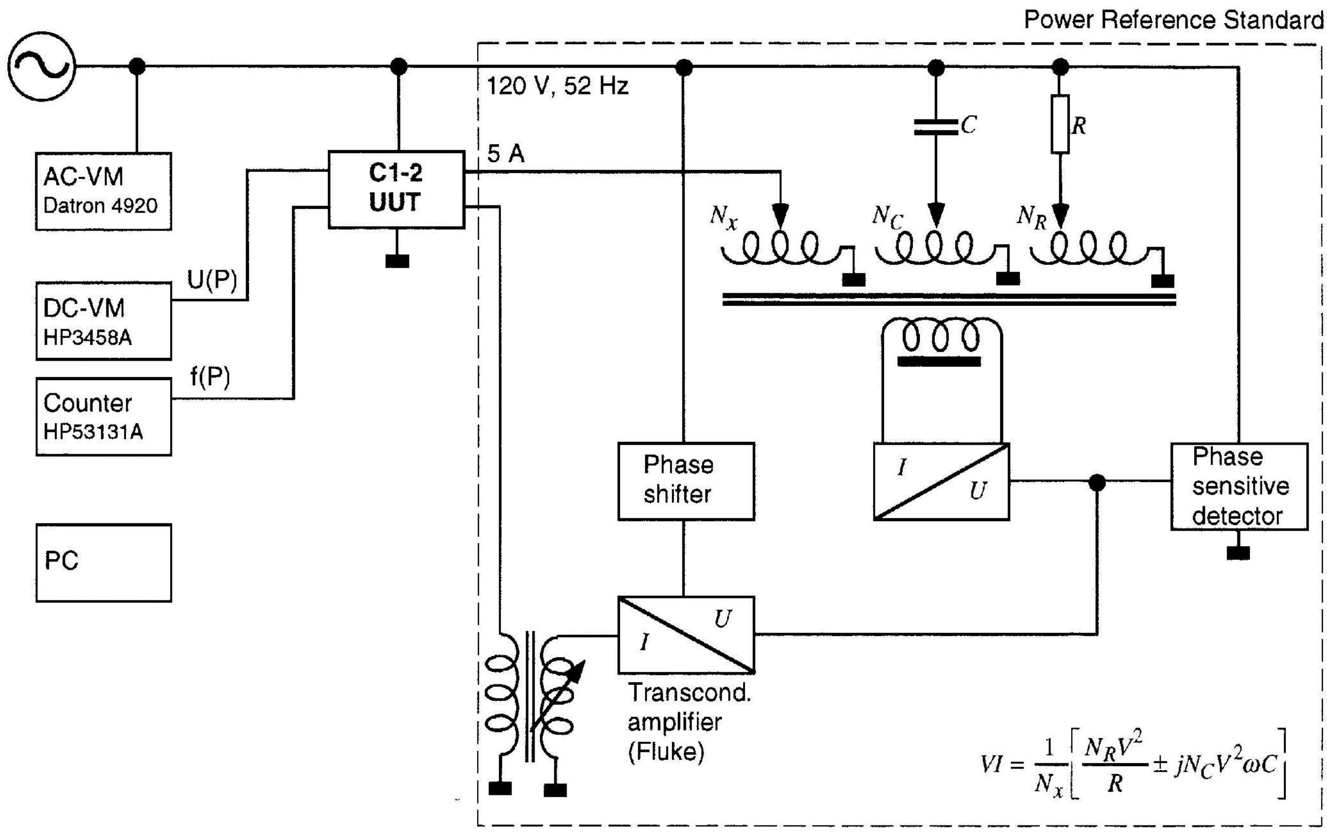


Fig 9.1 Schematic diagram of the METAS measuring system.

10. CMI

Measurement Method:

The power calibrator Rotek 811A was used as a source of power.

Simultaneously, the CMI standard and the converter C1-2 were supplied by this source.

The response DC voltage at the VOLT.OUT sockets of converter C1-2 was measured by multimeter Datron1281.

At the power factor 1 and 0,5 the thermal comparator HEG K2005 was used as a standard.

At the power factor = 0 (but usually CMI laboratory does not calibrate at this power factor), the watthour meter Radian RM-11-9 was used as standard, because HEG K2005 does not measure at this power factor. Energy consumed during the time 120 s was measured with watthour meter. The time was measured with frequency counter. Electronic switching of the start and of the end of measurement was used.

Standard used

- AC/DC Thermal Comparator HEG 2005, ser. number 64421
- Standard Watthour Meter Radian RM-11-09, ser. number 6266
- Multimeter Datron 1281, ser. number 17125
- Frequency Counter Tesla BM 520, ser. number 709198

11. OMH

The power converter HEG C1-2 (travelling standard) was directly compared to the three measurement systems of the three-phase Power Comparator ZERA COM 303-1 (OMH standard). Both instruments were connected to the R-phase circuit of a ZERA VCS 320-1 three-phase voltage/current source. A Datron Multimeter Type 1071 was used to measure the DC output voltage of the C1-2 power converter. Fig. 11.1 shows the connection diagram.

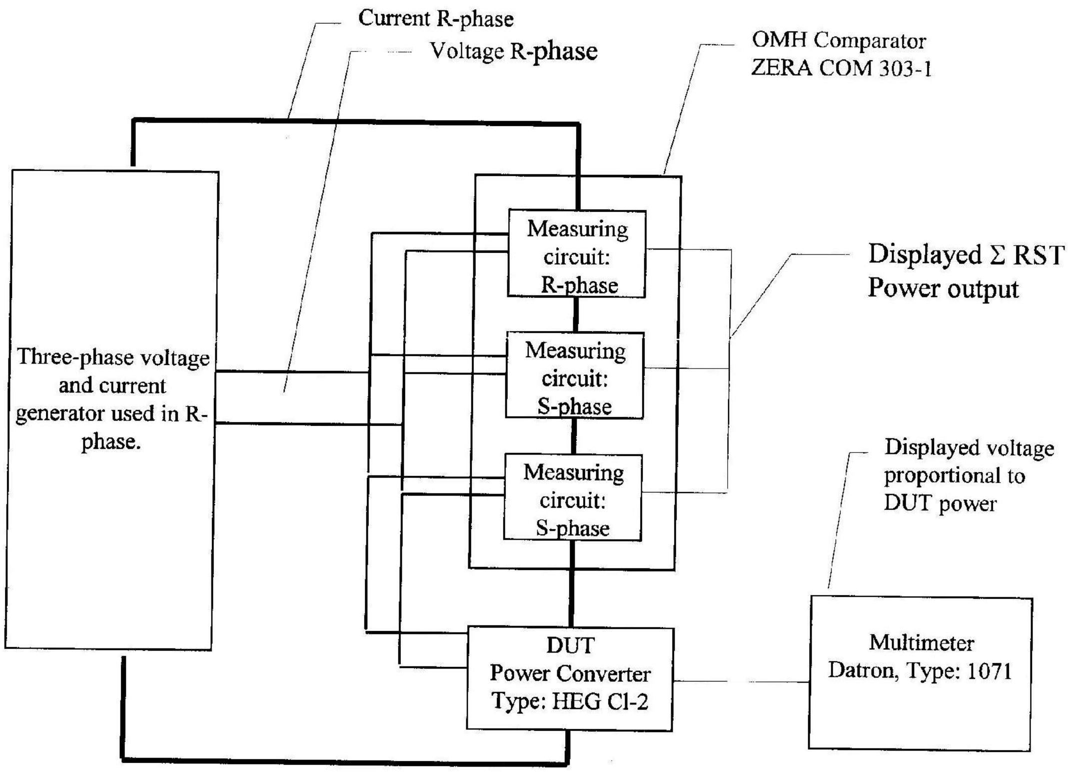


Fig 11.1 Schematic diagram of the OMH measuring system.

12. JV

The watt converter under test (C1-2 PTB) was compared to Jvs watt converter (C1-2 JV). They use the same measurement principle, but JVs watt converter has a slightly different exterior design.

Both instruments are supplied from a SWE 104-2 power source, made by HEG.

The dc output voltages of the two watt converters were measured using the voltmeters Keithley 2002 and Datron 1271, respectively.

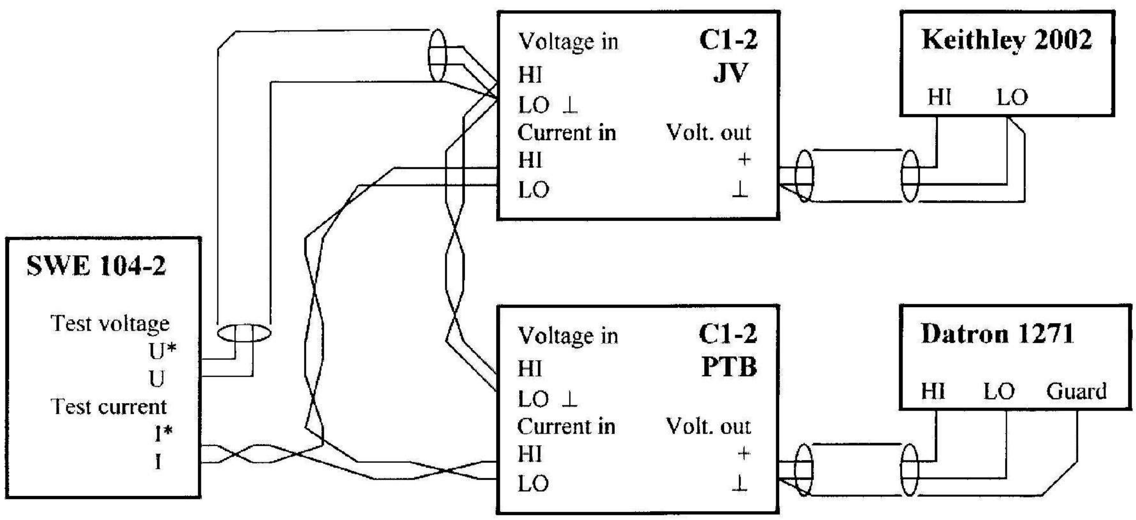


Fig 12.1 Schematic diagram of the JV measuring system.

13. CEM

The measurement system is based in a comparison between the device under test (DUT) and a Thermal Wattmeter HEG K2004. Previous comparisons show that this instrument is able to make transfer measurements at 20 ppm-level.

A phantom power generator HEG PLE 10A supplies simultaneously to the power converter HEG C1-2 and the wattmeter HEG K2004. The DC output of the DUT is measured by a DVM HP3458A. Measurements are taken in both instruments during an averaging time of 1000 seconds.

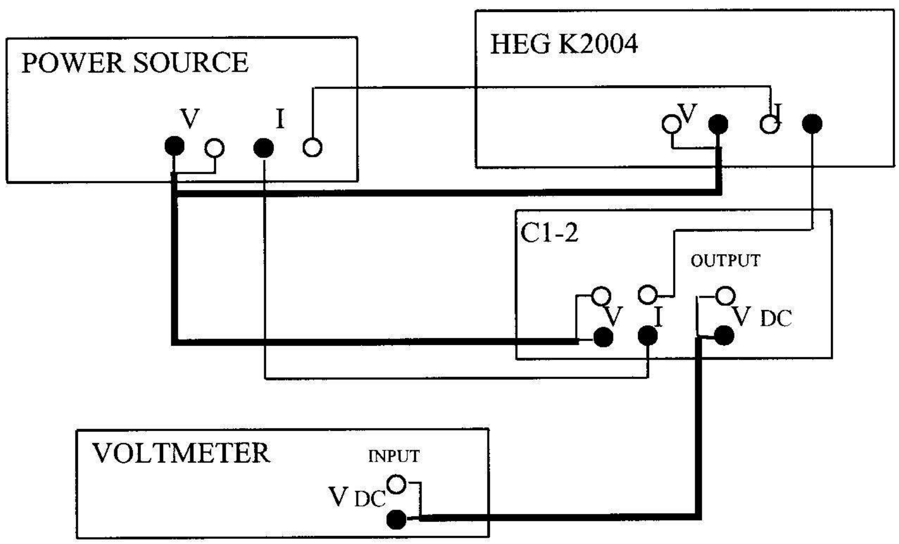


Fig 13.1 Schematic diagram of the CEM measuring system.

14. GUM

The comparison has been carried out using frequency output of C1-2 and frequency input of KOM 100.1. Readings of error have been made using error calculation function of KOM 100.1. Due to this method power factor 0,01 (inductive and capacitive) had been set instead of 0 value. The measuring time had been set to 60 s. Supply generator of EMH meter test station has been used. Because the current and voltage circuits can't have a common point in this source only voltage circuit had been grounded, that doesn't fulfil recommendations of C1-2 manual.

Comment: The measurement deviations resulting from the calibration of the frequency output of the C1-2 power converter have been converted to measurement deviations of the voltage output by the pilot laboratory. Throughout the PTB measurements the voltage output and the frequency output have been calibrated simultaneously, so the deviation between voltage output and frequency output of the C1-2 power converter was known.

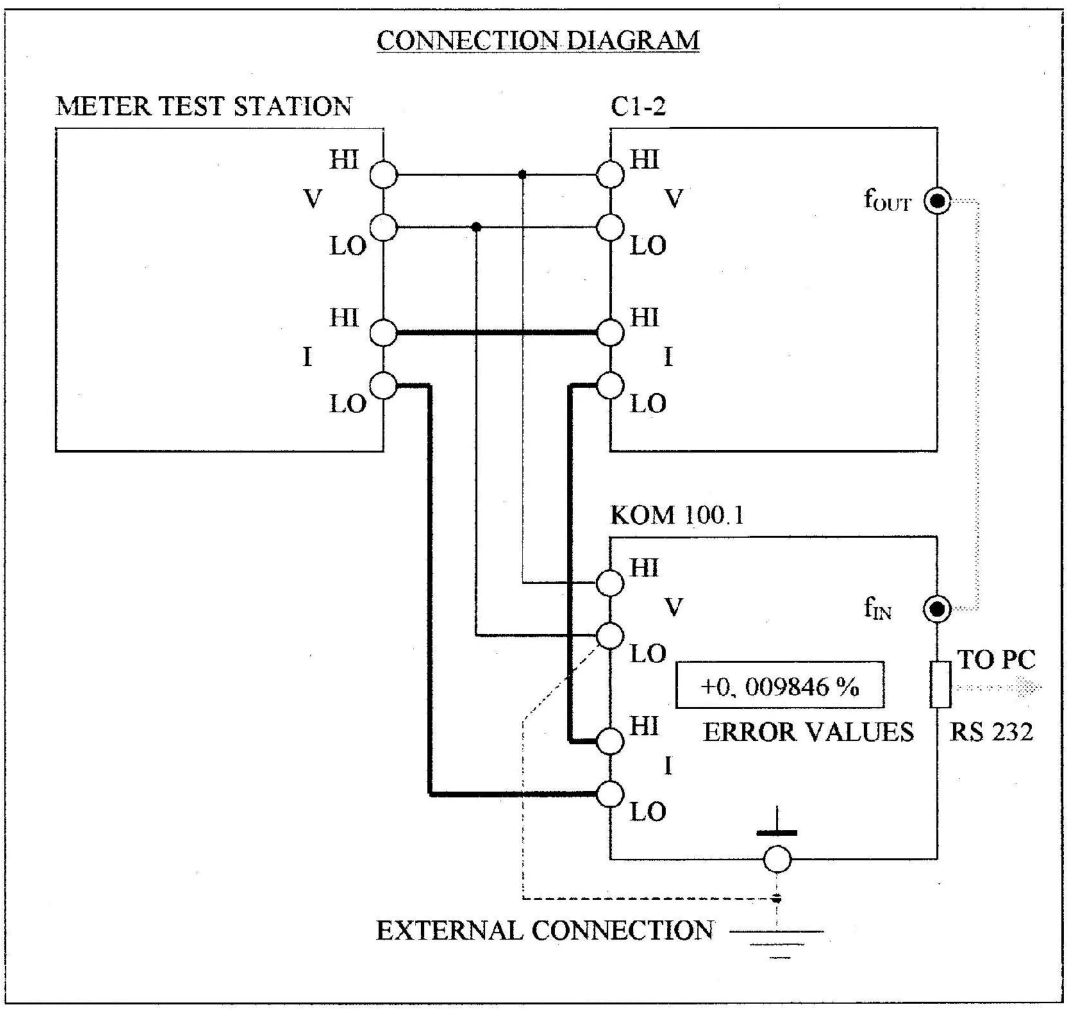


Fig 14.1 Schematic diagram of the GUM measuring system.

15. VTT/MIKES

The power measurement setup is based on two simultaneously triggered HP3458A DMMs and a Fluke 5520A calibrator used as a phantom power source. The trigger signal is derived from the 10 MHz clock of the calibrator. This ensures precise synchronization of the voltage and current signals.

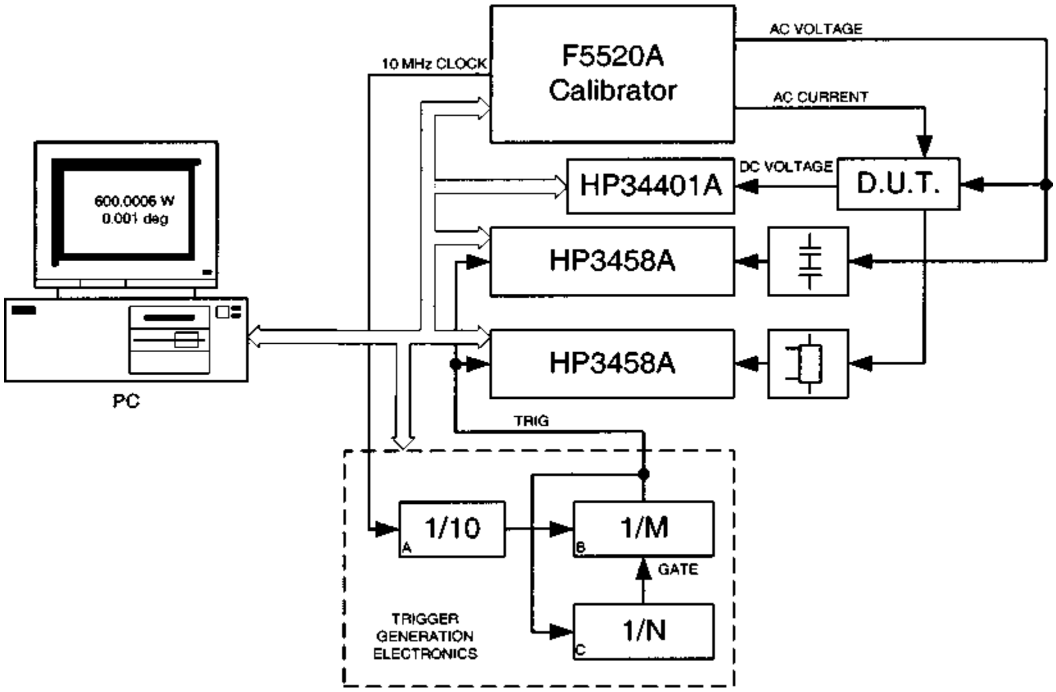


Figure 15.1: Measurement principle. DMMs are triggered simultaneously. N is the number of samples and M determines the triggering frequency.

The voltage is scaled down with a capacitive voltage divider (CVD) before it is sampled with the voltage DMM (hereafter UDMM). A 75 mΩ current shunt resistor is used to convert the current to voltage before the signal is sampled with the current DMM (hereafter IDMM). The shunt is designed for ac/dc transfer usage and it has low phase shift due to coaxial and non-inductive construction. Fig. 15.1 illustrates the basic setup of power measurements.

The triggering electronics is partly on a computer card placed inside he PC and partly in a separate box. The power converter (marked as D.U.T.) output is measured with a HP34401A DMM or with an additional HP3458A.

16. NMi/VSL

The HEG-Power converter (DUT) is compared with the Nmi/VSL reference Wattmeter system (REF).
This Ref consist of a two channel modified digital sinewave generator from Clarke-Hess.
A Fluke transconductance amplifier and a Fluke precision power amplifier deliver the voltage and current for the test.

The voltage and current are measured with the aid of two transformers.
The voltage transformer has a nominal ratio of 150:1 and transforms the 120 V into 0.8 V.
This transformer is a home made two stage transformer with separated magnetisation connection.
The current transformer is also a home made transformer with a nominal ratio of 500:1. This transformer transforms the nominal 5A current into 10 mA which is fed through a 80 Ohm Vishay type AC/DC resistor. This will generate 0.8 V.
The two low voltage signals which represent the voltage and current are measured with two HP-3458A digital voltmeters which are used in theire direct sampling DC mode on the 1 Volt range.

The sampling signals of the meters are delivered through a synchronization box which is also connected to the signal generator. We use always a aperture time of 26 µs and 512 samples per period. One measurement consist of 18 periods from the measuring signal. The frequency of the generator is modified to 52,931 Hz so that 18 periods of the measuring signals equal in time 17 periods of the main supply (50 Hz). This results in our system in maximum interference suppression with the main supply.

All the samples are stored in the meter memory and transported through the IEEE bus to the computer. The program (Testpoint from Keithley) calculated al the values.

Because of the use of the same range for both voltmeters it is possible to change the meters from position to eliminate systematic errors..

17. UME

Measurement Method:

Power calibration of the traveling standard, HEG C1-2, was carried out using method of comparison with a reference wattmeter for PF=1 and PF=0.5i/c, and a new system was used for the PF=0i/c measurements.

1) The calibration setup for PF=1 and PF=0.5i/c (120V, 5A, 53Hz) measurements was consisted of:

- The Traveling Standard (HEG C1-2),
- Reference Standard (HEG K2004 of UME-TURKEY),
- HP3458A Digital Multimeter for reading the Traveling Standard DCV output,
- Fluke 5720A Multifunction Calibrator and Fluke 5725A Transconductance Amplifier as a source for 5A generating,
- A hand-made phase-shifter,
- Fluke 5700A Multifunction Calibrator as a source for 120V generating,
- A data acquisition system consists of;
    - A computer,
    - Interfaces,
    - A software written at UME.

2) The calibration setup for PF=0i/c (120V, 5A, 53Hz) measurements was consisted of:

- The Traveling Standard (HEG C1-2),
- Zero Power Factor System consisted of;
    - A Mutual Inductor,
    - An Inductive Voltage Divider,
    - A Null Detector,
- Fluke 5700A Multifunction Calibrator as a source for 120V generating,
- Fluke 5720A Multifunction Calibrator and Fluke 5725A Transconductance Amplifier as a source for 5A generating,
- A hand-made phase-shifter,
- HP3458A Digital Multimeter for reading the Traveling Standard DCV output,
- A data acquisition system consists of;
    - A computer,
    - Interfaces,
    - Software written at UME.