Final Report

Key Comparison of 50/60 Hz Power SIM.EM-K5

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1. Introduction

Under the auspices of the Committee Consultative of Electromagnetism, CCEM, the SIM Electromagnetic Working Group carried out a key comparison of power standards at 50/60 Hz. CENAM is the pilot laboratory. This key comparison, identified as SIM.EM-K5, aims at providing a link to various NMIs in the SIM region to the CCEM-K5 key comparison on 50/60 Hz power completed in year 2001 and piloted by NIST [1].

Measurements in this key comparison were conducted from May 2010 to March 2012, and include testing points of active and reactive power. The CCEM-K5 key comparison 50/60 Hz power comprised measurements of active power only. In the SIM.EM-K5 key comparison of power the measurement standard is capable of measuring both active and reactive power with high reliability. Thus, the SIM Electromagnetic Working Group decided to include the measurement of reactive power.

Though reactive power measurements in this SIM.EM-K5 comparison cannot be linked to the CCEM-K5 comparison, for the participating laboratories this comparison is a meaningful tie to the key comparison data base of the CIPM.

The Draft B of this comparison was accepted in October 2014.

2. Participating laboratories and comparison organization

2.1 List of participants laboratories

Table 1. *List of participating laboratories.*

	Participating NMI	Contact person
1	NIST, National Institute of Standards and Technology, USA	Thomas L. Nelson thomas.nelson@nist.gov
2	Inmetro, Instituto Nacional de Metrologia, Qualidade e Tecnologia, Brazil	Ana M Ribeiro Franco amfranco@inmetro.gov.br Rosane Debatin rmdebatin@inmetro.gov.br
3	NRC, National Research Council, Canada	Eddy So. Eddy.So@nrc-cnrc.gc.ca
4	CENAM, Centro Nacional de Metrología, México (pilot laboratory)	René Carranza. rene.carranza@cenam.mx Sergio Antonio Campos acampos@cenam.mx Adrian Castruita acastrui@cenam.mx
5	INTI, Instituto Nacional de Tecnología Industrial, Argentina	Lucas Di Lillo ldili@inti.gob.ar
6	UTE, Administración Nacional de Usinas e Transmisiones Eléctricas, Uruguay	Alfredo Spaggiari ASpaggiari@ute.com.uy Daniel Slomovitz, Daniel Izquierdo, Carlos Faverio
7	SNM-INDECOPI, Servicio Nacional de Metrología, Instituto Nacional de Defensa de la Competencia y de la Protección de la Propiedad Intelectual, Perú	Henry Postigo hpostigo@indecopi.gob.pe Henry Díaz
8	ICE, Instituto Costarricense de Electricidad , Costa Rica	Harold Sanchez. hsanchez@ice.co.cr
9	CENAMEP AIP, Centro Nacional de Metrología de Panamá, Panamá	Julio González. jgonzalez@cenamep.org.pa
10	Laboratorio Custodio del Patrón Nacional de Magnitudes Eléctricas, LCPN-ME, Chile **NOTE 1**	Rodrigo Ramos. roramos@udec.cl
11	Instituto Nacional de Metrología, Colombia **NOTE 2**	Álvaro Zipaquirá Triana. azipaquira@inm.gov.co

Note 1. Though the reference standard was sent to the Laboratorio Custodio del Patrón Nacional de Magnitudes Eléctricas, LCPN-ME, in Chile, this laboratory did not submit its measurement results for this SIM.EM-K5 key comparison power.

Note 2. The Instituto Nacional de Metrología de Colombia was recently created. Her former name was Superintendencia de Industria y Comercio de Colombia. Here thereof this Institute is identified as INM.

2.2 Comparison schedule

The comparison was organized in two loops, j = 1, 2, each having a specific reference standard. Table 2 shows the original schedule of the comparison for each loop and its associated reference standard.

Table 2. *Original schedule of the SIM.EM-K5 comparison.*

Loop *j* = 1
Reference standard: RD-22-311

	Laboratory	Allocated time	
		receiving day	**sending day**
1	NIST, Thomas Nelson (USA)	28 Jun, 2010	16 Ju1, 2010
2	CENAM, Rene Carranza (México)	09 Ago, 2010	27 Ago, 2010
3	Inmetro, Ana Maria Ribeiro Franco (Brazil)	20 Sep, 2010	08 Oct, 2010
4	UTE, Alfredo Spaggiari (Uruguay)	1st Nov, 2010	19 Nov, 2010
5	INTI, Lucas Di Lillo (Argentina)	20 Dec, 2010	15 Jan, 2011
6	CENAM, Rene Carranza (México)	08 Feb, 2011	26 Feb, 2011
7	NRC, Eddy So (Canada)	22 Mar, 2011	09 Apr, 2011
8	CENAM, Rene Carranza (México)	03 May, 2011	21 May, 2011

Loop *j* = 2
Reference standard: RD-23-432

	Laboratory	Allocated time	
		receiving day	**sending day**
1	LCPN-ME, Rodrigo Ramos (Chile)	28 Jun, 2010	16 Ju1, 2010
2	SNM-INDECOPI, Henry Postigo (Peru)	09 Ago, 2010	27 Ago, 2010
3	INM, Álvaro Zipaquirá Triana (Colombia)	20 Sep, 2010	08 Oct, 2010
4	CENAM, Rene Carranza (México)	1st Nov, 2010	19 Nov, 2010
5	ICE, Harold Sánchez (Costa Rica)	20 Dec, 2010	15 Jan, 2011
6	CENAMEP AIP, Julio González (Panamá)	08 Feb, 2011	26 Feb, 2011
7	CENAM, Rene Carranza (México)	22 Mar, 2011	09 Apr, 2011

2.3 Organization of the comparison.

This comparison was arranged in two loops. Since measurements in one loop are independent of the measurements in the other, this SIM.EM-K5 comparison may be treated as two independent loops of measurement, being CENAM the link to the two loops. Some small problems occurred while clearing customs among countries, without affecting the original schedule of the comparison. Table 3 shows the final timing of the comparison.

Table 3. *Real timing of the comparison.*

Loop *j* = 1 **Reference standard: RD-22-311**		**Loop *j* = 2** **Reference standard: RD-23-432**	
CENAM	Dec 2009 10/06/2010	CENAM	Dec 2009 10/06/2010
NIST	02/07/2010 13/08/2010	LCPN-ME**NOTE 3**	14/07/2010 27/07/2010
CENAM	01/09/2010 27/10/2010	INDECOPI	31/08/2010 13/09/2010
INMETRO	06/12/2010 17/12/2010	INM	30/10/2010 01/11/2010
CENAM	25/02/2011 16/05/2011	CENAM	15/12/2010 26/01/2011
NRC	25/05/2011 05/06/2011	CENAM	03/02/2011 25/02/2011
CENAM	25/08/2011 24/10/2011	CENAM	04/03/2011 08/04/2011
UTE	15/12/2011 21/12/2011	ICE	11/05/2011 17/05/2011
INTI	15/01/2012 20/02/2012	CENAMEP	16/06/2011 23/06/2011
CENAM	15/03/2012 02/04/2012	CENAM	13/10/2011 02/04/2012

NOTE 3. The laboratory LCPN-ME received the reference standard on the date shown in Table 3. However, this laboratory did not submit its measurement results. The laboratory participated in the SIM.EM-S7 supplementary energy comparison in 50/60Hz piloted by CENAM, where the same traveling reference standard was used for both the power and energy comparisons.

This key comparison in power measurements was organized according to the CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons [2]. The protocol for the SIM.EM-K5 comparison was approved by the SIM.EM Subcommittee in year 2009 [3].

Measurements within loops were arranged in a daisy form in order to monitor any possible drift or transportation effects of the traveling reference standards against reference standards of the pilot laboratory.

Each participating laboratory covered the costs of transportation, customs and insurance while the traveling standard was at their premises. Transportation from the last participant to CENAM was covered by CENAM.

Pilot laboratory: Centro Nacional de Metrología, México.
Members of the support group: Lucas Di Lillo, Instituto Nacional de Tecnología Industrial, INTI, Argentina; Gregory Kyriazis, Instituto Nacional de Metrologia, Normalização, Qualidade e Tecnologia, Inmetro.

3. Reference standards

Two reference standards, a RD-22-311 and a RD-23-432 from RADIAN were used for this SIM.EM-K5 comparison. The Electromagnetism Committee of SIM is grateful to Radian Research Inc. for providing these measuring reference standards. Technical details and basic operations instructions of the reference standards were provided to the participating laboratories before the start of the comparison [3].

3.1 Description of the reference standards.

For loops j=1, 2, the reference standards have the following operating features:

	(loop j = 1) RD-22-311	**(loop j = 2) RD-23-432**
Input current	0.2 A to 125 A	0.2 A to 67 A
Input voltage	60 V to 600 V, auto ranging	30 V to 630 V, auto ranging
Frequency	45 Hz to 65 Hz	45 Hz to 75 Hz
Phase angle	0° to 360°	0° to 360°
Power factor	1 to 0 lead, lag	1 to 0 lead, lag
Temperature	18 °C to 30 °C	20 °C to 30 °C
Humidity	0% to 95% non-condensing	0% to 95 % non-condensing
Auxiliary power	24V DC power supply energized at 120V / 240 V, 45 Hz to 65 Hz	120 V- 240 V, 50 Hz – 60 Hz

3.2 Quantities to be measured

Table 4 shows the testing points for the SIM.EM-K5 which were agreed upon in year 2009 [3] by the participating laboratories. The test points for active power are the same as in the CCEM-K5 key comparison power [1]. The expression of measurement results and their associated uncertainty is given in terms of µW/VA and µvar/VA, for active and reactive power, respectively.

Table 4. *SIM.EM-K5 test points.*

Parameter	Active power (to be reported in µW/VA)	Reactive power (to be reported in µvar/VA)
RMS voltage	120 V	
RMS current	5 A	
Power factor	1.0 and 0.5 lead/lag	
Phase angle		30° and 90°, lead/lag
Frequencies	50, 53 and 60 Hz	50, 53 and 60 Hz

4. Measurement methods

The reader may refer to Appendix A for more information. The measurement methods of the participating laboratories, included the pilot laboratory, are shown in that Appendix.

5. Measurements of the pilot laboratory: performance of the reference standards

The performance of the reference standard was assessed by applying a regression model [4] to measurements carried out at CENAM. As shown in Table 5, CENAM carried out different sets of measurements on the traveling standards for loops j = 1 and 2.

Table 5. *Measurements carried out at CENAM on the reference standards used for loops j = 1 and 2.*

	Loop j = 1 Reference standard: RD-22-311	Loop j = 2 Reference standard: RD-23-432
Total number of measurements at CENAM	37	48
Number of sets of measurements at CENAM	6	11

Figures 1 and 2 show the measurements on the reference standards RD-22-311 and RD-23-432 carried out at CENAM from December 2009 to April 2012. Without loss of generality, Figures 1 and 2 show measurements at 120 V, 5 A, 50 Hz and unit power factor only.

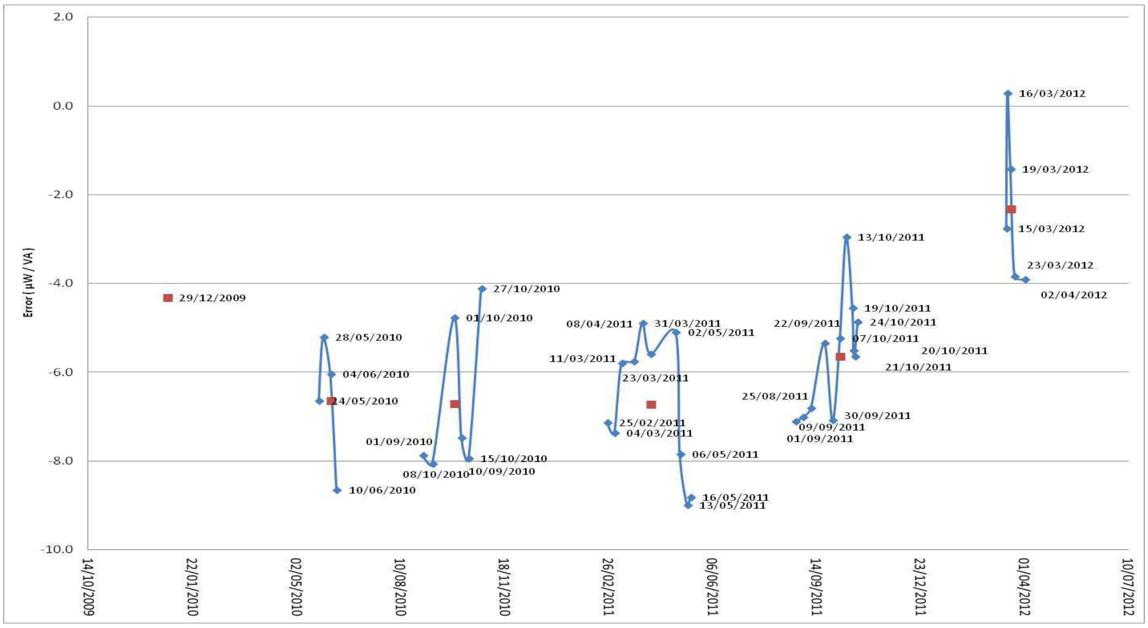


Figure 1. *Measurements carried out at CENAM on the reference standard RD-22-311 for loop j = 1. Individual measurements up to 37 are shown in blue, whereas the average values of six different sets of measurements are shown in red.*

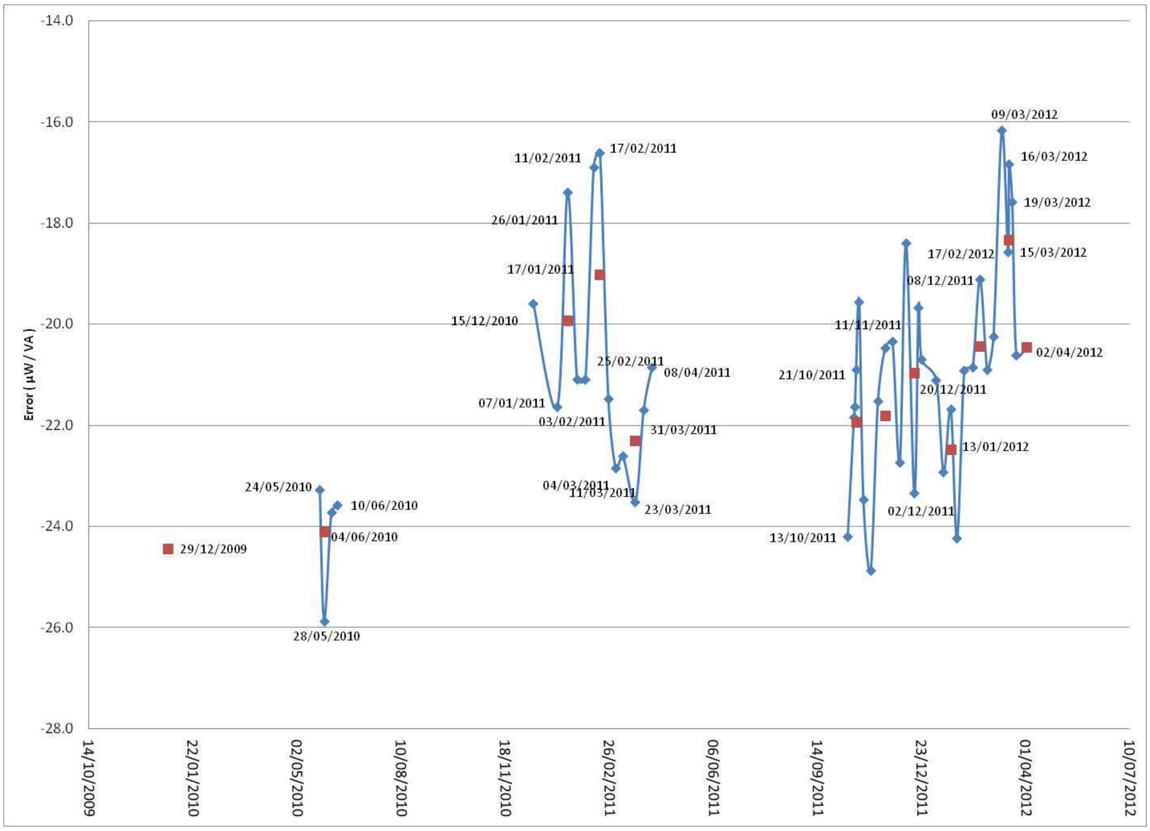


Figure 2. *Measurements carried out at CENAM on the reference standard RD-23-432 for loop j = 2. Individual measurements up to 48 are shown in blue, whereas the average value of eleven different sets of measurements are shown in red.*

Figures 1 and 2 aim at providing a better understanding of the performance of the reference standards at times where they stayed in one of the SIM laboratories away from CENAM.

The mean measurement dates are used for estimating a regression fitting to assess a possible drift of the reference standards RD-22-311 and RD-23-432. Table B.1 shows the average (mean) dates of measurements carried out at CENAM.

In order to estimate possible drifts of the reference standards, a second order polynomial was fitted to CENAM measured errors at each power factor for loops j = 1 and 2. The polynomial model is expressed as:

$$x_{CENAM,m}(t) = \mathrm{A} + \mathrm{B}t + \mathrm{C}t^2 + \varepsilon(t), \quad (1)$$

where:

- $x_{CENAM,m}(t)$ are the measurements made by CENAM;
- m corresponds to the test point;
- A, B and C are the coefficients of the regression fitting;
- The fitting is done such that the A coefficient is zero at $t = 0$
- t is the time at which measurements were made by CENAM during the comparison. Time t is given by the year, month and day of measurements at CENAM. As shown in Table B.1for loop j = 1, the starting and ending dates of measurements carried out on the reference standard are 29 December 2009 and 2 April 2012. The corresponding mean dates are 2009.99 and 2012.22, respectively.
- $\varepsilon(t)$ is a random error with zero mean and variance σ^2 associated with the regression fitting.

According to the Table 4 above, the test points in this comparison are nine for active power and twelve for reactive power, adding to a total of twenty one test points, that is m = 1, 2, … 21.
For the mth testing point, the regression fitting can be expressed in matrix form as:

$$\vec{X}_{CENAM,m} = T_{CENAM}\vec{B}(m), \tag{2}$$

where:

- $\vec{X}_{CENAM,m} = \left(x_{CENAM,m}(1), \dots, x_{CENAM,m}(I_j)\right)'$ is a column vector;
- T_{CENAM} is a I_j x 3 matrix with the elements in the first column all equal to one and the (k, n) elements (for k = 1, 2, … I_j and n = 2, 3), being $t_{CENAM}^{n-1}(k)$;
- The 3x1 vector $\vec{B}(m)$ shows the regression parameters;
- I_j is the total number of measurements of CENAM in loops j = 1, 2.

As mentioned before, this comparison was arranged in two loops, where a given reference standard was used for each loop. Since measurements in one loop are independent of measurements from the other, this comparison may be treated as two independent loops of measurements, being CENAM the link to the two loops. Having two independent measurement loops, a key comparison reference value and its uncertainty was calculated for each loop.

Tables 6 and 7 below show the coefficients of a regression fitting for the reference standards for loops j = 1 and 2. The standard deviation of the residuals is an estimate of the variance σ^2 and it is expressed in parts in 10^6.

Table 6. *Regression coefficients for loop j = 1, reference standard RD-22-311.*

Frequency	**Power Factor**	**Polynomial coefficients** (parts in 10^6)		**Standard deviation of residuals**
[Hz]		**B**	**C**	(parts in 10^6)
50 Hz	**Active Power**			
	1.0	-0.9	0.000 4	0.8
	0.5 lead	0.6	-0.000 3	0.5
	0.5 lag	-1.6	0.000 8	1.3
	Reactive Power			
	30° lead	-0.4	0.000 2	0.4
	30° lag	-1.3	0.000 6	1.1
	90° lead	0.9	-0.000 4	0.7
	90° lag	-0.8	0.000 4	0.7
53 Hz	**Active Power**			
	1.0	-0.9	0.000 5	0.8
	0.5 lead	0.7	-0.000 3	0.6
	0.5 lag	-1.6	0.000 8	1.4
	Reactive Power			
	30° lead	-0.5	0.000 3	0.4
	30° lag	-1.2	0.000 6	1.0
	90° lead	0.7	-0.000 4	0.6
	90° lag	-0.7	0.000 3	0.6
60 Hz	**Active Power**			
	1.0	-0.4	0.000 2	0.4
	0.5 lead	0.9	-0.000 5	0.8
	0.5 lag	-1.8	0.000 9	1.5
	Reactive Power			
	30° lead	-0.6	0.000 3	0.5
	30° lag	-1.2	0.000 6	1.0
	90° lead	0.6	-0.000 3	0.5
	90° lag	-0.6	0.000 3	0.5

Table 7. *Regression coefficients for loop j = 2, reference standard RD-23-432.*

Frequency [Hz]	Power Factor	Polynomial coefficients (parts in 10^6) B	C	Standard deviation of residuals (parts in 10^6)
50 Hz	**Active Power**			
	1.0	-1.5	0.000 8	1.1
	0.5 lead	1.0	-0.000 5	0.7
	0.5 lag	-2.4	0.001 2	1.8
	Reactive Power			
	30° lead	1.5	-0.000 8	1.1
	30° lag	-0.4	0.000 2	0.3
	90° lead	1.5	-0.000 7	1.1
	90° lag	-2.3	0.001 1	1.7
53 Hz	**Active Power**			
	1.0	-1.5	0.000 7	1.1
	0.5 lead	1.1	-0.000 5	0.8
	0.5 lag	-2.4	0.001 2	1.8
	Reactive Power			
	30° lead	1.4	-0.000 7	1.0
	30° lag	-0.2	0.000 1	0.1
	90° lead	1.3	-0.000 7	1.0
	90° lag	-2.1	0.001 0	1.5
60 Hz	**Active Power**			
	1.0	-1.4	0.000 7	1.1
	0.5 lead	1.5	-0.000 7	1.1
	0.5 lag	-2.5	0.001 2	1.9
	Reactive Power			
	30° lead	1.7	-0.000 9	1.3
	30° lag	0.1	-0.000 1	0.1
	90° lead	1.4	-0.000 7	1.1
	90° lag	-1.5	0.000 8	1.1

If a third order polynomial were used for the regression fitting, the standard deviation of the residuals would be larger than using a second order polynomial. Figure 3 shows the regression fitting using second and third order polynomials applied to the measurements of the reference standard RD-22-311 at 50 Hz, unit power factor (loop j = 1).

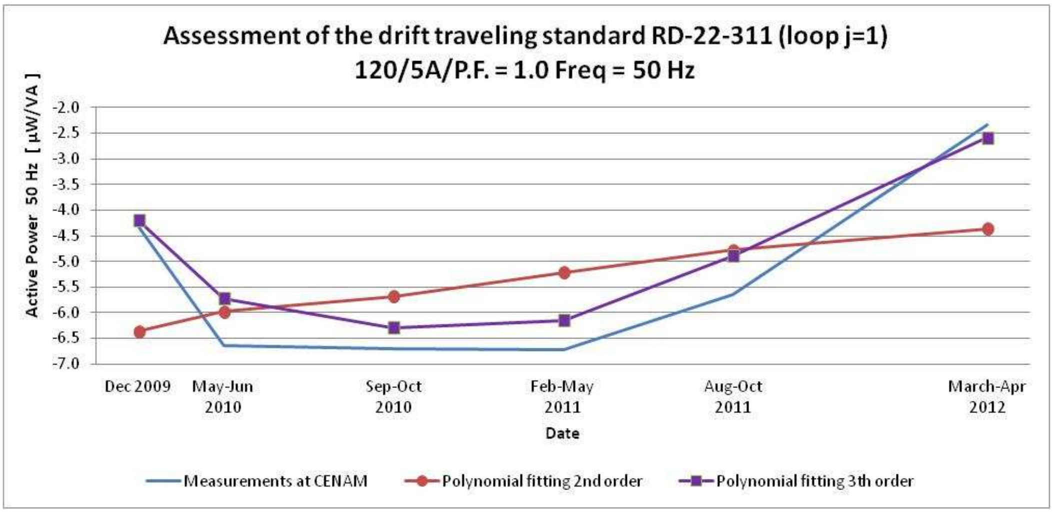


Figure 3. *Measurements of the reference standard RD-22-311 taken at CENAM and the regression fitting with polynomials of second and third order.*

There is not a physical ground for using a third order regression fitting in order to explain the real behavior of the traveling reference standards during the comparison. For the RD-22-311, the differences between a second order regression fitting and a third order are lower than 2 parts in 10^6.

6. Measurement results

In order to estimate the key comparison reference value (KCRV) and the degrees of equivalence (DoEs), the work of N. Oldham, T. Nelson, N. F. Zhang and H. Liu [1] has been followed.

This section includes:

6.1 Measurement results as reported by the participating laboratories.
6.2 The calculation of the key comparison reference value (KCRV) and its uncertainty.
6.3 The differences of the participating laboratories with respect to the KCRV.
6.4 Formula to obtain the bilateral degrees of equivalence (DoEs). The bilateral degrees of equivalence have not presented in this Report.
6.5 Impact of comparisons on the calibration and measurement capabilities of participating laboratories (CMCs). To be reported by the participants.

6.1 Measurement results as reported by the participating laboratories.

As shown above in Table 3, measurements were arranged in a daisy pattern. Appendix B shows the measurement results and associated uncertainties as reported by the participating laboratories. For loop j = 1 and reference standard RD-22-311, measurement results are shown in Tables B.1 to B.4. For loop j = 2 and reference standard RD-23-432, measurement results are shown in Tables B.5 to B.8. Figures 1 to 42 show the measurement results and the uncertainty for k=2.0 of the participating laboratories.

6.2 The calculation of the key comparison reference value (KCRV) and its uncertainty.

The difference of the measurement results $x_{i,m}$ of the i_{th} laboratory made at time t and $\overline{x}_{i,m}$ (the prediction of the value of the standard at time t based on the regression fitting as discussed in section 5 above), is expressed as:

$$D_i(m) = x_{i,m} - \overline{x}_{i,m}. \qquad (3)$$

The uncertainty of the difference $D_i(m)$, is calculated from:

$$u_{D_i(m)}^2 = u_i^2(m) + s_r^2(m)\left(1 + \vec{t}_i\left(T'_{CENAM}\,T_{CENAM}\right)^{-1}\vec{t}'_i\right), \qquad (4)$$

where:

- $s_r^2(m)$ is an estimate of the variance of the residuals associated with the regression fitting at the m-test point, based on measurements of the pilot laboratory,
- T_{CENAM} is a rectangular matrix with dimensions I_j x 3, whose elements in the first column are all equal to one and the other (k,n) elements (k = 1, 2, … I_j and n = 2, 3) are $t_{CENAM}^{n-1}(m)$,
- T'_{CENAM} is the transpose of T_{CENAM}

When the i_{th} laboratory is CENAM (the pilot laboratory), an average of her measurements is made:

$$\overline{D}_{CENAM}(m) = \frac{\sum_{k=1}^{I_j}\left[x_{CENAM,k}(m) - x_{P_{CENAM,k}}(m)\right]}{I_j}, \qquad (5)$$

where:
$x_{P_{CENAM,k}}(m)$ is the predicted value of CENAM´s measurement at the time of prediction;
I_j is the total number of measurements of CENAM in loops j = 1, 2.

In general, the average in equation 5 is very close to zero. The uncertainty of this difference is:

$$u^2_{\bar{D}_{CENAM}}(m) = \frac{u^2_{A,CENAM}(m)}{I_j} + u^2_{B,CENAM}(m). \quad (6)$$

The key comparison reference values $X_{KCRV}(m)$ for each of the twenty one test points m = 1, 2 … 21 are calculated as the weighted mean of $D_i(j)$ from the participating laboratories in a loop, including CENAM as the first NMI.

At a given loop j = 1, 2, the KCRV for each of the testing points is calculated as:

$$X_{KCRV}(m) = \sum_{i=1}^{I_j} w_i(m) D_i(m) \ , \quad (7)$$

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

$$w_i(m) = \frac{\frac{1}{u^2_{D_i(m)}}}{\sum_{k=1}^{I_j} \frac{1}{u^2_{D_k(m)}}} \ , \quad (8)$$

and I_j is the total of participating laboratories in loops j = 1, 2.

Since a regression fitting on the measurements of CENAM is used to estimate the predicted values of measurements $\overline{x}_{i,m}$ of the participating laboratories, the predictions are statistically dependent from each other and the difference between measurements and predicted values, as in equation 3 above, is statistically correlated. Thus the uncertainty of the key comparison reference value given in equation 3 is:

$$u^2_{KCRV}(m) = \frac{1}{\sum_{i=1}^{I_j} \frac{1}{u^2_{D_i(m)}}} + \frac{2 s_r^2(m)}{\left(\sum_{i=1}^{I_j} \frac{1}{u^2_{D_i(m)}}\right)^2} \times \sum_{i>k,i=2}^{I_m} \sum_{k=2}^{I_m} \frac{\overline{t}_i (T'_{CENAM} T_{CENAM})^{-1} \vec{t'}_k}{u^2_{D_i(m)} \times u^2_{D_k(m)}} . \quad (9)$$

The second term in equation 9 shows the contribution to the uncertainty of the KCRV of the regression fitting (the residuals of the approximation), and the correlation between the predictions of the measurement results of the pilot laboratory with respect of the estimated KCRV. The residual value r_S of the regression fitting is shown in Tables 6 and 7, whose maximum value is 1.9 parts in 10^6.

Tables 8.A and 8.B show the key comparison reference values and their uncertainties (in parts in 10^6) for the m = 21 testing points of loops j = 1 and 2:

Table 8.A. *Key Comparison Reference Values and uncertainty in parts in 10^6, loop j = 1.*

Loop j = 1 Standard RD-22-311	$X_{KCRV}(m)$			$u_{KCRV}(m)$ (k = 2)		
	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
120 V / 5 A / 0°	1.4	1.7	1.5	4.8	4.8	4.6
120 V / 5 A / +60°	0.9	0.7	1.4	4.7	4.9	4.9
120 V / 5 A / -60°	0.5	-0.9	1.3	5.3	5.5	5.6
120 V / 5 A / +90°	-3.1	-2.9	-1.5	4.8	4.9	4.7
120 V / 5 A / -90° **NOTE 4**	6.2	6.1	4.4	4.8	4.9	4.7
120 V / 5 A / +30°	-0.1	0.9	-1.4	4.7	4.8	4.8
120 V / 5 A / -30°	-1.3	-1.5	-0.7	5.1	5.1	5.1

NOTE 4: *At 90° lag, the measurement results of one of the participating laboratory were not used to define the KCRV because the difference between the laboratory results and the predicted value of the reference standard exceeded more than twice the uncertainty of the laboratory.*

Table 8.B. *Key Comparison Reference Values and uncertainty in parts in* 10^6*, loop j = 2*

Loop j = 2 Standard RD-23-432	$X_{KCRV}(m)$			$u_{KCRV}(m)$ (k = 2)		
	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
120 V / 5 A / 0°	0.0	0.1	0.1	5.8	5.8	5.8
120 V / 5 A / +60°	0.1	0.3	0.2	5.8	5.8	5.8
120 V / 5 A / -60°	-0.1	-0.2	-0.2	5.9	5.9	5.9
120 V / 5 A / +90°	0.0	0.0	0.5	5.8	5.8	5.8
120 V / 5 A / -90°	0.3	0.2	-0.1	5.9	5.9	5.8
120 V / 5 A / +30°	0.2	0.2	0.4	5.8	5.8	5.8
120 V / 5 A / -30°	0.2	0.2	0.2	5.8	5.8	5.8

6.3 Differences of the participating laboratories with respect to the KCRV.

Differences between the measurement results of the *i*th participating laboratory and the $X_{KCRV}(m)$ value are calculated at each of the *m* testing points in the loops *j* = 1, 2:

$$D_{i,KCRV}(m) = D_i(m) - X_{KCRV}(m). \tag{10}$$

The uncertainty of the difference between the *i*th non-laboratory and the $X_{KCRV}(m)$ value is given by:

$$u^2_{D_{i,KCRV}}(m) = \\ [1 - 2w_i(m)]u^2_{D_{i(m)}} + u^2_{KCRV}(m) - 2s_r^2(m)\sum_{k\neq1,k=2}^{I_j} w_k\,(m)\left[\vec{t}_i(T'_{CENAM}T_{CENAM})^{-1}\vec{t}'_k\right] \ . \tag{11}$$

When the laboratory is the pilot, its difference with the $X_{KCRV}(m)$ value and the corresponding uncertainty are given with reference to equations 5 and 7:

$$D_{CENAM,KCRV}(m) = \overline{D}_{CENAM}\,(m) - X_{KCRV}(m)\ , \tag{12}$$

$$u^2_{D_{CENAM,KCRV}}(m) = [1 - 2w_1(m)]\left[u^2_{B,CENAM}(m) + \frac{u^2_{A,CENAM}(m)}{I_j}\right] + u^2_{KCRV}(m)\ , \tag{13}$$

where w_1 is the corresponding weight for CENAM.

For any of the *m* = 1 to 21 testing points, Tables 9 and 10 show the differences between the *i*th laboratory including CENAM and the $X_{KCRV}(m)$. Tables 9.A and 9.B stand for the measurement results of active and reactive power in loop *j* = 1, whereas Tables 10.A and 10.B stand for the corresponding measurement results for loop *j* = 2.

Table 9.A. *Loop j = 1, Active Power. Difference between the i*th *laboratory and the* $X_{KCRV}(m)$ *value and its associated uncertainty, expressed in μW/VA.*

Active Power Reference Standard RD-22-311		Difference with $X_{KCRV}(m)$			Uncertainty (k=2)		
		0°	+60°	-60°	0°	+60°	-60°
50 Hz	CENAM	-1.4	-0.9	-0.5	20	20	20
	NIST	3.4	2.0	1.5	8	8	8
	INMETRO	0.0	6.1	-4.7	22	26	26
	NRC	-2.9	-1.5	-0.6	7	7	7
	UTE	3.1	0.7	9.8	20	40	40
	INTI	10.1	2.7	-0.4	25	32	32
53 Hz	CENAM	-1.7	-0.7	0.9	20	20	20
	NIST	2.8	0.5	-1.0	8	8	9
	INMETRO	-2.4	3.2	-7.3	22	26	26
	NRC	-4.0	-1.0	0.4	7	7	8
	UTE	13.6	3.9	9.1	20	40	40
	INTI	13.6	10.9	-2.1	25	32	32
60 Hz	CENAM	-1.5	-1.4	-1.4	20	20	20
	NIST	3.2	2.1	1.8	8	8	9
	INMETRO	-2.3	5.1	-4.0	22	26	26
	NRC	-2.6	-2.3	0.3	7	7	8
	UTE	0.2	2.0	9.2	23	41	41
	INTI	17.2	21.1	-5.0	25	32	32

Table 9.B. *Loop j = 1, Reactive Power. Difference between the i*th *laboratory and the* $X_{KCRV}(m)$ *value and its associated uncertainty, expressed in μvar/VA.*

Reactive Power Reference Standard RD-22-311		Difference with $X_{KCRV}(m)$				Uncertainty (k=2)			
		+90°	-90°	+30°	-30°	+90°	-90°	+30°	-30°
50 Hz	CENAM	3.1	-6.2	0.1	1.3	20	20	20	20
	NIST	-4.9	1.9	-0.8	-3.1	8	8	8	8
	INMETRO	2.0	-4.6	-3.2	-2.7	22	22	26	26
	NRC	-6.3	5.8	0.1	1.2	7	7	7	7
	UTE	24.8	1.7	-2.6	-6.0	26	26	41	41
	INTI	41.9	51.6	19.4	9.9	26	26	40	40
53 Hz	CENAM	2.9	-6.1	-0.9	1.5	20	20	20	20
	NIST	-4.5	1.8	-0.4	-3.7	8	8	8	8
	INMETRO	2.7	-6.6	0.6	-3.1	22	22	26	26
	NRC	-8.3	6.1	-0.1	1.2	8	8	7	7
	UTE	32.5	11.7	7.1	1.7	26	26	41	41
	INTI	39.5	48.7	23.0	11.6	26	26	40	40
60 Hz	CENAM	1.5	-4.4	1.4	0.7	20	20	20	20
	NIST	-7.0	5.3	-5.6	-1.7	8	8	8	8
	INMETRO	0.4	-3.7	5.1	-2.9	22	22	26	26
	NRC	-1.8	0.3	1.7	0.4	7	7	7	7
	UTE	21.0	7.7	3.5	-11.0	27	27	42	42
	INTI	40.1	60.6	18.4	21.9	26	26	40	40

Table 10.A. *Loop j = 2, Active Power. Difference between the* ith *laboratory and the* X_{KCRV} *(m) value and its associated uncertainty, expressed in μW/VA.*

Active Power Reference Standard RD-23-432		Difference with			Uncertainty (*k*=2)		
		0°	**+60°**	**-60°**	**0°**	**+60°**	**-60°**
50 Hz	CENAM	0.0	-0.1	0.1	19	19	19
	CENAMEP	4.8	7.6	0.3	62	93	93
	INM	-9.7	-17.8	24.5	110	116	112
53 Hz	CENAM	-0.1	-0.3	0.2	19	19	19
	CENAMEP	12.0	30.5	-18.8	62	93	93
	INM	18.2	30.4	-5.8	110	110	131
60 Hz	CENAM	-0.1	-0.2	0.2	19	19	19
	CENAMEP	19.8	42.9	-16.2	64	94	95
	INM	-5.4	-31.1	16.0	93	93	103
	ICE	3.9	27.3	-5.6	103	202	202
	SNM-INDECOPI	-1.7	-1.9	4.2	133	70	70

Table 10.B. *Loop j = 2, Reactive Power. Difference between the* ith *laboratory and the* X_{KCRV} *(m) value and its associated uncertainty, expressed in μvar/VA.*

Reactive Power Reference Standard RD-23-432		Difference with				Uncertainty (*k*=2)			
		+90°	**-90°**	**+30°**	**-30°**	**+90°**	**-90°**	**+30°**	**-30°**
50 Hz	CENAM	0.0	-0.3	-0.2	-0.2	19	19	19	19
	CENAMEP	-6.1	46.4	9.7	23.4	65	65	95	95
53 Hz	CENAM	0.0	-0.2	-0.2	-0.2	19	19	19	19
	CENAMEP	3.1	25.1	5.2	0.6	65	65	95	95
60 Hz	CENAM	-0.5	0.1	-0.4	-0.2	19	19	19	19
	CENAMEP	63.7	-21.5	26.2	-16.4	67	66	96	95
	ICE	19.9	13.9	27.8	7.7	116	116	116	116

As an example of the differences between the results of the laboratories results and the KCRV, Figures 4 and 5 show the difference between the KCRV and the results of the laboratories for loops *j* = 1 and 2.

Figure 4.A. *Difference between the KCRV and the results of the laboratories of loop j = 1, at pf= 1, 50 Hz.*

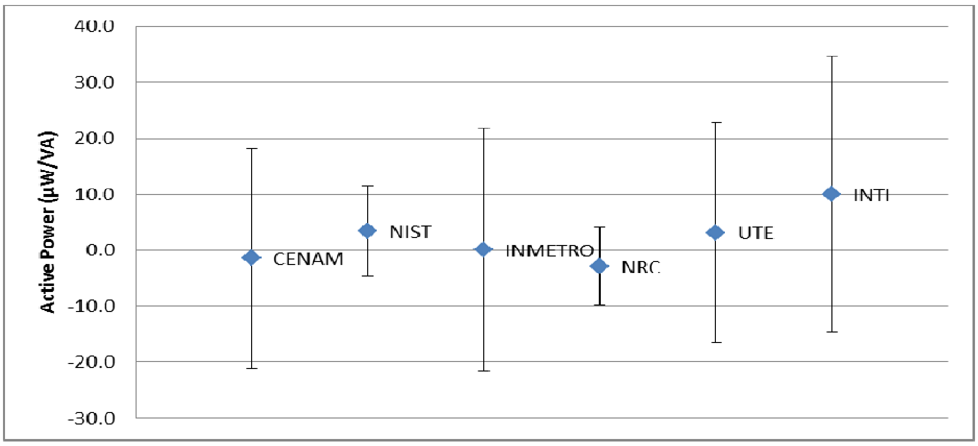


Figure 4.B. *Difference between the KCRV and the results of the laboratories of loop j = 2, at pf= 1, 50 Hz.*

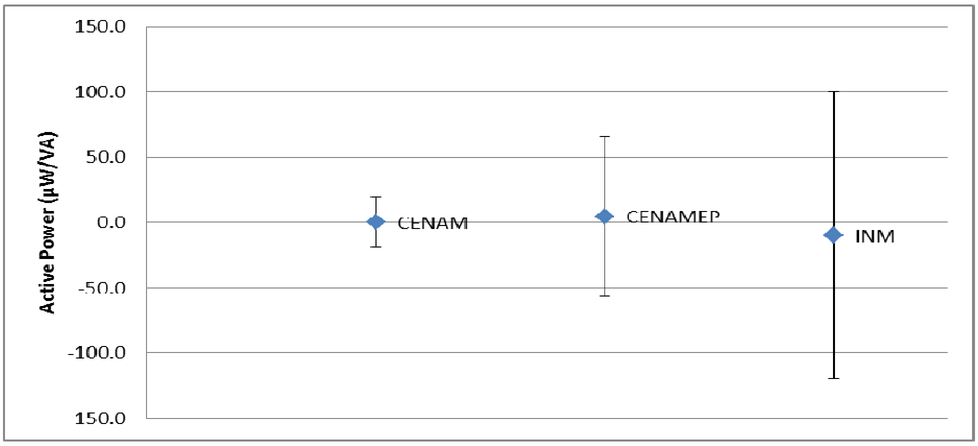


Figure 5.A. *Difference between the KCRV and the results of the laboratories of loop j = 1, at pf= 1, 60 Hz.*

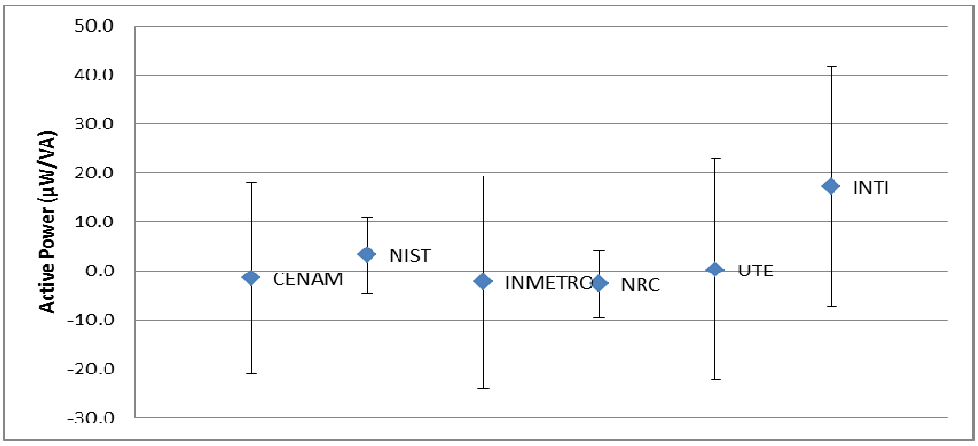
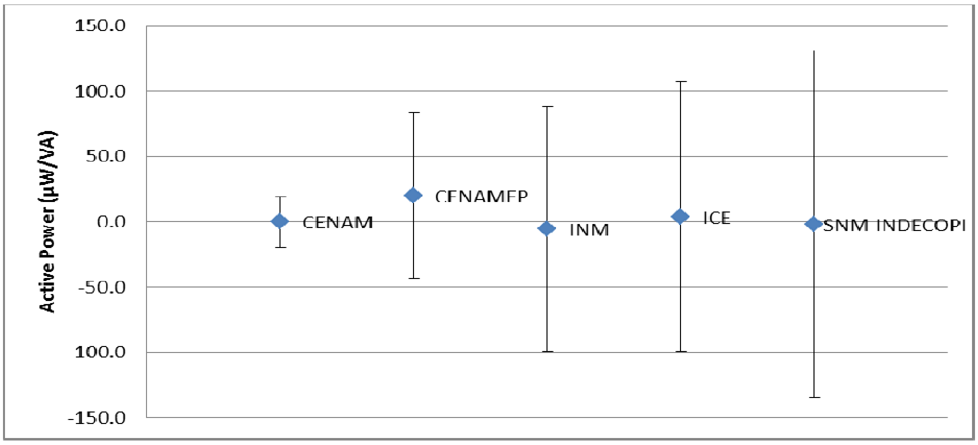


Figure 5.B. *Difference between the KCRV and the results of the laboratories of loop j = 2, at pf= 1, 60 Hz.*



6.4 The bilateral degrees of equivalence.

As requested per the CCEM, the bilateral degrees of equivalence among the participating laboratories in a key comparison should not be explicitly shown, but the formula for obtaining them may be included, thus allowing the participating laboratories to calculate their bilateral degree of equivalence from the data resulting from the difference between the participating laboratory and the KCRV.

The calculation of pairwise degrees of equivalence in this comparison has been arranged in two sections:

6.4.1 Pairwise degrees of equivalence for laboratories in the same loop (*j* = 1 or 2).

The pairwise degree of equivalence between the *i*th and the *k*th participating laboratories ($i \neq k$) is

$$D_{i,k}(m) = D_i(m) - D_k(m)\ , \tag{14}$$

where m stands for any of $m = 1, 2, .. 21$ testing points.

The uncertainty associated with the pairwise degree of equivalence when neither i nor k are the pilot laboratory, is given by:

$$\begin{aligned} u_{i,k}^2(m) = u_i^2(m) + u_k^2(m) \\ + s_r^2(m)\big[2 + \vec{t}_i(T'_{CENAM}T_{CENAM})^{-1}\vec{t'}_i + \vec{t}_k(T'_{CENAM}T_{CENAM})^{-1}\vec{t'}_k \\ - 2\vec{t}_i(T'_{CENAM}T_{CENAM})^{-1}\vec{t'}_k\big]. \end{aligned} \tag{15}$$

The difference between the *i*th laboratory and the pilot laboratory, and the associated uncertainty are given by:

$$D_{1,i}(m) = D_{CENAM,i}(m) = D_{CENAM}\ (m) - D_i\ (m)\ , \tag{16}$$

$$u_{CENAM,i}^2(m) = \frac{u_{A,CENAM}^2(m)}{I_j} + u_{B,CENAM}^2(m) + u_i^2(m) + s_r^2(m)\big[1 + \vec{t}_i(T'_{CENAM}T_{CENAM})^{-1}\vec{t'}_i\big]\ . \tag{17}$$

6.4.2 Pairwise degrees of equivalence for laboratories in different loops.

This corresponds to the case when the *i*-laboratory is in loop $j = 1$ and the *k*-laboratory is in loop $j = 2$.

Based on equations 15 and 16, the degree of equivalence is given by:

$$D_{i,k}(m)\ =\ D_{CENAM,i}(m) -\ D_{CENAM,k}(m)\ , \tag{17}$$

where m stands for any of the $m = 1, 2, \dots 21$ testing points.

Based on equations 15 and 17 the associated uncertainty is given by:

$$u_{i_{loop\ 1},k_{loop\ 2}}^2(m) = u_{i_{loop\ 1}}^2(m) + u_{k_{loop\ 2}}^2(m). \tag{18}$$

7. Conclusions

Measurements of active and reactive power were included in this regional key comparison. As agreed upon by the SIM Electromagnetism Working Group, this key comparison included measurements of reactive power at 90° and 30° lead/lag in order to support the traceability of modern power meters which allow for high accuracy measurements of both active and reactive power.

The regression fitting on the measurements of the pilot laboratory provides a robust estimate of the key comparison reference value. A second order polynomial was used for the regression fitting resulting in a standard deviation of the residuals lower than 1.9 parts in 10^6. It is estimated that a third order fitting may not be well supported by the uncertainty associated with the long term stability of the traveling reference standards.

As explained in section 6.3 above, a regression fitting on the measurements of CENAM was carried out in order to estimate the predicted values of her measurement results $\overline{x}_{i,m}$. Thus, the predictions are statistically dependent from each other, and the differences between the measurement results of the laboratories and the key comparison reference value may be correlated. The second term in equation 9 shows the contribution to the uncertainty of the KCRV from the regression curve (the residuals of the approximation), and the correlation between the predictions of the measurement results of the participating laboratories with respect of the estimated KCRV. From Tables 5 and 6, it may be concluded that the main source of correlation among the differences of the results of the participating laboratories and the key comparison reference value is due to the residuals r_S of the regression fitting by an amount lower than 1.9 parts in 10^6 for all the m = 21 testing points. The contribution from the correlation is lower than 0.1 µW/VA.

Differences between the measurement results of the participating laboratories and the KCRV, calculated at each of the 21 testing points, show a good infrastructure of national standards of measurement of electric power in the SIM region. This is a rewording exercise of comparison of the national standards of measurement as recommended by the CIPM. The participating laboratories are fully recommended for their enthusiastic participation in the comparison. Their individual efforts to maintain the national standards of power measurement are acknowledged.

As stated in the introduction to the present report, this SIM.EM-K5 aims at providing a link to the CCEM-K5 key comparison of 50/60 Hz power in 2002. As reported in reference [5], such link consists of a correction to be added to the results of the SIM.EM-K5 comparison so that the transformed results can be directly compared with the results of the CCEM-K5:2002 comparison. The estimate of the link is based on the work of F. Delahaye and T. Witt [6]. The SIM link laboratories participating in the two comparisons accepted that their measurement results be used to estimate the link. Concerning the reproducibility of the results of the link laboratories over the time span between the two comparisons, a reproducibility value of r_C = 10 at k = 2 was accepted by the SIM link laboratories. Tables 3, 4 and 5 in Section 4 in reference [5] are particularly important showing the link between the results of the SIM.EM-K5 and the CCEM-K5 at 120 V, 5 A and frequency equal to 53 Hz at different power factors. Tables 5.1 to 5.3 in reference [5], show the degrees of equivalence among all the laboratories in the SIM-EM-K5 comparison, as if all of them had participated with satisfactory results in the CCEM-K5 comparison in year 2002.

As reported in Table 6 in reference [5], a proof of consistency in the link between the results of the CCEM-K5 and SIM.EM-K5 key comparisons was applied based on the Birge ratio. The obtained Birge ratio yielded a value lower than1.0, which means that: 1) the reproducibility value r_C = 10 at k = 2 may be overestimated and, 2) the link between the two comparisons is consistent. From this it follows that the link between the CCEM-K5 and SIM.EM-K5 key comparisons is reliable.

It may be said, that the metrology infrastructure in power of the SIM region is in a satisfactory state, and it has improved with the time.

It is fully appreciated the support of the SIM Electromagnetic Committee for including the measurements of reactive power in the scope of this 50/60 Hz key comparison of power. The results of this SIM.EM-K5 comparison in reactive power support very well the capabilities of modern measurement technologies of power which offer the simultaneous measurement of active and reactive power in the same measurement standards.

It is important to mention that many of the participating laboratories in the SIM.EM-K5 key comparison power also participated at the same time in the supplementary comparison SIM.EM-S7 of energy, where the testing points of energy measurements are similar to those of the power comparison.

Gratitude is due to Radian Research Inc. for their support to this SIM.EM-K5 key comparison 50/60 Hz power, and to the SIM.EM-S7 supplementary comparison 50/60 Hz energy, for the provision of the traveling standards RD-22-311 and RD-23-432.

8. References

1. N. Oldham, T. Nelson, N. F. Zhang and H. Liu, "Final Report CCEM-K5 Comparison of 50/60 Hz Power," NIST, USA, Jun. 2002.

2. CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons. CCEM, 21 Mar. 2007.

3. SIM.EM-K5 Key Comparison 50/60 Hz Power Protocol, May 2010.

4. Mary G. Natrella, Experimental Statistics, National Bureau of Standards Handbook 91, Aug. 1963.

5. ADDENDUM: Link between the CCEM-K5:2002 and SIM.EM-K5:2012, CENAM, Mexico, Nov. 2014.

6. F. Delahaye and T. J. Witt, "Linking the Results of Key Comparison CCEM-K4 with the 10 pF Results of EUROMET Project 345", Metrologia 39 (Tech. Suppl.) 01005, 2002.

7. B. N. Taylor, W. H. Parker and D. N. Langenberg, "Determination of e/h, using macroscopic quantum phase coherence in superconductors: implications for quantum electrodynamics and the fundamental physical constants", Rev. Mod. Phys., Vol. 41, pp. 373-496, Jul. 1969.

Appendix A. Measurement methods

A.1. Measurement standard at CENAM, Mexico.

A current comparator power bridge, as proposed by E. So *et al* at the INMS-NRC, is used at CENAM as the national standard of power and energy measurements. Measurements of power are traceable to AC and DC voltage national measurement standards established at CENAM; the reference standards for the in-phase and quadrature currents of the current comparator power bridge are traceable to national standards of measurement at the INMS-NRC, Canada.

For this SIM.EM-K5 comparison, the reference standard is a wattmeter traceable to the national measurement standard of electrical power and energy. This standard was measured during the comparison with a transfer standard every week since the beginning of the Comparison.

Table A1. *Reference transfer standard.*

Manufacturer:	Radian Research
Model:	RD-22-231
Serial number:	201512

CENAM´s transfer standard is an automated energy calibration system which is capable to measure all the test points for this Comparison. In the same way, CENAM’s transfer standard provides traceability for the two reference standards of the Comparison to the national measurement standard of electrical power and energy.

Table A2. *Transfer standard.*

Manufacturer:	Radian Research
Model:	RS-703A
Serial number:	704333

A.1.2. Reference standards.

Two reference standards, a RD-22-311 and a RD-23-432 from RADIAN were used for this SIM.EM-K5 comparison. The Electromagnetism Committee of SIM is grateful to Radian Research Inc. for providing these measuring instruments.

Table A3. *Reference standard.*

Manufacturer:	Radian Research	Manufacturer:	Radian Research
Model:	RD-22-311	Model:	RD-23-432
Serial number:	204359	Serial number:	203412

A.1.3. Measurement procedure followed.

A.1.3.1. Test procedures.

The power bridge, CENAM´s transfer and working standards and the reference standards were energized at 120 V / 55 Hz by an ELGAR-3001 AC voltage source. The following table shows the external power applied to the instruments during the measurements at CENAM.

Table A4. *Auxiliary power supply applied to the instruments.*

Comparison test point	Current comparator power bridge external power supply	CENAM´s Working standard	CENAM’s Transfer standard	Traveling standard external power supply
120 V / 5 A / 50 Hz	120 V / 55 Hz	120 V / 55 Hz	120 V / 55 Hz	120 V / 55 Hz
120 V / 5 A / 53 Hz	120 V / 55 Hz	120 V / 55 Hz	120 V / 55 Hz	120 V / 55 Hz
120 V / 5 A / 60 Hz	120 V / 55 Hz	120 V / 55 Hz	120 V / 55 Hz	120 V / 55 Hz

As shown above, all the instruments used in this comparison were powered at a frequency that differs from the testing frequency by some hertz in order to avoid frequency beating with the power supply.

A.1.3.2. Measurement arrangement of the reference standards

- The external power supplies of the instruments were applied at least 4 hours before every set of measurements.
- A total of 10 sets of measurements were performed at every test point.
- A single set of measurements consists of 10 independent measurements at each one of the comparison test points.
- Following a set of measurements, the instruments were denergized for at least 12 hours before performing the next set of measurements.

A.1.3.3. Environmental conditions during the measurements.

- Laboratory temperature: (23 ± 1.0) ºC
- Laboratory relative humidity: (50 ± 30) % RH.

A.1.3.4. Measurement method in the comparison.

The Reference standards were compared against CENAM´s transfer standard which is traceable to the national measurement standard of electrical power and energy at CENAM.

Testing signals from the working standard were applied at the same time to CENAM´s transfer standard and the travelling standards for each set of measurements.

The measured values of voltage, current, frequency, power factor, phase angle, apparent power, active power and reactive power were recorded in a PC using the RS232 port of each instrument.

A.1.3.5. Measurement setting up at CENAM.

Figure 1 shows a schematic diagram of the measurement arrangement of the transfer standard and the reference standards.

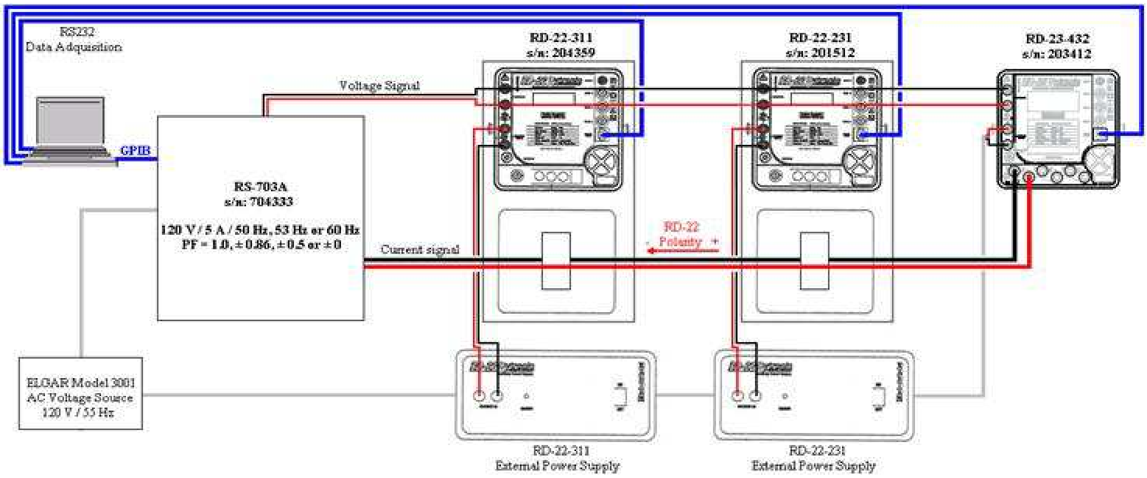


Figure A1. *Schematic diagram of the measurement arrangement.*

A.1.4. Uncertainty statement of the reference standards.

The measurement uncertainty was estimated according to the Guide to the Expression of Uncertainty in Measurement, BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML (1995).

The expanded uncertainty reported in this comparison, includes the assessment of the type A uncertainty during the calibration of our reference standards and the instrument under calibration, which is estimated from an average of ten sets of measurements, and the type B uncertainty, which is associated with the known uncertainty of our reference standards. The expanded uncertainties of measurement of the reference standards are estimated to enclose a confidence interval higher than 95 % with a coverage factor k = 2.0.

Table A5. *Active power: uncertainties type A, B and expanded.*

Voltage	Current	Frequency	Power Factor	Type A k = 1.0	Type B k = 1.0	Expanded k = 2.0
(V)	(A)	(Hz)	(λ)	(μW / VA)	(μW / VA)	(μW / VA)
120	5	50	1.0	< 1	10	20
			0.5 lead	< 1	10	20
			0.5 lag	< 1	10	20
		53	1.0	< 1	10	20
			0.5 lead	< 1	10	20
			0.5 lag	< 1	10	20
		60	1.0	< 1	10	20
			0.5 lead	< 1	10	20
			0.5 lag	< 1	10	20

Table A6. *Reactive power: uncertainties type A, B and expanded.*

Voltage	Current	Frequency	Power Factor	Type A k = 1	Type B k = 1	Expanded k = 2.0
(V)	(A)	(Hz)	(λ)	(μvar / VA)	(μvar / VA)	(μvar / VA)
120	5	50	0 lead	< 1	10	20
			0 lag	< 1	10	20
			0.866 lead	< 1	10	20
			0.866 lag	< 1	10	20
		53	0 lead	< 1	10	20
			0 lag	< 1	10	20
			0.866 lead	< 1	10	20
			0.866 lag	< 1	10	20
		60	0 lead	< 1	10	20
			0 lag	< 1	10	20
			0.866 lead	< 1	10	20
			0.866 lag	< 1	10	20

A.2 Measurement standard at INTI, Argentina.

A.2.1 Description of the measuring method:

The power measurement standard used at INTI is a digital sampling wattmeter known as WATT-1[1]. The wattmeter consists in two transformers, one AC resistor, one ACV and ACI source, and two digital voltmeters, all this linked to a computer through IEEE488BUS.

As shown in the Figure A2.1, TU is a voltage transformer with 240 V, 120 V and 60 V input ranges and a 6 V output value, and TI is a current transformer with 5 A, 2 A and 1 A input ranges and a 100 mA output value, that is applied to RWATT-1, the AC resistor, to obtain a 1 V output value. DMM MASTER and DMM SLAVE are the two digital voltmeters used to perform the digital sampling. Swerlein's algorithm[2] is used to define the sampling parameters of the two signals, and Pogliano's work about power measurements[3], to calculate power values.

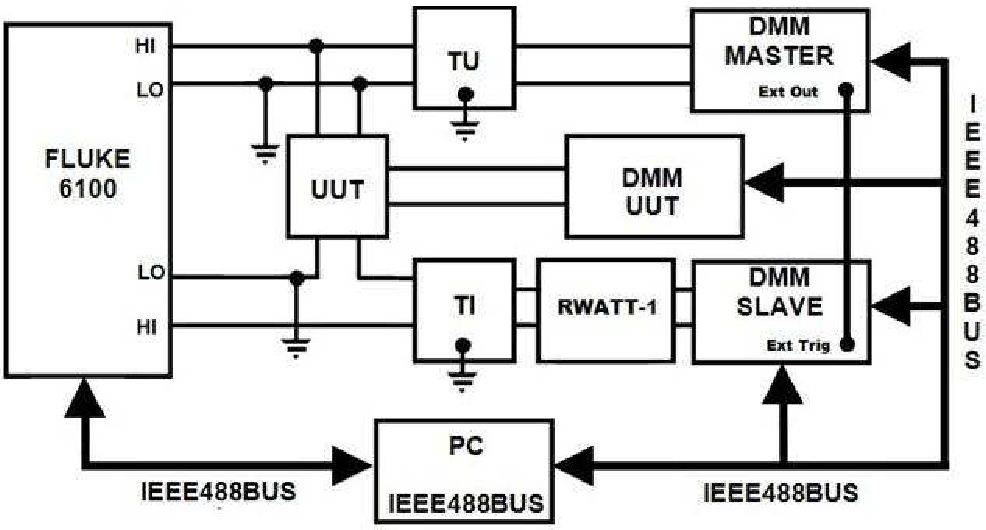


Figure A.2.1. *Measuring set-up.*

1.- FLUKE6100= Fluke 6100 calibrator
2.- UUT= Unit under test
3.- TU= voltage transformer
4.- TI= current transformer
5.- DMM UUT= Digital multimeter Fluke 8508
6.- DMM MASTER= Digital multimeter HP 3458 Master
7.- DMM SLAVE= Digital multimeter HP 3458 Slave
8.- PC= Personal computer

The GUARD connector of the voltage transformer was connected to earth.
The GUARD connector of the current transformer was connected to earth.
The internal GUARD of the DMMs were connected to the LO terminal
The EXT OUT output connector of the DMM identified as MASTER was connected to the EXT TRIG input connector of the DMM identified as SLAVE

1 Lucas Di Lillo et al. "Sampling wattmeter at INTI", VIII SEMETRO, Joao Pessoa, September 2009.
2 Ronald Swerlein, "A 1O ppm accurate digital AC Measurement algorithm", August 9,1991
3 Umberto Pogliano, "Use of integrative analog-to-digital converters for high-precision measurement of electrical power", IEEE Trans. Instrum. Meas., vol. 50, No. 5, 2001

A.3 Measurement standard at Inmetro, Brazil.

Inmetro has a measurement system based on the sampling method, using digital multimeters, 3458A. The layout of the circuit is shown in Fig. A.3.1.

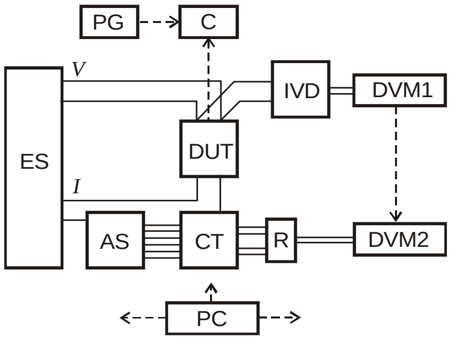


Figure A.3.1. *Layout of the measuring circuit.*

ES is the energy source of the circuit. As a reasonable choice, it may be a ROTEK 8000 calibrator, which has been upgraded by Rotek for the research, run by this laboratory, providing voltages up to 700 volts and currents up to 50 amps. Beyond this current other sources, e.g. a EMH PPS 120.3 can also be used, providing current up to 120 A. DUT is the device under test, which may be a wattmeter or a watt-hour meter. The voltage is reduced by an inductive voltage divider, IVD, to 6 volts rated value, to facilitate the sampling of the voltage by digital voltmeter DVM1, a HP-3458A, always in the 10 volts range. The programmable IVD, model DI-4 of CONIMED, offers four voltage ranges from 60 volts up to 600 volts. Restrictions to measure exclusively sinusoidal currents at power line frequency made possible the application of a current transformer, CT, developed by CALIN for this project, which ensures measurements between 250 mA and 60 A. By the application of a cascade standard current transformer, the current range can be extended up to 120 A. CT is a two-stage, passive device, providing 100 mA rated secondary current. The special compensation method of the CT requires twin standard resistors, R. 2×10 ohms or 2×20 ohms can be applied, offering 1V or 2V rated voltage on the output, respectively. The output voltage of the resistors, proportional to the current, is sampled by digital voltmeter DVM2, another HP-3458A. The two digital voltmeters work in a master-slave relation. DVM1, as the master, takes the samples at a programmed rate, at each instant emitting a trigger pulse, to control the sampling of DVM2, as a slave. AS is an automated switch, developed by this laboratory, to change the ranges of the CT automatically. When watt-hour meters are to be calibrated, a high precision pulse generator, PG, is applied, to provide the time base. C is a special, programmable counter, developed by CALIN for this laboratory, to count the number of pulses emitted by PG and DUT. Control of the equipment is done partially by IEEE 488.2, partially by RS 232 control, as the case may be.

The fully automated calibration process is controlled by an interactive program, which was developed in LabWindows/CVI (product of National Instruments), by the Power and Energy Laboratory.

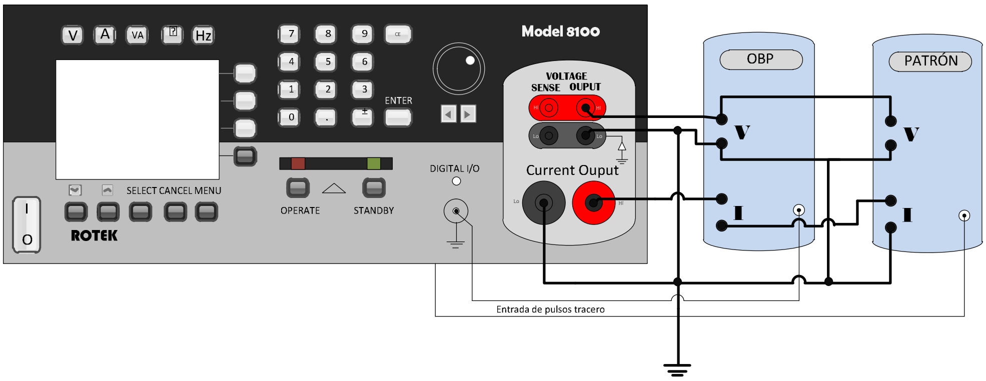
A.4 Measurement standard at ICE, Costa Rica.

A.4.1 Measurement procedure for Energy.

Energy by comparison: compare the energy applied to the device under test and the energy measured with the energy standard simultaneously.

A.4.2 Measurement procedure for Power.

Power by comparison: compare the power applied to the device under test and the energy measured with the energy standard simultaneously.



A.4.3 Traceability.

A Rotek 8100 source was used to feed simultaneously the travelling standard (OPB) and the ICE-LMVE standard (PATRON), a Radian RD-22-331, SN 205061, single phase power and energy standard. This power and energy standard is traceable to METAS Switzerland.

A.5 Measurement standard at CENAMEP AIP, Panama.

A.5.1 Measurement Procedure for Power.

CENAMEP AIP measurement system, is based on the direct comparison of readings indicated by the equipment under test and the readings indicated by the commercial reference standard (KOM 200.3)
Control and configuration of the reference, such as data, are performed automatically, using a program developed in LabView.
The error is set as the difference between the average of readings on the equipment under calibration and the readings of the reference standard.

A.5.2 Measurement Procedure for Energy.

CENAMEP AIP measurement system, is based on the direct comparison of emitted pulses between the equipment under calibration and those issued by the reference standard (KOM 200.3).
The output frequency of the equipment under test is connected to a pulses conditioner, which raises and set the received signal pulse of 2V to an output pulse signal of 5V, eliminating the effect of the high input impedance of the reference standard, on the equipment under test.
The reference, through an internal pulse comparator, compares the signals and the difference represents it as an error of the equipment under calibration.

A.5.3 Traceability

Prior to comparisons of power and energy, the reference standard (200.3 KOM) was calibrated at PTB.

A.6 Measurement standard at SNM-INDECOPI, Peru.

A.6.1 Description of the measuring method for Power.

The measuring method is by comparison.
The travelling standard and the local standard are connected with a constant power source.
The auxiliary power and the test signal were applied during 4 hours before testing.
The measurements were done during 10 days, with one independent measurement each day.
The traveling standard was de-energized two times during the tests as indicated in the protocol.

A.6.2 Description of the measuring method for Energy.

The measuring method is by comparison.
The travelling standard and the local standard are connected with a constant power source simultaneously, both are measured during the same time, in order to assure that the measurements are, exactly, over the same energy quantity in the same conditions.
The auxiliary power and the test signal were applied during 4 hours before testing.
The integration period was 60 seconds.
The measurements were done during 10 days, with one independent measurement each day.
The traveling standard was de-energized two times during the tests as indicated in the protocol.

A.6.3 Used Equipment.

Local standard radian rd 21-332

A.6.4 Traceability.

To the primary standard of energy and power, Lapen - Inmetro

A.7 Measurement standard at NIST, USA.

The system used at NIST for this comparison is shown in Fig. A.7.1 and is based on the development of a system for the generation of 120 V, 5 A, active and reactive power over the 50 Hz to 400 Hz frequency range[4]. The system uses a differential sampling technique[4,5] to relate the amplitudes and phases of two, sinusoidal, spectrally-pure voltage signals, VV and VI, which are scaled versions of the voltage and current signals applied to the meter under test (MUT), to a single, piecewise-approximated voltage signal, VJ, generated using a programmable Josephson voltage standard (PJVS)[6]. The differential sampling is performed with two, commercially-available, sampling digital voltmeters (DVMs) by selectively ignoring the values in the acquired data sets that correspond to the time periods in which the PJVS signal is changing state. Additional circuitry is added to each DVM that locks their time-bases to the 20 MHz system reference clock and allows for the comparison of the PJVS signal to the sinusoidal voltage signals to be performed with accuracies better than 2 parts in 10^7. The system also includes a voltage amplifier that scales the 1.2 VRMS VV signal to 120 VRMS. The voltage amplifier features additional self-calibration circuitry that allows for its errors to be determined and corrected in-situ to better than 3 parts in 10^7. The generated current is measured using an accurate, temperature-controlled current shunt whose dc value is traceable to the quantum Hall resistance and whose ac response is calculable from the dimensions of its bifilar resistance element[7]. The temperature of the shunt is controlled to better than 0.02 °C, thereby reducing its resistance change to less than 5 parts in 10^7 over the full range of applied currents. A three-stage, electronically-enhanced transformer[8], T1, is used to measure the output voltage of the current shunt in the presence of large common-mode voltages.

[4] B. Waltrip, B. Gong, T. Nelson, Y. Wang, C. Burroughs, A. Rüfenacht, S. Benz, and P. Dresselhaus, "AC power standard using a programmable Josephson voltage standard," IEEE Trans. Instrum. Meas., vol. 58-4, pp. 1041–1048, Apr. 2009.
[5] A. Rüfenacht et al., "Precision Differential Sampling Measurements of Low-Frequency Voltages Synthesized with an AC Programmable Josephson Voltage Standard," IEEE Trans. Instrum. Meas., vol. 58-4, pp. 809–815, Apr. 2009.
[6] Y. Chong, C. Burroughs, P. Dresselhaus, N. Hadacek, H. Yamamori, and S. Benz, "Practical high resolution programmable Josephson voltage standards using double- and triple- stacked MoSi2 barrier junctions," IEEE Trans. Appl. Supercon., vol. 15, no. 2, pp. 461-464, Jun. 2005.
[7] O. Laug, T. Souders, B. Waltrip, "A Four-Terminal Current Shunt with Calculable AC Response," NIST Tech. Note 1462, August 2004.
[8] P. Miljanic, E. So, W. Moore, "An Electronically Enhanced Magnetic Core for Current Transformers," IEEE Trans. Instrum. Meas., vol. 40, no. 2, pp. 410-414, April 1991.

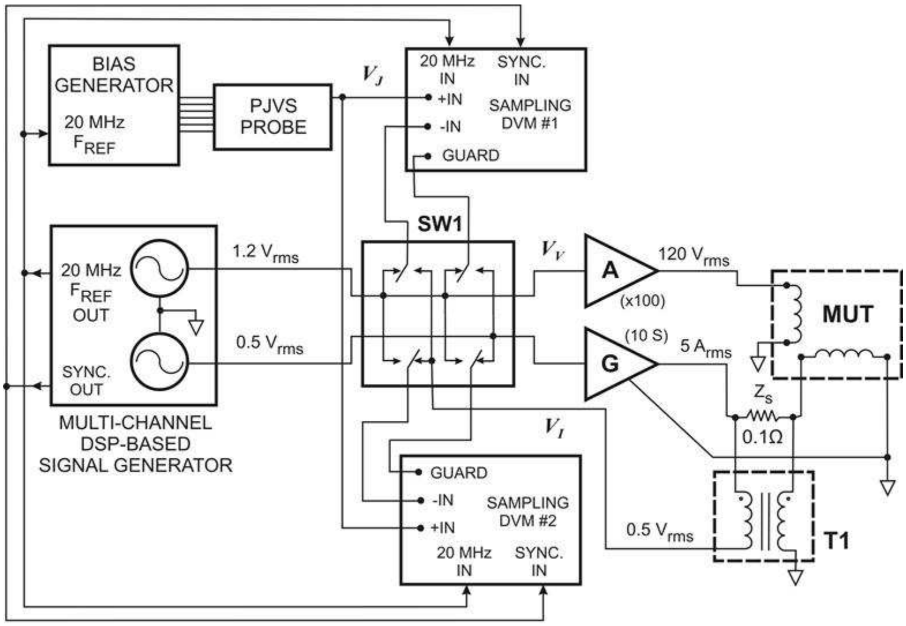


Fig. A.7.1. *Simplified diagram of the NIST power generation system.*

A.8 Measurement standard at NRC, Canada

Description of NRC Power Bridge

In the NRC power bridge[9], the apparent power is divided into two orthogonal components - the active power and the reactive power. A reference resistor and a reference capacitor are used to derive the in-phase and quadrature currents to the power bridge. When used in a calibration system the current comparator can be connected in a feedback arrangement to control the magnitude and phase of the test current in accordance with the bridge settings of the corresponding current comparator windings. This, together with the voltage, establishes the measurement conditions and makes possible the calibration of power and energy meters and other similar types of metering instruments. For this comparison of power and energy meters using the corresponding transfer instrument, the combined standard uncertainties (Type A and B uncertainties) range from 5 to 8 µW/VA and 5 to 8 µVARh/VAh, respectively.

A.9 Measurement standard at UTE, Uruguay

The meter under test, Radian RD-22-311, was tested by UTE standard Wattmeter (adding device).

The Radian values were read by means of software RR-PC Suite via RS-232 port. The standard used by UTE is based on the adding principle described in reference[10], its output was measured using a digital voltmeter (Agilent 3458A) running with Swerlein Algorithm[11].

The current was measured with a Current - Voltage Transducer.

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[9] E. So, R. Arseneau, and D. Angelo, “An improved current-comparator-based power standard at 120 V/5 A, 50 Hz–60 Hz, with an uncertainty of 2.5 µW/VA (k = 1),” IEEE Trans. Instrum. Meas., vol. IM-62, no. 6, pp. 1704–1709, June 2013.

[10] RMS VOLTMETER BASED POWER AND POWER-FACTOR MEASURING SYSTEM. P. Braga, D. Slomovitz, International Journal of Electronics, vol. 75, No 3, pp. 561-565, Set. 1993.

[11] EVALUATION OF UNCERTAINTY IN AC VOLTAGE MEASUREMENT USING A DIGITAL VOLTMETER AND SWERLEIN’S ALGORITHM. G.A. Kyriazis, R. Swerlein, 0-7803-7242-5/02/©2002 IEEE

The reactive power of the reference wattmeter was calculated as $Q = \sqrt{(VI)^2 - P^2}$

Both meters were driven by a Calibrator Fluke 5500A, being the currents inputs in series and the voltages inputs in parallel.

A.10 Measurement standard at INM, Colombia

Method for electrical power: the used method was the differential direct comparison between our reference gauge standard, COM 3003DC, brand: Zera; Serial: 018832 and the test gauge.

Appendix B. Measurement results of the participating laboratories

Tables B.1 to B.8 show the measurement results of the participating laboratories including the pilot laboratory. The Tables also show the expanded uncertainty of measurements at a level of confidence p = 95.45 %

Information of measurement results is arranged with respect to the loops j=1, 2, which are also associated with the traveling standards RD-22-311 or RD-23-432. Tables B.1 to B.4, for loop j =1, show those NMIs in SIM which took part in the CCEM-K5 key comparison of power [1]. The laboratory UTE from Uruguay is also included in loop j=1 because of his reduced measurement uncertainty. Tables B.5 to B.8, for loop j = 2, show the remaining participants.

Tables B.1 to B.9 show the DATE and mean date of measurement, the latter being an average of the dates of measurement of the participants. It is used to calculate the Key Comparison Reference Value (KCRV), the difference between the laboratories measurements and the KCRV (DOEs), and the pair-wise degrees of equivalence (DOEs).

Measurement results and uncertainty of measurement of active power are expressed in terms of µW/VA, whereas those for reactive power are expressed in terms of µvar/VA.

As shown in the tables below, some participants did not carried out measurements at all the testing points as shown in Table 4. A blank cell shows that the participating laboratory did not submit its measurement results.

Table B.1. *Measurement results of Active Power. Loop j=1 in μW/VA.*

	Laboratory	Date	Mean date	P. F. = 1			P. F. = +0.5			P. F. = -0.5		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				Error [μW/VA]			Error [μW/VA]			Error [μW/VA]		
1	**CENAM**	29/12/2009	2009.99	-4.3	-4.1	-2.8	3.3	3.7	-1.4	-8.1	-2.4	-3.3
2	**CENAM**	24/05/2010 10/06/2010	2010.42	-6.6	-6.6	-6.5	-2.4	-2.3	-8.0	-4.7	1.4	1.0
3	**NIST**	02/07/2010 13/08/2010	2010.56	-1.0	-1.1	-0.6	2.1	0.6	-2.6	-3.5	-1.5	3.1
4	**CENAM**	01/09/2010 27/10/2010	2010.75	-5.1	-5.0	-5.4	-2.3	-2.4	-8.1	-3.0	2.8	2.2
5	**INMETRO**	06/12/2010 17/12/2010	2010.97	-4.0	-6.0	-6.0	6.0	3.0	0.0	-9.0	-7.0	-2.0
6	**CENAM**	25/02/2011 16/05/2011	2011.27	-6.7	-6.2	-6.6	-2.6	-2.5	-8.3	-4.2	1.7	1.3
7	**NRC**	25/05/2011 05/06/2011	2011.43	-6.5	-7.2	-6.1	-1.9	-1.5	-7.8	-4.2	1.4	3.1
8	**CENAM**	25/08/2011 24/10/2011	2011.75	-5.7	-5.4	-5.6	-1.5	-1.5	-7.2	-4.2	1.7	1.2
9	**UTE**	15/12/2011 21/12/2011	2011.97	0.0	11.0	-3.0	0.0	3.0	-4.0	7.0	11.0	13.0
10	**INTI**	15/01/2012 20/02/2012	2012.07	7.0	11.0	14.0	2.0	10.0	15.0	-3.0	0.0	-1.0
11	**CENAM**	15/03/2012 02/04/2012	2012.22	-2.3	-2.2	-2.4	0.4	0.4	-5.4	-3.2	2.9	2.5

Table B.2. *Expanded uncertainty (p=95.45%) in Active Power. Loop j=1 in μW/VA.*

	Laboratory	Date	Mean date	P. F. = 1			P. F. = +0.5			P. F. = -0.5		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				U [μW/VA]			U [μW/VA]			U [μW/VA]		
1	**CENAM**	29/12/2009	2009.99	20	20	20	20	20	20	20	20	20
2	**CENAM**	24/05/2010 10/06/2010	2010.42	20	20	20	20	20	20	20	20	20
3	**NIST**	02/07/2010 13/08/2010	2010.56	9	9	9	9	9	9	9	9	9
4	**CENAM**	01/09/2010 27/10/2010	2010.75	20	20	20	20	20	20	20	20	20
5	**INMETRO**	06/12/2010 17/12/2010	2010.97	22	22	22	26	26	26	26	26	26
6	**CENAM**	25/02/2011 16/05/2011	2011.27	20	20	20	20	20	20	20	20	20
7	**NRC**	25/05/2011 05/06/2011	2011.43	8	8	8	8	8	8	8	8	8
8	**CENAM**	25/08/2011 24/10/2011	2011.75	20	20	20	20	20	20	20	20	20
9	**UTE**	15/12/2011 21/12/2011	2011.97	20	20	23	40	40	41	40	40	41
10	**INTI**	15/01/2012 20/02/2012	2012.07	25	25	25	32	32	32	32	32	32
11	**CENAM**	15/03/2012 02/04/2012	2012.22	20	20	20	20	20	20	20	20	20

Table B.3. *Measurement results of Reactive Power. Loop j=1 in µvar/VA.*

	Laboratory	DATE	Mean date	90° lead			90° lag			30° lead			30° lag		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				Error [µvar/VA]			Error [µvar/VA]			Error [µvar/VA]			Error [µvar/VA]		
1	**CENAM**	29/12/2009	2009.99	-8.2	-8.1	-7.4	-9.2	-9.0	-9.2	-2.4	-6.3	-2.7	8.7	7.3	1.3
2	**CENAM**	24/05/2010 10/06/2010	2010.42	-5.7	-5.7	-5.0	-11.9	-11.6	-11.6	0.3	-3.6	0.1	8.8	7.4	1.5
3	**NIST**	02/07/2010 13/08/2010	2010.56	-14.5	-13.9	-14.2	-2.8	-2.9	-1.3	-1.8	-4.2	-7.9	4.1	1.9	-1.3
4	**CENAM**	01/09/2010 27/10/2010	2010.75	-7.3	-7.1	-5.8	-10.2	-10.1	-10.6	-1.4	-5.0	-0.9	8.8	7.4	1.3
5	**INMETRO**	06/12/2010 17/12/2010	2010.97	-8.0	-7.0	-7.0	-9.0	-11.0	-10.0	-4.0	-3.0	3.0	5.0	3.0	-2.0
6	**CENAM**	25/02/2011 16/05/2011	2011.27	-5.7	-5.7	-4.8	-11.6	-11.5	-11.7	-0.1	-3.9	0.0	8.6	7.1	1.1
7	**NRC**	25/05/2011 05/06/2011	2011.43	-16.6	-18.4	-9.5	1.7	2.0	-5.7	-0.5	-3.5	-0.1	9.5	7.8	1.8
8	**CENAM**	25/08/2011 24/10/2011	2011.75	-6.4	-6.3	-5.2	-11.1	-11.0	-11.3	0.0	-3.6	0.3	9.4	7.9	1.9
9	**UTE**	15/12/2011 21/12/2011	2011.97	14.0	22.0	13.0	-2.0	8.0	2.0	-3.0	4.0	2.0	3.0	9.0	-9.0
10	**INTI**	15/01/2012 20/02/2012	2012.07	31.0	29.0	32.0	48.0	45.0	55.0	19.0	20.0	17.0	19.0	19.0	24.0
11	**CENAM**	15/03/2012 02/04/2012	2012.22	-10.2	-9.9	-8.9	-7.5	-7.5	-7.8	-1.0	-4.7	-0.9	11.9	10.4	4.3

Table B.4. *Expanded uncertainty (p=95.45%) in Reactive Power. Loop j=1 in µvar/VA.*

	Laboratory	Date	Mean date	90° lead			90° lag			30° lead			30° lag		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				U [µvar/VA]			U [µvar/VA]			U [µvar/VA]			U [µvar/VA]		
1	**CENAM**	29/12/2009	2009.99	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
2	**CENAM**	24/05/2010 10/06/2010	2010.42	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
3	**NIST**	02/07/2010 13/08/2010	2010.56	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
4	**CENAM**	01/09/2010 27/10/2010	2010.75	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
5	**INMETRO**	06/12/2010 17/12/2010	2010.97	22.0	22.0	22.0	22.0	22.0	22.0	26.3	26.3	26.4	26.3	26.3	26.4
6	**CENAM**	25/02/2011 16/05/2011	2011.27	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
7	**NRC**	25/05/2011 05/06/2011	2011.43	8.0	9.0	8.0	8.0	9.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
8	**CENAM**	25/08/2011 24/10/2011	2011.75	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
9	**UTE**	15/12/2011 21/12/2011	2011.97	26.0	26.0	27.0	26.0	26.0	27.0	41.0	41.0	42.0	41.0	41.0	42.0
10	**INTI**	15/01/2012 20/02/2012	2012.07	26.0	26.0	26.0	26.0	26.0	26.0	40.0	40.0	40.0	40.0	40.0	40.0
11	**CENAM**	15/03/2012 02/04/2012	2012.22	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0

Table B.5. *Measurement results of Active Power. Loop j=2 in μW/VA.*

	Laboratory	Date	Mean date	P. F. = 1			P. F. = +0.5			P. F. = -0.5		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				Error [μW/VA]			Error [μW/VA]			Error [μW/VA]		
1	**CENAM**	29/12/2009	2009.99	-24.4	-18.7	-3.5	-13.8	-11.3	-9.2	-10.9	-1.5	6.4
2	**CENAM**	24/05/2010 10/06/2010	2010.42	-24.1	-17.8	-1.5	-17.5	-14.7	-12.9	-7.0	2.5	10.7
3	**INDECOPI**	31/08/2010 13/09/2010	2010.68	-----	-----	-2.5	-----	-----	-12.6	-----	-----	13.9
4	**INM**	30/10/2010 01/11/2010	2010.83	-32.0	2.0	-6.0	-33.0	18.0	-42.0	17.0	-4.0	26.0
5	**CENAM**	15/12/2010 26/01/2011	2011.02	-19.9	-14.2	1.3	-14.4	-11.9	-10.8	-6.0	3.4	11.8
6	**CENAM**	03/02/2011 25/02/2011	2011.12	-19.0	-13.0	2.6	-13.1	-10.6	-9.3	-6.4	3.0	11.2
7	**CENAM**	04/03/2011 08/04/2011	2011.22	-22.3	-15.7	-0.1	-15.8	-13.0	-11.4	-6.6	2.8	11.1
8	**ICE**	11/05/2011 17/05/2011	2011.37	-----	-----	4.1	-----	-----	15.6	-----	-----	5.8
9	**CENAMEP**	16/06/2011 23/06/2011	2011.47	-16.6	-3.3	20.1	-8.2	17.4	31.0	-5.6	-15.5	-4.6
10	**CENAM**	13/10/2011 28/10/2011	2011.81	-21.9	-16.0	-0.5	-17.6	-15.2	-14.4	-4.7	4.7	13.1
11	**CENAM**	04/11/2011 25/11/2011	2011.87	-21.8	-16.1	-0.9	-16.5	-14.3	-13.6	-5.9	3.7	12.1
12	**CENAM**	02/12/2011 23/12/2011	2011.95	-21.0	-15.1	0.3	-15.5	-13.2	-12.1	-5.9	3.6	11.8
13	**CENAM**	06/01/2012 26/01/2012	2012.04	-22.5	-16.4	-0.9	-17.5	-14.9	-13.7	-5.4	4.0	12.1
14	**CENAM**	02/02/2012 24/02/2012	2012.12	-20.4	-14.5	1.2	-18.0	-15.4	-14.1	-3.0	6.4	14.7
15	**CENAM**	01/03/2012 23/03/2012	2012.20	-18.3	-12.2	3.4	-15.1	-12.5	-11.2	-3.7	5.8	14.0
16	**CENAM**	02/04/2012	2012.25	-20.5	-14.5	1.2	-15.1	-12.6	-11.0	-5.8	3.5	11.5

Note: Cells in blank on Tables B5 to B8 correspond to null measurements of the participants.

Table B.6. *Expanded uncertainty (p=95.45%) in Active Power. Loop j=2 in µW/VA.*

	Laboratory	Date	Mean date	P. F. = 1			P. F. = +0.5			P. F. = -0.5		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				U [µW/VA]			U [µW/VA]			U [µW/VA]		
1	**CENAM**	29/12/2009	2009.99	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
2	**CENAM**	24/05/2010 10/06/2010	2010.42	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
3	**INDECOPI**	31/08/2010 13/09/2010	2010.68	-----	-----	133.0	-----	-----	70.0	-----	-----	70.0
4	**INM**	30/10/2010 01/11/2010	2010.83	110.0	110.0	93.6	116.2	110.3	93.6	111.9	130.8	102.7
5	**CENAM**	15/12/2010 26/01/2011	2011.02	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
6	**CENAM**	03/02/2011 25/02/2011	2011.12	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
7	**CENAM**	04/03/2011 08/04/2011	2011.22	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
8	**ICE**	11/05/2011 17/05/2011	2011.37	-----	-----	103.2	-----	-----	202.2	-----	-----	202.0
9	**CENAMEP**	16/06/2011 23/06/2011	2011.47	61.9	62.1	64.0	92.7	92.9	94.2	92.7	92.8	94.7
10	**CENAM**	13/10/2011 28/10/2011	2011.81	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
11	**CENAM**	04/11/2011 25/11/2011	2011.87	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
12	**CENAM**	02/12/2011 23/12/2011	2011.95	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
13	**CENAM**	06/01/2012 26/01/2012	2012.04	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
14	**CENAM**	02/02/2012 24/02/2012	2012.12	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
15	**CENAM**	01/03/2012 23/03/2012	2012.20	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
16	**CENAM**	02/04/2012	2012.25	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0

Note: Cells in blank on Tables B5 to B8 correspond to null measurements of the participants.

Table B.7. *Measurement results of Reactive Power. Loop j=2 in µvar/VA.*

	Laboratory	Date	Mean date	90° lead			90° lag			30° lead			30° lag		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				Error [µvar/VA]			Error [µvar/VA]			Error [µvar/VA]			Error [µvar/VA]		
1	**CENAM**	29/12/2009	2009.99	11.3	5.6	-8.5	-34.4	-28.0	-11.3	2.2	-5.4	-9.3	-9.2	-7.9	-6.6
2	**CENAM**	24/05/2010 10/06/2010	2010.42	9.8	3.4	-12.1	-31.3	-25.1	-9.3	0.6	-6.8	-12.0	-8.4	-7.2	-5.9
3	**INDECOPI**	31/08/2010 13/09/2010	2010.68	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
4	**INM**	30/10/2010 01/11/2010	2010.83	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
5	**CENAM**	15/12/2010 26/01/2011	2011.02	5.8	0.1	-14.9	-27.0	-21.3	-5.9	-0.4	-7.7	-13.0	-5.2	-4.6	-3.7
6	**CENAM**	03/02/2011 25/02/2011	2011.12	4.9	-0.9	-15.7	-25.7	-20.0	-4.7	0.2	-7.2	-12.2	-3.5	-2.8	-1.9
7	**CENAM**	04/03/2011 08/04/2011	2011.22	8.2	1.9	-13.3	-29.0	-22.8	-7.3	0.3	-7.0	-12.1	-6.4	-5.5	-4.4
8	**ICE**	11/05/2011 17/05/2011	2011.37	-----	-----	7.4	-----	-----	6.3	-----	-----	15.6	-----	-----	2.7
9	**CENAMEP**	16/06/2011 23/06/2011	2011.47	1.4	4.8	51.0	18.1	2.6	-28.9	9.5	-2.3	13.8	16.7	-5.2	-21.4
10	**CENAM**	13/10/2011 28/10/2011	2011.81	8.1	2.5	-12.1	-28.8	-23.1	-8.1	-0.9	-8.2	-13.5	-7.7	-7.1	-6.8
11	**CENAM**	04/11/2011 25/11/2011	2011.87	8.3	2.6	-12.1	-29.1	-23.3	-8.4	-0.1	-7.4	-12.7	-7.1	-6.4	-6.2
12	**CENAM**	02/12/2011 23/12/2011	2011.95	7.2	1.7	-13.1	-28.0	-22.5	-7.4	0.0	-7.2	-12.3	-6.1	-5.3	-4.7
13	**CENAM**	06/01/2012 26/01/2012	2012.04	8.3	2.5	-12.6	-29.1	-23.2	-7.9	-0.8	-7.9	-13.0	-7.8	-6.8	-6.0
14	**CENAM**	02/02/2012 24/02/2012	2012.12	7.2	1.4	-13.6	-28.0	-22.1	-6.8	-2.9	-10.1	-15.2	-8.9	-7.9	-7.1
15	**CENAM**	01/03/2012 23/03/2012	2012.20	4.4	-1.4	-16.5	-25.3	-19.3	-4.0	-2.3	-9.7	-14.8	-5.5	-4.7	-3.8
16	**CENAM**	02/04/2012	2012.25	6.5	0.6	-14.4	-27.3	-21.2	-5.9	0.1	-7.0	-11.8	-5.0	-3.9	-2.9

Note: Cells in blank on Tables B5 to B8 correspond to null measurements of the participants.

Table B.8. *Expanded uncertainty (p=95.45%) in Reactive Power. Loop j=2 in µvar/VA.*

	Laboratory	Date	Mean date	90° lead			90° lag			30° lead			30° lag		
				50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz	50 Hz	53 Hz	60 Hz
				U [µvar/VA]			U [µvar/VA]			U [µvar/VA]			U [µvar/VA]		
1	**CENAM**	29/12/2009	2009.99	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
2	**CENAM**	24/05/2010 10/06/2010	2010.42	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
3	**INDECOPI**	31/08/2010 13/09/2010	2010.68	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
4	**INM**	30/10/2010 01/11/2010	2010.83	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
5	**CENAM**	15/12/2010 26/01/2011	2011.02	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
6	**CENAM**	03/02/2011 25/02/2011	2011.12	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
7	**CENAM**	04/03/2011 08/04/2011	2011.22	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
8	**ICE**	11/05/2011 17/05/2011	2011.37	-----	-----	116.5	-----	-----	116.3	-----	-----	116.5	-----	-----	116.6
9	**CENAMEP**	16/06/2011 23/06/2011	2011.47	65.5	65.7	67.2	65.5	65.7	66.6	95.4	95.5	95.8	95.4	95.6	95.5
10	**CENAM**	13/10/2011 28/10/2011	2011.81	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
11	**CENAM**	04/11/2011 25/11/2011	2011.87	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
12	**CENAM**	02/12/2011 23/12/2011	2011.95	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
13	**CENAM**	06/01/2012 26/01/2012	2012.04	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
14	**CENAM**	02/02/2012 24/02/2012	2012.12	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
15	**CENAM**	01/03/2012 23/03/2012	2012.20	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
16	**CENAM**	02/04/2012	2012.25	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0

Note: Cells in blank on Tables B5 to B8 correspond to null measurements of the participants.

Figures 1 to 42 show the measurement results and the uncertainty for k = 2 of the participating laboratories. A single figure is devoted for each one of the testing points of the comparison as shown in Table 4 in this document.

Figures 1 to 9: *Active Power, Loop j = 1.*

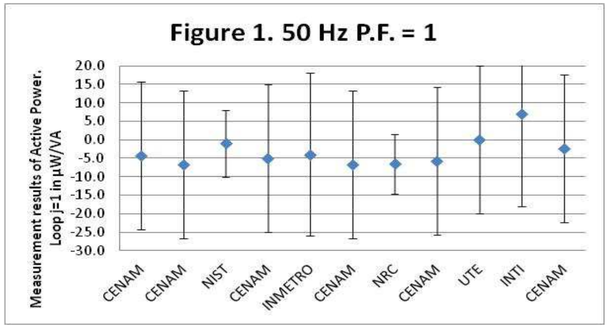


Figure 1. 50 Hz P.F. = 1

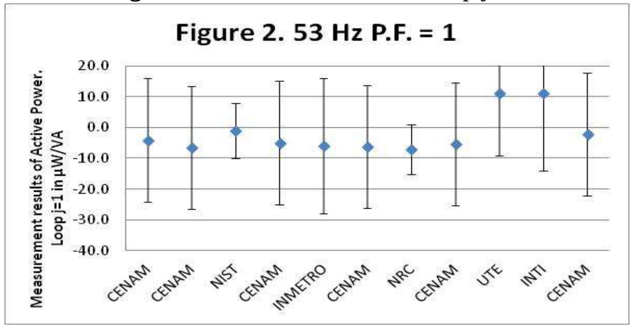


Figure 2. 53 Hz P.F. = 1

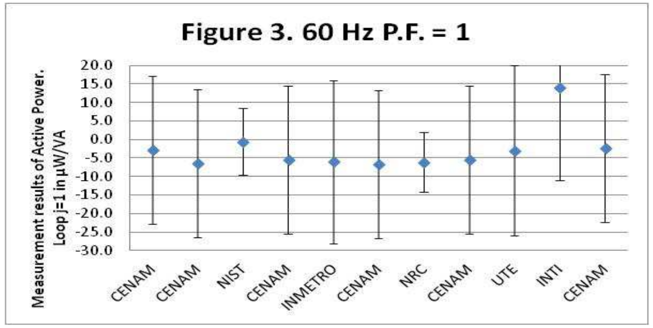


Figure 3. 60 Hz P.F. = 1

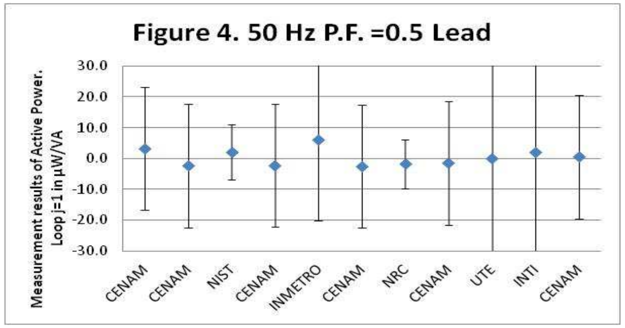


Figure 4. 50 Hz P.F. =0.5 Lead

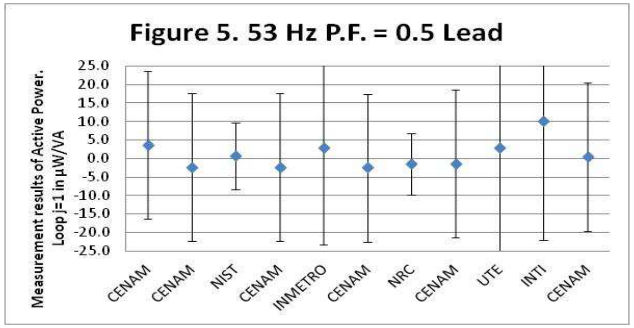


Figure 5. 53 Hz P.F. = 0.5 Lead

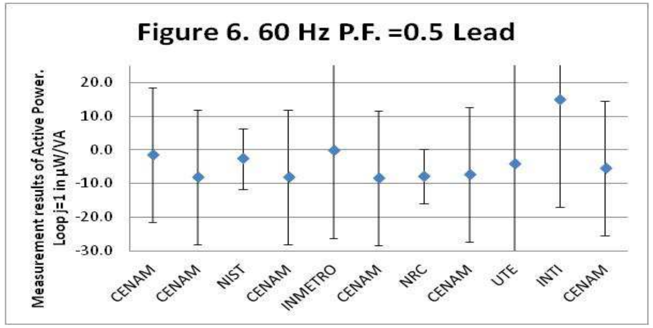


Figure 6. 60 Hz P.F. =0.5 Lead

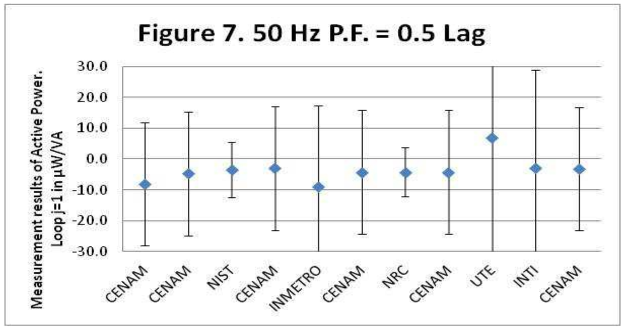


Figure 7. 50 Hz P.F. = 0.5 Lag

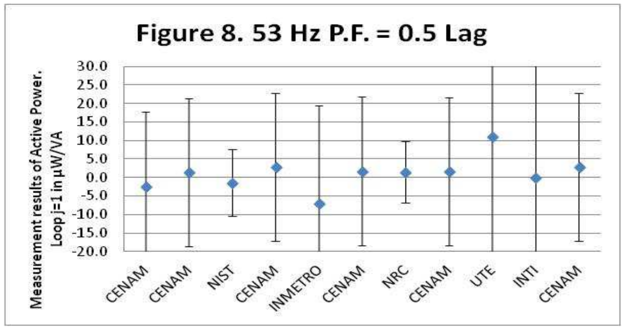


Figure 8. 53 Hz P.F. = 0.5 Lag

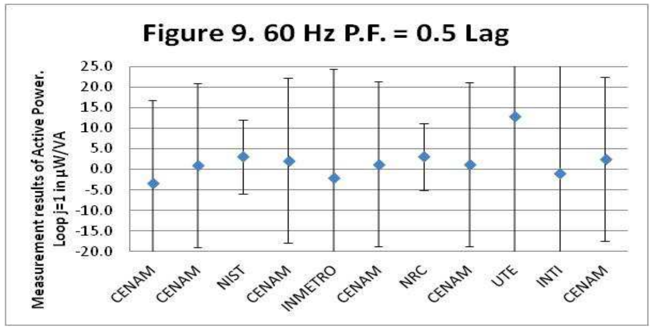


Figure 9. 60 Hz P.F. = 0.5 Lag

Figures 10 to 21: Reactive Power, Loop j = 1

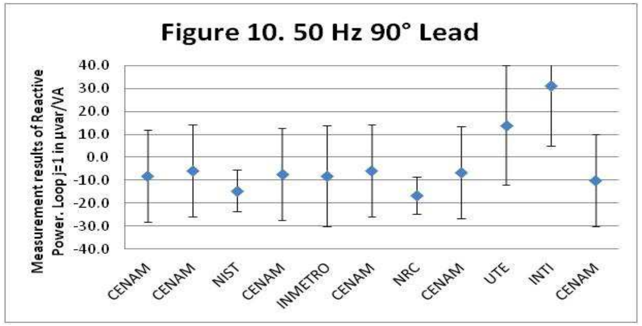


Figure 10. 50 Hz 90° Lead

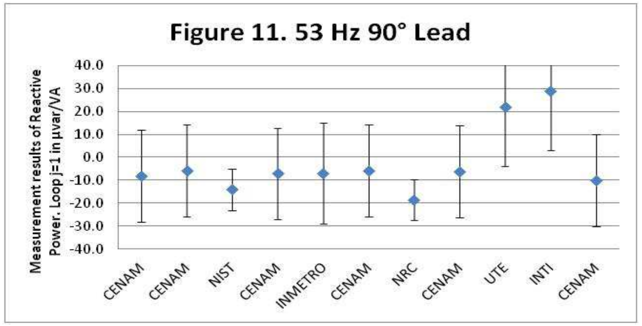


Figure 11. 53 Hz 90° Lead

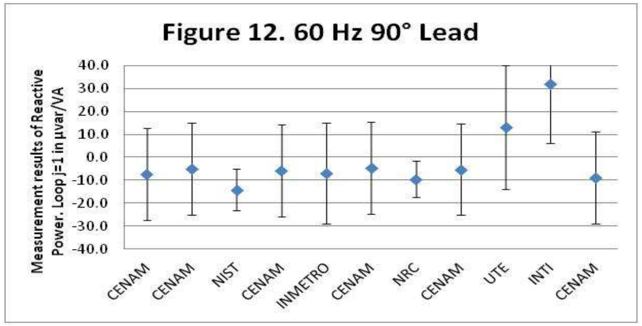


Figure 12. 60 Hz 90° Lead

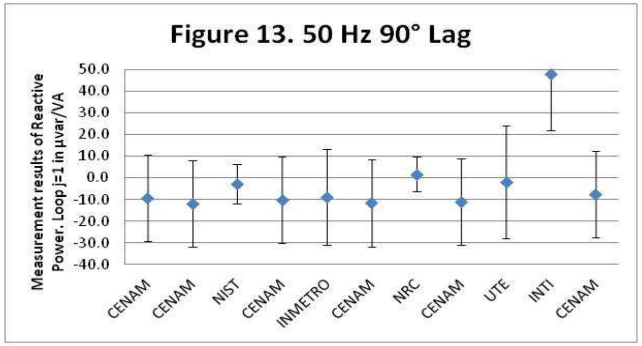


Figure 13. 50 Hz 90° Lag

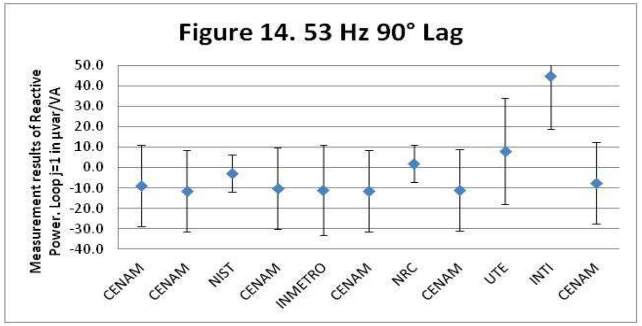


Figure 14. 53 Hz 90° Lag

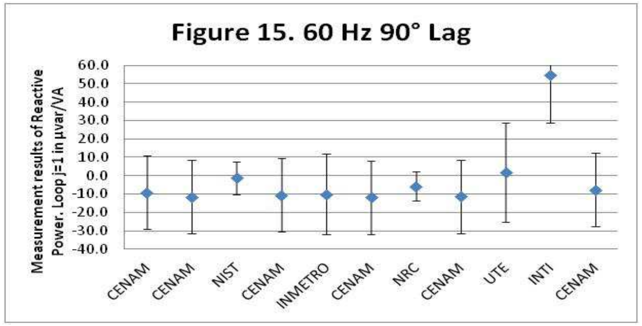


Figure 15. 60 Hz 90° Lag

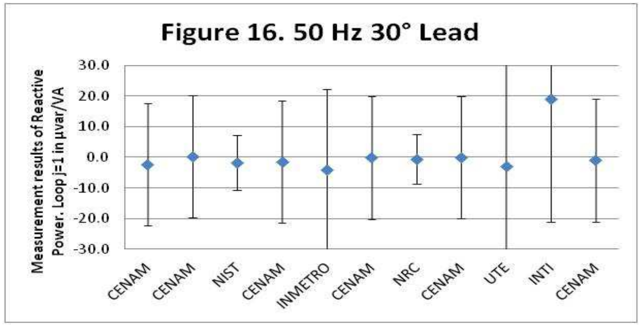


Figure 16. 50 Hz 30° Lead

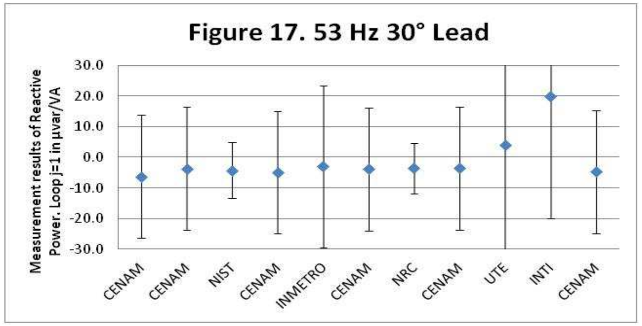


Figure 17. 53 Hz 30° Lead

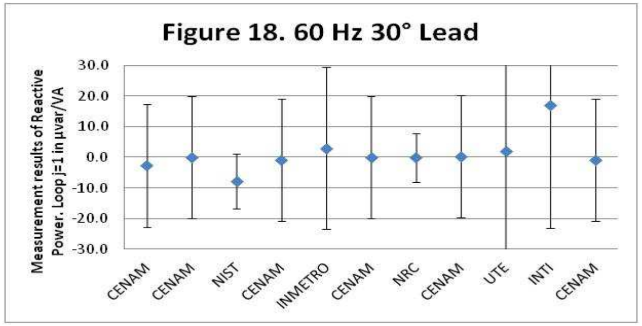


Figure 18. 60 Hz 30° Lead

Figure 19. 50 Hz 30° Lag

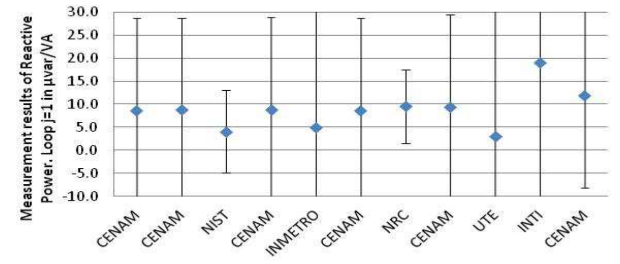


Figure 20. 53 Hz 30° Lag

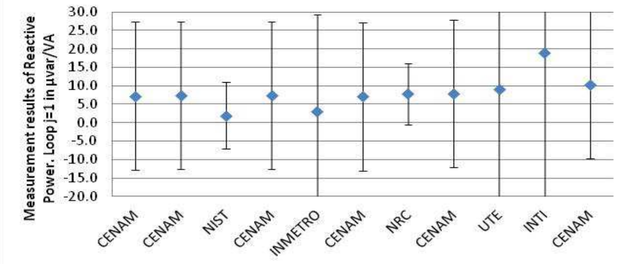
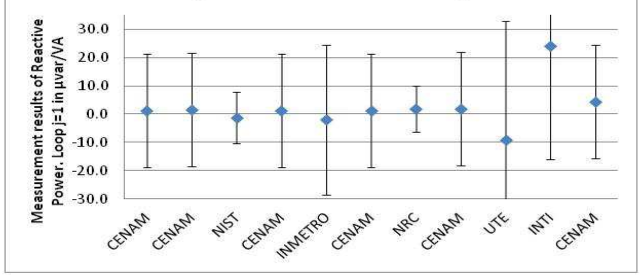


Figure 21. 60 Hz 30° Lag



Figures 22 to 30: Active Power. Loop *j* = 2

Figure 22. 50 Hz P.F. = 1

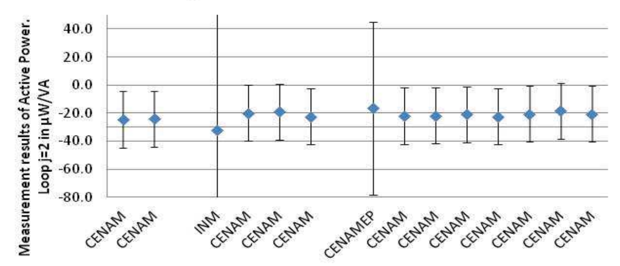


Figure 23. 53 Hz P.F. = 1

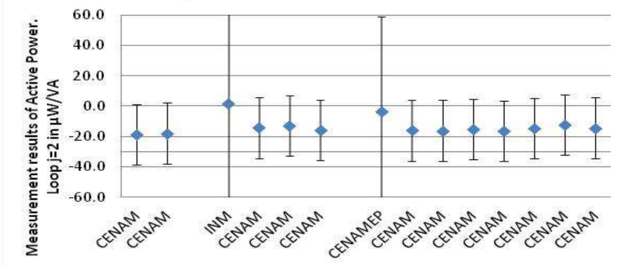


Figure 24. 60 Hz P.F. = 1

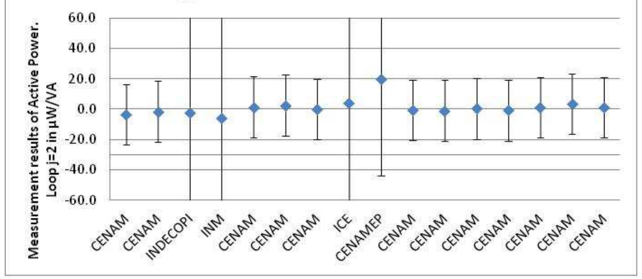


Figure 25. 50 Hz P.F. = 0.5 Lead

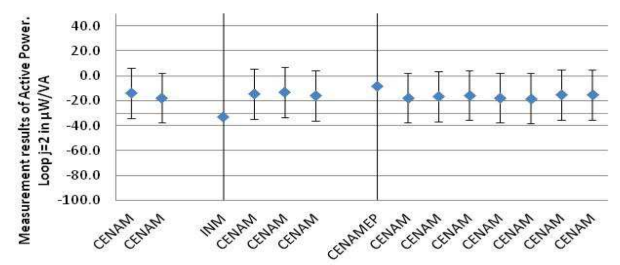


Figure 26. 53 Hz P.F. = 0.5 Lead

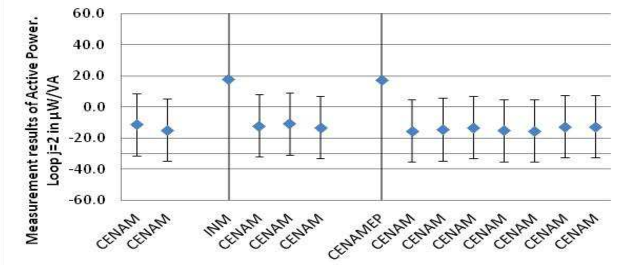
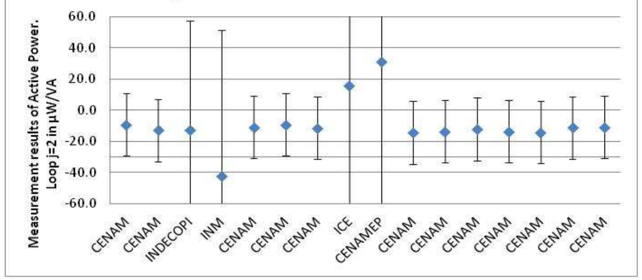


Figure 27. 60 Hz P.F. = 0.5 Lead



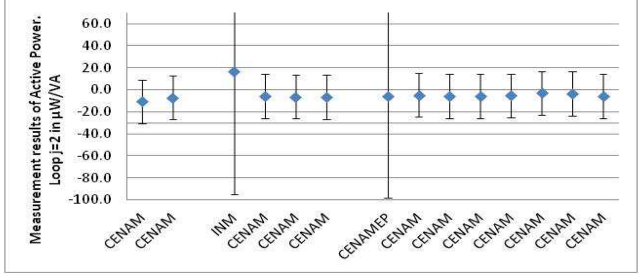


Figure 28. 50 Hz P.F. = 0.5 Lag

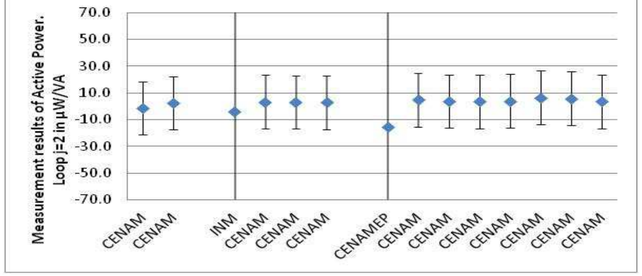


Figure 29. 53 Hz P.F. = 0.5 Lag

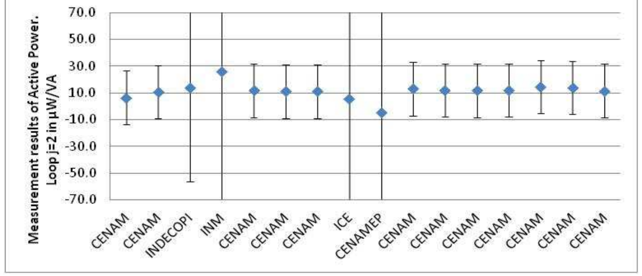


Figure 30. 60 Hz P.F. = 0.5 Lag

Figures 31 to 42: Reactive Power. Loop *j* = 2

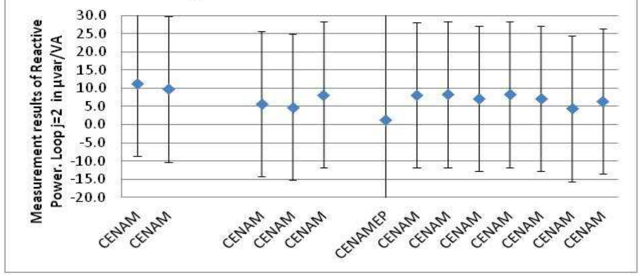


Figure 31. 50 Hz 90° Lead

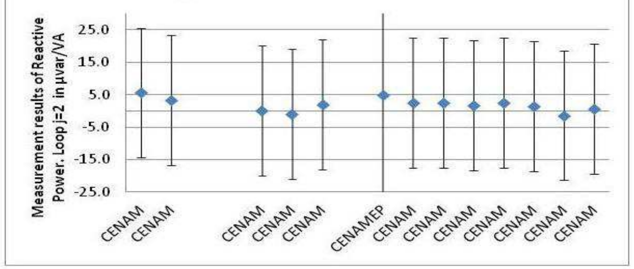


Figure 32. 53 Hz 90° Lead

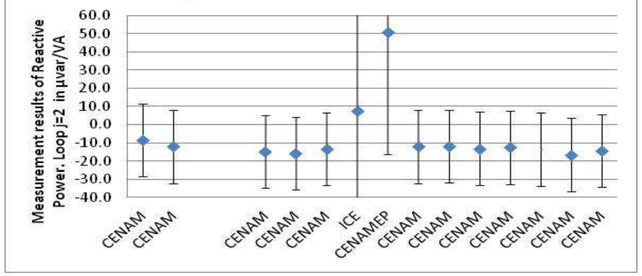


Figure 33. 60 Hz 90° Lead

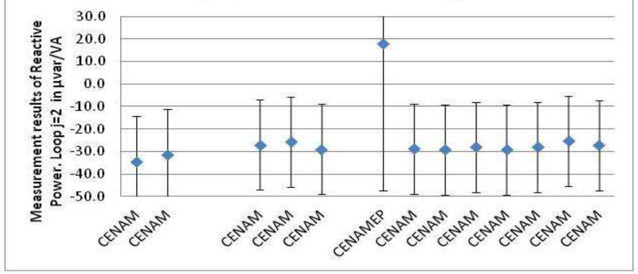


Figure 34. 50 Hz 90° Lag

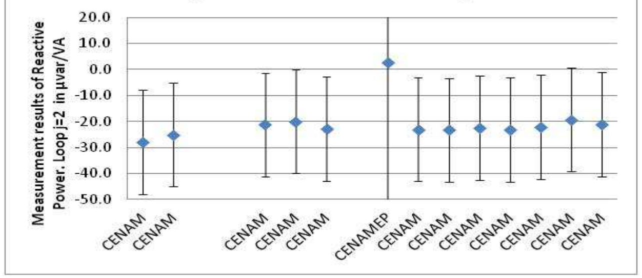


Figure 35. 53 Hz 90° Lag

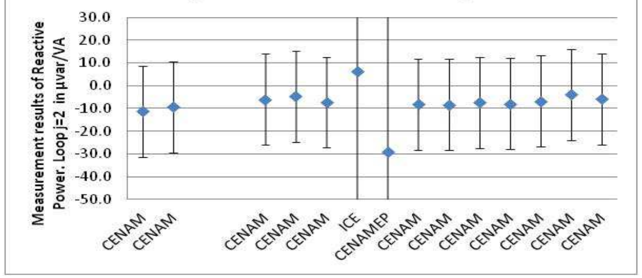


Figure 36. 60 Hz 90° Lag

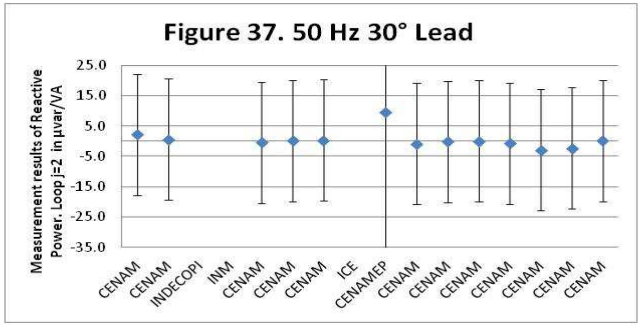


Figure 37. 50 Hz 30° Lead

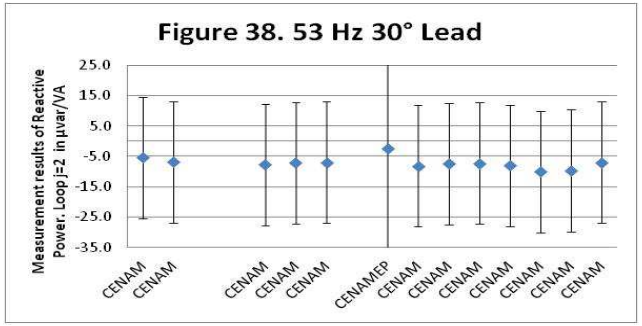


Figure 38. 53 Hz 30° Lead

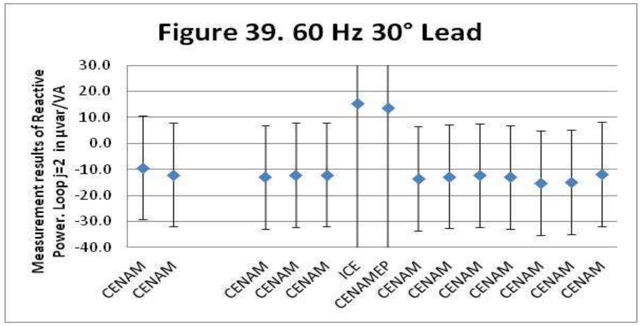


Figure 39. 60 Hz 30° Lead

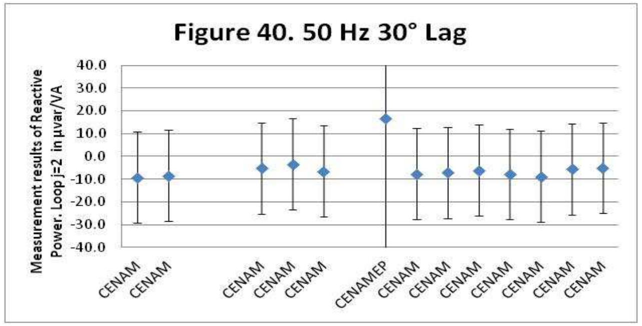


Figure 40. 50 Hz 30° Lag

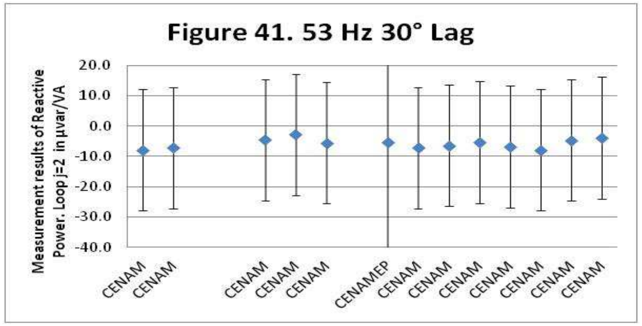


Figure 41. 53 Hz 30° Lag

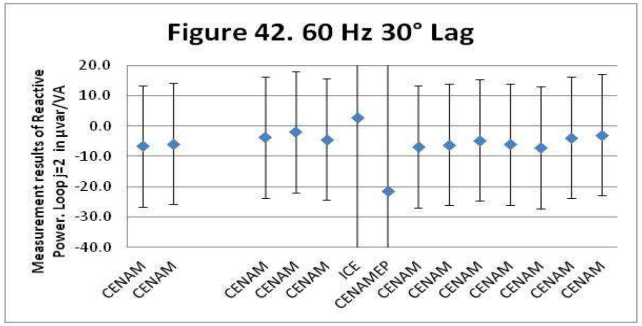


Figure 42. 60 Hz 30° Lag

SIM.EM-K5 key comparison 50/60 Hz power.

ADDENDUM

Link between the CCEM-K5:2002 and SIM.EM-K5:2012.

CENAM, México. November 2014

As requested per the CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons, the results of the recently completed SIM.EM-K5 key comparison 50/60 Hz power have to be linked with the results of the last key comparison organized by the CIPM, the CCEM-K5 in the same key quantity.

This Addendum to the Final Report of the SIM.EM-K5 key comparison 50/60 Hz power [1] recently submitted by CENAM to the CCEM, aims at proposing a link of this comparison with the results of the CCEM-K5 key comparison of 50/60 Hz power piloted by NIST, completed in year 2000 and reported in June 2002 [2].

The link in this Addendum between the CCEM-K5 and SIM.EM-K5 is based on the work of F. Delahaye and T. Witt, published in June 2002 [3]. The link basically consists of a correction to be added to the results of the SIM.EM-K5 comparison so that the transformed results can be directly compared with the results of the CCEM.K5 comparison, where the additive correction is determined by a weighted mean of the corresponding differences of the linking laboratories. This criterion may be applicable since the CCEM-K5 and SIM.EM-K5 are of the same quantity of active power at 120 V, 5 A, 53 Hz and power factor equal to 1 and 0.5 lead-lag. This procedure does not change the CCEM-K5 key comparison reference value. From this link the degrees of equivalence DOEs are calculated.

In order to have a meaningful link between the two comparisons, the laboratories of the SIM region which took part in both comparisons accepted that their measurement results in both cases were used to link the SIM.EM-K5 results with those of the CCEM-K5. The measurement results provide a 1σ estimate of the uncertainty corresponding to the imperfect reproducibility of the measurements carried out by the link laboratories of SIM during the time span between the two comparisons.

1. Information from the CCEM-K5 and SIM.EM-K5 key comparisons of 50/60 Hz power.

1.1. CCEM-K5 key comparison of 50/60 Hz power. Pilot laboratory: NIST, USA. Duration 1996-2000, and reported in June 2002 [2].

Test points: 120 V, 5 A, 53 Hz, power factor: 1.0; 0.5 and 0.0 lead-lag.

Participants, region and measurement dates:

Laboratory	Region	Measurement Date
NIST, National Institute of Standards and Technology, USA	**SIM**	Jun 1996-Oct 2000
NRC, National Research Council, Canada	**SIM**	Jun 1996 and Sep 1998
PTB, Physikalische-Technische Bundesanstalt, Germany	EUROMET/COOMET	Aug 1996 and May 1999
SP, Swedish National Research and Testing Institute, Sweden	EUROMET	Sep 1996 and Oct 2000
CSIRO-NML, Commonwealth Scientific and Industrial Research Organization – National Measurement Laboratory, Australia	APMP	Nov 1996
MSL, Measurement Standards Laboratory, New Zealand	APMP	Dec 1996 and Aug 2000
NPL, National Physical Laboratory, UK	EUROMET	Mar 1997
IEN, Istituto Elettrotecnico Nazionale, Italy	EUROMET	Apr 1997
INTI, Instituto Nacional de Tecnología Industrial, Argentina	**SIM**	Aug 1997
NIM, National Institute of Metrology, China	APMP	Mar 1998 and Jun 2000
VNIIM, D. I. Mendeleyev Institute of Metrology, Russia	COOMET	Jun 1998
PSB, Productivity and Standards Board, Singapore	APMP	Dec 1998
CSIR-NML, Council for Scientific and Industrial Research – National Measurement Laboratory, South Africa	SADCMET	Feb 1999 and Sep 2000
INMETRO, Instituto Nacional de Metrologia, Normalização e Qualidade Industrial, Brazil	**SIM**	Jul 1999
CENAM, Centro Nacional de Metrología, México	**SIM**	Aug 1999

The name of some national metrology institutes in the above table are taken from the CEEM-K5 key comparison as reported in year 2002 [2].

1.2 SIM.EM-K5 key comparison of 50/60 Hz power [1]. Pilot laboratory: CENAM, México. Duration: April 2010 to April 2012 [1].

Test points:

Parameter	**Active power [W]**	**Reactive power [var]**
RMS voltage	120 V	
RMS current	5 A	
Power factor	1.0 and 0.5 lead/lag	
Phase angle		30 ° and 90 ° lead/lag
Frequencies	50, 53 and 60 Hz	50, 53 and 60 Hz

Participating laboratories and measurement dates:

LABORATORY	**date**	**LABORATORY**	**date**

Loop *j* = 1 NOTE 1 Reference standard: RD-22-311	
CENAM, México	Dec 2009 to Jun 2010
NIST, USA	Jul-Aug 2010
CENAM, México	Sep to Oct 2010
INMETRO, Brazil	Dec 2010
CENAM, México	Feb-May 2011
NRC, Canada	May-Jun 2011
CENAM, México	Aug-Oct 2011
UTE, Uruguay	Dec 2011
INTI, Argentina	Jan-Feb 2012
CENAM, Mexico	Mar-Apr 2012

Loop *j* = 2 Reference standard: RD-23-432	
CENAM, México	Dec 2009 to Jun 2010
LCPN-ME NOTE 2, Chile	Jul 2010
INDECOPI, Perú	Sep 2010
INM, Colombia	Nov 2010
CENAM, México	Dec 2010-Apr 2011
ICE, Costa Rica	May 2011
CENAMEP, Panamá	Jun 2011
CENAM, México	Oct 2011- Apr 2012

Notes:

1. In order of linking the SIM.EM-K5 and the CCEM-K5 measurement results, reference is made for laboratories participating in the SIM.EM-K5 using the reference standard RD-22-311 as shown in the above Table for loop *j* = 1. It should be said that UTE, Uruguay did not participate in the CCEM-K5 comparison.

2. The laboratory LCPN-ME received the reference standard RD-23-432 on the date shown above, but it did not submit its measurement results of power. This laboratory participated in the SIM.EM-S7 supplementary comparison 50/60 Hz energy piloted by CENAM, where the same traveling standard was used.

2. Measurement results from the linking laboratories participating in both comparisons.

The CCEM-K5 and SIM.EM-K5 comparisons have the following measuring points in common: 120 V, 5A, frequency = 53 Hz; power factor: 1.0 and 0.5 lead/lag. Thus, the linking procedure between both comparisons is limited to these measuring points.

2.1 CCEM-K5 Key Comparison Reference Value (KCRV) and uncertainty at k=2. Values are expressed in µW/VA [2].

Power Factor	X_{KCRV}	U_{KCRV}
1.0	7	5
0.5 lead	-1	5
0.5 lag	-1	5

2.2 CCEM-K5 Differences with respect of the KCRV and combined standard uncertainties [2].

$D_{i,KCRV}$: differences in µW/VA

$U_{D_{i,KCRV}}$: expanded combined uncertainties of $D_{i,KCRV}$ (k=2) in µW/VA

Table 1. Differences of $KCRV_{CCEM\text{-}K5}$

	Laboratory	**1.0 pf**		**0.5 lead**		**0.5 lag**	
		$D_{i,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,KCRV}$	$U_{D_{i,KCRV}}$
1	NIST	-7	12	1	12	1	12
2	INTI	15	20	9	34	4	34
3	NRC	-4	14	5	12	-3	12
4	INMETRO	-9	60	15	60	-26	60
5	CENAM	4	34	-2	34	2	34

2.3 **SIM.EM-K5 Key Comparison Reference Value (KCRV) and uncertainty at k=2. Values expressed in µV/VA [3].**

Power Factor	$\mathbf{X_{KCRV}}$	$\mathbf{U_{KCRV}}$
1.0	2.0	5.5
0.5 lead	1.5	7.0
0.5 lag	-1.2	5.9

2.4 SIM.EM-K5 Differences with respect of the KCRV and combined standard uncertainties [3].

$D_{i,\,KCRV}$: differences in µW/VA
$U_{D_{i,KCRV}}$: expanded combined uncertainties of $D_{i,\,KCRV}$ (k=2) in µW/VA

Table 2. Differences of $KCRV_{SIM.EM-K5}$

	laboratory	**1.0 pf**		**0.5 lead**		**0.5 lag**	
		$D_{i,\,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,\,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,\,KCRV}$	$U_{D_{i,KCRV}}$
1	NIST	2.8	8	0.5	8	-1	9
2	INTI	13.6	25	10.9	32	-2.1	32
3	NRC	-4	7	-1	7	0.4	8
4	INMETRO	-2.4	22	3.2	26	-7.3	26
5	CENAM	-1.7	20	-0.7	20	0.9	20

3. Method for linking the CCEM-K5 and SIM.EM-K5 key comparisons of 50/60 Hz power.

The following linking method is based on the work of Delahaye and Witt, 2002 [3].

i. The key comparison reference value derived from the CCEM-K5, denoted as $KCRV_{CCEM-K5}$, is used as the reference value for linking the SIM.EM-K5. The measurement results and uncertainties from the CCEM-K5 are unaltered by this linking procedure.

ii. Let D_S to denote the difference with respect of the $KCRV_{SIM-K5}$ of a laboratory participating only in the SIM.EM-K5 comparison. The present linking method aims at providing an estimate $\widehat{D}_S$ of D_S, if such laboratory would had participated in the CCEM-K5:

$$\widehat{D}_S = D_S + d, \tag{1}$$

where d is a correction which may be estimated by a weighted mean of the differences d_C of the c = 1, 2, … C linking laboratories which participated in both the CCEM-K5 and SIM.EM-K5 comparisons:

$$d = \sum_{c=1}^{C} w_c\, d_c \ , \tag{2}$$

where the weights are determined by the uncertainties of the linking laboratories:

$$w_c = \frac{\frac{1}{s_c^2}}{\sum_{c=1}^{C} \frac{1}{s_c^2}} \ , \tag{3}$$

and

$$d_c = D_c - D_{cs}, \tag{4}$$

D_C: difference from the KCRV$_{CCEM\text{-}K5}$ for a linking laboratory CCEM-K5 and SIM.EM-K5

D_{CS}: difference from the KCRV$_{SIM.EM\text{-}K5}$ for a linking laboratory CCEM-K5 and SIM.EM-K5

iii. In the above rationale the following underlying assumptions may apply:

- there is a possibility that a bias in the measurement results of the linking laboratories may exist which may remain constant within an uncertainty interval, over the time between the CCEM-K5 and the SIM.EM-K5 comparisons;
- the bias and its associated uncertainty, may be referred to as the reproducibility of the measurement results from the linking laboratories.

iv. The uncertainty s_C of the linking laboratories associated with the weighted mean in equation 3 is given by:

$$s_c^2 = u_c^2 + u_s^2 + 2r_c^2 \, , \qquad (5)$$

where:

- u_c^2 : uncertainty of difference D_c of a linking laboratory with respect of the KCRV$_{CCEM\text{-}K5}$;
- u_s^2: uncertainty of difference D_{cs} of a linking laboratory with respect of the KCRV$_{SIM.EM\text{-}K5}$;
- $2r_c^2$: uncertainty of the imperfect reproducibility of results of a linking laboratory in the time period, which spans its measurements at the CCEM-K5 and at the SIM.EM-K5 comparisons, whence the factor of 2.

4. Linking the SIM.EM-K5 and the CCEM-K5 comparisons.

By the time of preparing the present Link Report, all the SIM linking laboratories have agreed upon that their measurement results and uncertainties obtained in the CCEM-K5 be used to link the SIM.EM-K5 comparison. Hence, the following calculations have been done:

1. As a way to estimate how much impact using the CCEM-K5 results in the SIM.EM-K5 would have, a conservative value of reproducibility of results over the time span between the two comparisons was accepted to be r_c = 10 at k= 2.
2. From Tables 1 and 2, and using the above equations 1 to 4, the link calculations are carried out at the different power factors:

4.1 Linking results at pf= 1.0

Laboratory	d_C	r_C	s_C		w_C	w_C*d_C
NIST	-9.8	10	20	0.0025	0.388	-3.80
INTI	1.4	10	35	0.0008	0.129	0.18
NRC	0	10	21	0.0022	0.356	0.00
INMETRO	-6.6	10	65	0.0002	0.037	-0.24
CENAM	5.7	10	42	0.0006	0.090	0.51

From equations 1 and 2 above, $\boldsymbol{d_{pf\,=}}$ **1.0 = -3.4 µW/VA**. The uncertainty associated with d_{pf} = 1.0 is $\boldsymbol{u_d}$ **= 2(1.8) = 3.6 µW/VA** at k =2.

Lab.	$D_{KCRV_{SIM-K5}}$	$U_{D_{KCRV_{SIM-K5}}}$	$U_{KCRV_{CCEM-K5}}$	$U_{KCRV_{SIM-K5}}$	$U_{d_{PF=1.0}}$	$\boldsymbol{\hat{D}_S = D_S + d}$	$\boldsymbol{U_{\hat{D}_S}}$
UTE	12.8	20	10	5.5	3.5	**9**	**23**
CENAMEP	11.5	62	10	5.5	3.5	**8**	**63**
INM	17.8	110	10	5.5	3.5	**14**	**111**

From the above, the following table shows the equivalence degrees and its expanded uncertainty (k=2) at 120V, 5A, pf = 1.0, 53 Hz, between CCEM-K5 and SIM.EM-K5, expressed in µW/VA:

Table 3. Link of the SIM.EM-K5 with the CCEM-K5 at 120 V, 5 A, 53 Hz, pf = 1.0.

Laboratory	$\boldsymbol{D_i}$	$\boldsymbol{U_{Di}}$/ **(k=2)**
NIST	-7	12
INTI	15	20
NRC	-4	14
INMETRO	-9	60
CENAM	4	34
UTE	$\boldsymbol{\hat{D}_S}$ = 9	$\boldsymbol{U_{\hat{D}_S}}$= 23
CENAMEP	$\boldsymbol{\hat{D}_S}$ = 8	$\boldsymbol{U_{\hat{D}_S}}$= 63
INM	$\boldsymbol{\hat{D}_S}$ = 14	$\boldsymbol{U_{\hat{D}_S}}$= 111

4.2 Linking results at pf = 0.5 lead

Laboratory	$\boldsymbol{d_C}$	$\boldsymbol{r_C}$	$\boldsymbol{s_C}$		$\boldsymbol{w_C}$	$\boldsymbol{w_C * d_C}$
NIST	0.5	10	20.2	0.0025	0.395	0.20
INTI	-1.9	10	48.8	0.0004	0.068	-0.13
NRC	6	10	19.8	0.0025	0.410	2.46
INMETRO	11.8	10	66.9	0.0002	0.036	0.42
CENAM	-1.3	10	41.9	0.0006	0.092	-0.12

From equations 1 and 2 above**,** $\boldsymbol{d_{pf\,=}}$ **0.5 lead = 2.8 µW/VA**. The uncertainty associated with d_{pf} = 0.5 lead is $\boldsymbol{u_d}$ **= 2(1.1) = 2.2 µW/VA** at k =2.

Lab.	$D_{KCRV_{SIM-K5}}$	$U_{D_{KCRV_{SIM-K5}}}$	$U_{KCRV_{CCEM-K5}}$	$U_{KCRV_{SIM-K5}}$	$U_{d_{PF=1.0}}$	$\boldsymbol{\hat{D}_S = D_S + d}$	$\boldsymbol{U_{\hat{D}_S}}$
UTE	2.4	40	10	5.5	2.2	**5**	**42**
CENAMEP	30.6	93	10	5.5	2.2	**33**	**94**
INM	30.5	110	10	5.5	2.2	**33**	**111**

From the above, the following table shows the equivalence degrees and its expanded uncertainty (k=2) at 120V, 5A, pf = 0.5 lead, 53 Hz, between CCEM-K5 and SIM.EM-K5, expressed in µW/VA:

Table 4. Link of the SIM.EM-K5 with the CCEM-K5 at 120V, 5A, 53 Hz, pf = 0.5 lead.

Laboratory	$\boldsymbol{D_i}$	$\boldsymbol{U_{Di}}$ / (k=2)
NIST	1	12
INTI	9	34
NRC	5	12
INMETRO	15	60
CENAM	-2	34
UTE	$\boldsymbol{\hat{D}_S}$ = 5	$\boldsymbol{U_{\hat{D}_S}}$= 42
CENAMEP	$\boldsymbol{\hat{D}_S}$ = 33	$\boldsymbol{U_{\hat{D}_S}}$= 94
INM	$\boldsymbol{\hat{D}_S}$ = 33	$\boldsymbol{U_{\hat{D}_S}}$= 111

4.3 **Linking results at pf = 0.5 lag.**

Laboratory	$\boldsymbol{d_C}$	$\boldsymbol{r_C}$	$\boldsymbol{s_C}$		$\boldsymbol{w_C}$	$\boldsymbol{w_C * d_C}$
NIST	2	10	20.6	0.0024	0.391	0.78
INTI	6.1	10	48.8	0.0004	0.070	0.43
NRC	-3.4	10	20.2	0.0025	0.407	-1.38
INMETRO	-18.7	10	66.9	0.0002	0.037	-0.69
CENAM	1.1	10	41.9	0.0006	0.095	0.1

From equations 1 and 2 above, $\boldsymbol{d_{pf\,=}}$ **0.5 lag = -0.8 µW/VA**. The uncertainty associated with d_{pf} = 0.5 lag is $\boldsymbol{u_d}$ **= 2(0.9) = 1.8 µW/VA** at k =2.

Lab.	$D_{KCRV_{SIM-K5}}$	$U_{D_{KCRV_{SIM-K5}}}$	$U_{KCRV_{CCEM-K5}}$	$U_{KCRV_{SIM-K5}}$	$U_{d_{PF=1.0}}$	$\boldsymbol{\hat{D}_S = D_S + d}$	$\boldsymbol{U_{\hat{D}_S}}$
UTE	9.7	40	10	5.5	1.76	**9**	**42**
CENAM EP	-19.3	93	10	5.5	1.76	**-20**	**94**
INM	-6.3	110	10	5.5	1.76	**-7**	**132**

From the above, the following table shows the equivalence degrees and its expanded uncertainty (k=2) at 120V, 5A, pf = 0.5 lag, frequency = 53 Hz, between the CCEM-K5 and SIM.EM-K5 comparisons and expressed in µW/VA:

Table 5. Link of the SIM.EM-K5 with the CCEM-K5 at 120 V, 5 A, 53 Hz, pf = 0.5 lag.

Laboratory	$\boldsymbol{D_i}$	$\boldsymbol{U_{Di}}$ / (k=2)
NIST	1	12
INTI	4	34
NRC	-3	12
INMETRO	-26	60
CENAM	2	34
UTE	$\boldsymbol{\hat{D}_S}$ = 9	$\boldsymbol{U_{\hat{D}_S}}$= 42
CENAMEP	$\boldsymbol{\hat{D}_S}$ = -20	$\boldsymbol{U_{\hat{D}_S}}$= 94
INM	$\boldsymbol{\hat{D}_S}$ = -7	$\boldsymbol{U_{\hat{D}_S}}$= 132

5. Degrees of equivalence for the linked SIM.EM-K5 comparison

The degrees of equivalence (DOEs) of the laboratories of the SIM.EM-K5 as referred to the results of the CCEM-K5 comparison are calculated at each of the power factors: 1.0 and 0.5 lead/lag, at 120 V, 5 A and at a frequency equal to 53 Hz.

Having accepted the link laboratories a value of reproducibility of their results over the time span between the CCEM-K5 and SIM. EM-K5 comparisons to be r_c = 10 at k= 2, the following tables show the DOEs for the SIM.EM-K5. The uncertainty associated with the DOEs is calculated by the quadrature sum of the uncertainties of the link laboratories.

5.1 Table 6. Degrees of Equivalence and associated uncertainty (k=2) at pf = 1.0, expressed in μW/VA.

	NIST		INTI		NRC		INMETRO		CENAM		UTE		CENAMEP		INM	
	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}
NIST			22	23	3	18	-2	61	11	36	16	26	15	64	21	111
INTI	-22	23			-19	24	-24	63	-11	39	-6	31	-7	66	-1	112
NRC	-3	18	19	24			-5	62	8	37	13	27	12	65	18	112
INMETRO	2	61	24	63	5	62			13	69	18	64	17	87	23	126
CENAM	-11	36	11	39	-8	37	-13	69			5	41	4	72	10	116
UTE	-16	26	6	31	-13	27	-18	64	-5	41			-1	67	5	113
CENAMEP	-15	64	7	66	-12	65	-17	87	-4	72	1	67			6	127
INM	-21	111	1	112	-18	112	-23	126	-10	116	-5	113	-6	127		

5.2 Table 7. Degrees of Equivalence and associated uncertainty (k=2) at pf = 0.5 lead, expressed in μW/VA.

	NIST		INTI		NRC		INMETRO		CENAM		UTE		CENAMEP		INM	
	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}
NIST			8	36	4	17	14	61	-3	36	4	43	32	94	32	111
INTI	-8	36			-4	36	6	69	-11	48	-4	54	24	100	24	116
NRC	-4	17	4	36			10	61	-7	36	0	43	28	94	28	111
INMETRO	-14	61	-6	69	-10	61			-17	69	-10	73	18	111	18	126
CENAM	3	36	11	48	7	36	17	69			7	54	35	100	35	116
UTE	-4	43	4	54	0	43	10	73	-7	54			28	103	28	118
CENAMEP	-32	94	-24	100	-28	94	-18	111	-35	100	-28	103			0	145
INM	-32	111	-24	116	-28	111	-18	126	-35	116	-28	118	0	145		

5.3 Table 8. Degrees of Equivalence and associated uncertainty (k=2) at pf = 0.5 lag, expressed in μW/VA.

	NIST		INTI		NRC		INMETRO		CENAM		UTE		CENAMEP		INM	
	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}	DOES	U_{DOEs}
NIST			3	36	-4	17	-27	61	1	36	8	43	-21	94	-8	132
INTI	-3	36			-7	36	-30	69	-2	48	5	54	-24	100	-11	136
NRC	4	17	7	36			-23	61	5	36	12	43	-17	94	-4	132
INMETRO	27	61	30	69	23	61			28	69	35	73	6	111	19	145
CENAM	-1	36	2	48	-5	36	-28	69			7	54	-22	100	-9	136
UTE	-8	43	-5	54	-12	43	-35	73	-7	54			-29	103	-16	138
CENAMEP	21	94	24	100	17	94	-6	111	22	100	29	103			13	161
INM	8	132	11	136	4	132	-19	145	9	136	16	138	-13	161		

6. Tests of consistency between the CCEM-K5 and SIM.EM-K5 measurement results

It is important to ensure the consistency of the link between the SIM.EM-K5 and the CCEM-K5 measurement results. The main concern is the criterion of "reproducibility" of the measurement results over the time span between the two comparisons. As pointed out in section 4, the link laboratories have agreed upon a reproducibility factor r_C equal to 10 at k= 2.

Delahaye [3] used the proposal of B. N. Taylor [4], based on the Birge ratio [4], between an internal and an external consistency.

The internal consistency is related with the uncertainty associated with the weighted mean difference of measurement results coming out from the two comparisons. It is expressed in terms of the standard deviation of the correction *d*, given in equation 2 above; it is calculated as:

$$var_{int}(d) = \frac{1}{\sum_{c=1}^{C}\left({}^{1}/_{var(d_C)}\right)}, \tag{6}$$

where the variance of d_C is given by s_C^2 as in equation 5 for k = 1.

The external consistency is related with the standard deviation of the weighted difference between the difference of measurement results of CCEM-K5 and SIM.EM-K5 measurement results of the linking laboratories and the correction factor *d*. It is expressed as:

$$var_{ext}(d) = \frac{\sum_{c=1}^{C} w_C\,(d_C - d)^2}{(C-1)}. \tag{7}$$

The Birge ratio is defined as: $BR = \frac{var_{ext}(d)}{var_{int}(d)}$, and the criterion of consistency based on this ratio is:

1. BR = 1: there is consistency in the link between the measurement results of the CCEM-K5 and the SIM.EM-K5.
2. BR > 1: some of the uncertainty values of the linking laboratories are underestimated, thus, there is not consistency in the link between the measurement results of the CCEM-K5 and the SIM.EM-K5.
3. BR < 1: some of the uncertainty values of the linking laboratories may be overestimated. It is possible that the reproducibility factor r_C is overestimated. The link between the comparisons is consistent.

Table 6 shows the results of applying the Birge ratio to the CCEM-K5 and SIM.EM-K5 measurement results. At the three power factors, the Birge ratio is lower than one, meaning that the link between the CCEM-K5 and SIM.EM-K5 comparisons is reliable.

Table 6. Consistency of measurement results according to the Birge ratio.

Testing points	var_{ext}	var_{int}	Birge ratio
P. F. = 1.0	2.78	6.29	**0.441**
P. F. = 0.5 lead	1.75	6.35	**0.276**
P. F. = 0.5 lag	2.31	6.45	**0.359**

7. Conclusions.

In this Addendum a link between the SIM.EM-K5 and the CCEM.K5 key comparisons in 50/60 Hz power is presented. The SIM.EM-K5 [1] comparison was conducted by CENAM between years 2010 and 2012, whereas the CCEM-K5 was conducted by NIST in years 1996-2000 [2]. The link laboratories in the two comparisons are: NIST-USA; INTI-Argentina; NRC-Canada; INMETRO-Brazil and CENAM-Mexico. The link of the comparisons applies to the testing points: 120 V, 5 A, frequency of 53 Hz and power factor equal to 1.0 and 0.5 lead/lag.

The link procedure is based on the work of Delahaye and Witt [3]. It basically consists of an additive correction which is applied to the results of the SIM.EM-K5 comparison so that the transformed results can be directly compared with the results of the CCEM.K5 comparison. The additive correction is determined by a weighted mean of the corresponding differences of the linking laboratories. This criterion may be applicable since the CCEM-K5 and SIM.EM-K5 comparisons are of the same quantity of electrical power at 120 V, 5 A, 53 Hz and power factor equal to 1 and 0.5 lead-lag. This procedure does not change the CCEM-K5 key comparison reference value.

The differences of the results of the laboratories with respect of the CCEM.K5 results have been estimated considering that the link laboratories have accepted a value of reproducibility of their results over the time span between the CCEM-K5 and SIM. EM-K5 comparisons to be r_c = 10 at k= 2. From this link the degrees of equivalence DOEs are the calculated and the uncertainty associated with them is calculated by the quadrature sum of the uncertainties of the laboratories. Tables 2.2 and 2.4, show the difference of the laboratories with respect of the KCRV of the CCEM.K5 and SIM.EM-K5 key comparisons, respectively. Tables 3 to 5 show the linking results between the SIM.EM-K5 and CCEM-K5 comparisons at the three different power factors. Tables 5.1 to 5.3 show the degrees of equivalence among the SIM laboratories and the associated uncertainty (k =2), and expressed in µW/VA.

In Section 6, a consistency test is applied to the link between the two comparisons based on the proposal of Delahaye and B. N. Taylor. Table 6 shows the consistency results, indicating that the link between the CCEM-K5 and SIM.EM-K5 comparisons is reliable.

From the results shown in this Addendum it may be confirmed that the SIM.EM-K5 is properly linked to the CCEM-K5 comparison.

8. References.

1. Final Report, SIM.EM-K5 key comparison of 50/60 Hz power. Centro Nacional de Metrología, CENAM, Mexico, Nov. 2014.
2. N. Oldham, T. Nelson, N. F. Zhang and H. Liu, “Final Report. CCEM-K5 Comparison of 50/60 Hz Power”, National Institute of Standards and Technology, NIST, USA, Jun. 2002.
3. F. Delahaye and T. J. Witt, “Linking the Results of Key Comparison CCEM-K4 with the 10 pF Results of EUROEMT Project 345”, Metrologia 39 (Tech. Suppl.) 01005, 2002.
4. B. N. Taylor, W. H. Parker and D. N. Langenberg, “Determination of e/h, using macroscopic quantum phase coherence in superconductors: implications for quantum electrodynamics and the fundamental physical constants”, Rev. Mod. Phys., Vol. 41, pp. 373-496, Jul. 1969.