

# Final Report

## Supplementary Comparison of 50/60 Hz Energy SIM.EM-S7

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## 1. Introduction

Under the auspices of the Committee Consultative of Electromagnetism, CCEM, the SIM Electromagnetic Working Group carried out a supplementary comparison of energy standards at 50/60 Hz. CENAM is the pilot laboratory. This supplementary comparison, identified as SIM.EM-S7, aims at providing a link to various NMIs in the SIM region to the SIM International Comparison 50/60 Hz Energy (2002-2007) conducted by NIST an completed in year 2007[1].

Measurements in this supplementary comparison were conducted from May 2010 to March 2012.

The reference standards used in this comparison in energy are capable of measuring power and energy with high accuracy. This feature of the standards allowed to carry out the SIM.EM-S7 supplementary comparison of 50/60 Hz energy and the SIM.EM-K5 key comparison of 50/60 Hz power which was published in 2014 [2].

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

## 2. Participating laboratories and comparison organization

### 2.1 List of participants laboratories

**Table 1.** List of participating laboratories.

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

#### Note 1.

INTI not submitted his measurement results for this supplementary energy comparison.

#### 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-S7 comparison.

<b>Loop <math>j = 1</math></b>			
<b>Reference standard: RD-22-311</b>			
	<b>Laboratory</b>	<b>Allocated time</b>	
		<b>receiving day</b>	<b>sending day</b>
1	NIST, Thomas Nelson (USA)	28 Jun, 2010	16 Jul, 2010
2	CENAM, Rene Carranza (México) <sup>NOTE 4</sup>	09 Ago, 2010	27 Ago, 2010
3	INMETRO, Ana Maria Ribeiro Franco (Brazil) <sup>NOTE 4</sup>	20 Sep, 2010	08 Oct, 2010
4	UTE, Alfredo Spaggiari (Uruguay)	1st Nov, 2010	19 Nov, 2010
5	INTI, Lucas Di Lillo (Argentina) <sup>NOTE 3</sup>	20 Dec, 2010	15 Jan, 2011
6	CENAM, Rene Carranza (México)	08 Feb, 2011	26 Feb, 2011
7	NRC, Eddy So (Canada) <sup>NOTE 4</sup>	22 Mar, 2011	09 Apr, 2011
8	CENAM, Rene Carranza (México)	03 May, 2011	21 May, 2011

<b>Loop <math>j = 2</math></b>			
<b>Reference standard: RD-23-432</b>			
	<b>Laboratory</b>	<b>Allocated time</b>	
		<b>receiving day</b>	<b>sending day</b>
1	LCPN-ME, Rodrigo Ramos (Chile)	28 Jun, 2010	16 Jul, 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

**Note 3.**

INTI received the reference standard but did not submit his measurement results for this energy comparison.

**Note 4.**

The following NMIs did carry out measurements of active and reactive energy: INMETRO; NRC and CENAM.

**2.3 Organization of the comparison.**

This comparison in energy was arranged in two loops. Since measurements in one loop are independent of measurements in the other, this SIM.EM-S7 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.*

<b>Loop j = 1</b>		<b>Loop j = 2</b>	
<b>Reference standard: RD-22-311</b>		<b>Reference standard: RD-23-432</b>	
CENAM	Prior to 10/06/2010	CENAM	Prior to 10/06/2010
NIST	02/07/2010 13/08/2010	LCPN-ME	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 <sup>NOTE 5</sup>	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 5.**

INTI received the traveling standard but did not submit his measurement results for this comparison in energy. This laboratory participated in the SIM.EM-K5 power key comparison in 50/60 Hz piloted by CENAM. The same traveling reference standard was used for both the power and energy comparisons.

This key comparison in energy measurements was organized according to the CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons [3]. The protocol for the SIM.EM-K5 comparison was approved by the SIM.EM Subcommittee in year 2009 [4].

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 RADIANT were used for this SIM.EM-S7 supplementary comparison of energy. 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 [4].

### 3.1 Description of the reference standards.

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

**Table 4.** Reference standards features.

	<b>(loop <math>j = 1</math>) RD-22-311</b>	<b>(loop <math>j = 2</math>) RD-23-432</b>
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
Energy constant $K_h$	100 000 pulses/Wh	100 000 pulses/Wh
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 5 shows the testing points for the SIM.EM-S7 which were agreed upon in year 2010 [4] by the participating laboratories. The expression of measurement results and their associated uncertainty is given in terms of  $\mu\text{Wh}/\text{VAh}$  and  $\mu\text{varh}/\text{VAh}$ , for active and reactive energy, respectively. The total amount of testing points is 21.

**Table 5.** SIM.EM-S7 test points.

<b>Parameter</b>	<b>Active energy</b> (to be reported in $\mu\text{Wh}/\text{VAh}$ )	<b>Reactive energy</b> (to be reported in $\mu\text{varh}/\text{VAh}$ )
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.

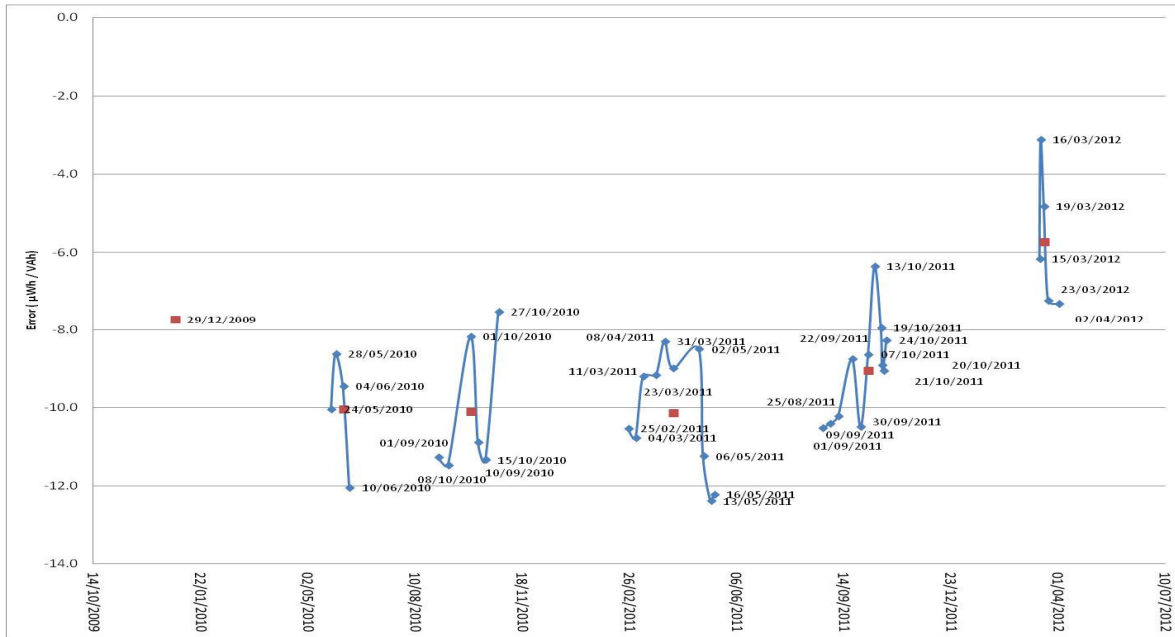
## 5. Measurements of the pilot laboratory: performance of the reference standards

The performance of the reference standard was assessed by applying a regression model [5] 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.

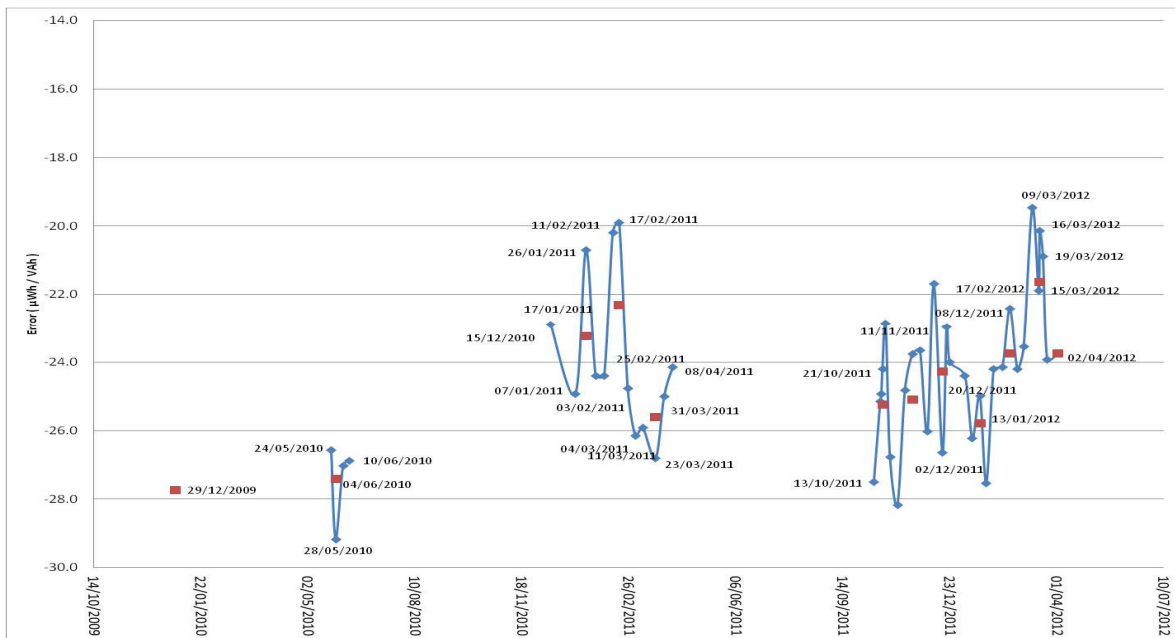
**Table 6.** Measurements carried out at CENAM on the reference standards used for loops  $j = 1$  and 2.

	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	12

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. Tables B.1 and B.3 show the average (mean) dates of measurements of active and reactive energy 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:

$$x_{CENAM,m}(t) = A + Bt + Ct^2 + \varepsilon(t), \quad (1)$$

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; A equals zero.
- 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.1 for 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  $\sigma^2$  associated with the regression fitting.

According to the Table 4 above, the test points in this comparison are nine for active energy and twelve for reactive energy, adding to a total of twenty one test points, that is  $m = 1, 2, \dots, 21$ .

For the  $m$ th testing point, the regression fitting can be expressed in matrix form as:

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

where:

- $\vec{X}_{CENAM,m} = (x_{CENAM,m}(1), \dots, x_{CENAM,m}(I_j))'$  is a column vector;
- $T_{CENAM}$  is a  $I_j \times 3$  matrix with the elements in the first column all equal to one and the  $(k, n)$  elements (for  $k = 1, 2, \dots, I_j$  and  $n = 2, 3$ ), being  $t_{CENAM}^{n-1}(k)$ ;
- The  $3 \times 1$  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 7 and 8 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  $\sigma^2$  and it is expressed in parts in  $10^6$ .



**Table 7.** Regression coefficients for loop  $j = 1$ , reference standard RD-22-311.

Frequency [ Hz ]	Power Factor	Polynomial coefficients (parts in $10^6$ )		Standard deviation of residuals (parts in $10^6$ )
		B	C	
50 Hz	<b>Active Energy</b>			
	1.0	-0.759 8	+0.000 4	0.6
	0.5 lead	+0.660 5	-0.000 3	0.6
	0.5 lag	-1.511 0	+0.000 7	1.3
	<b>Reactive Energy</b>			
	30° lead	-0.477 6	+0.000 2	0.4
	30° lag	-1.156 3	+0.000 6	1.0
	90° lead	+0.708 0	-0.000 4	0.6
	90° lag	-0.646 1	+0.000 4	0.5
53 Hz	<b>Active Energy</b>			
	1.0	-0.777 4	+0.000 4	0.6
	0.5 lead	+0.786 1	-0.000 4	0.7
	0.5 lag	-1.602 6	+0.000 8	1.3
	<b>Reactive Energy</b>			
	30° lead	-0.564 5	+0.000 3	0.5
	30° lag	-1.078 7	+0.000 5	0.9
	90° lead	+0.594 7	-0.000 3	0.5
	90° lag	-0.528 4	+0.000 3	0.4
60 Hz	<b>Active Energy</b>			
	1.0	-0.304 1	+0.000 1	0.2
	0.5 lead	+1.022 7	-0.000 5	0.9
	0.5 lag	-1.755 9	+0.000 9	1.5
	<b>Reactive Energy</b>			
	30° lead	-0.642 0	+0.000 3	0.5
	30° lag	-1.056 1	+0.000 6	0.9
	90° lead	+0.475 9	-0.000 2	0.4
	90° lag	-0.499 7	+0.000 2	0.4

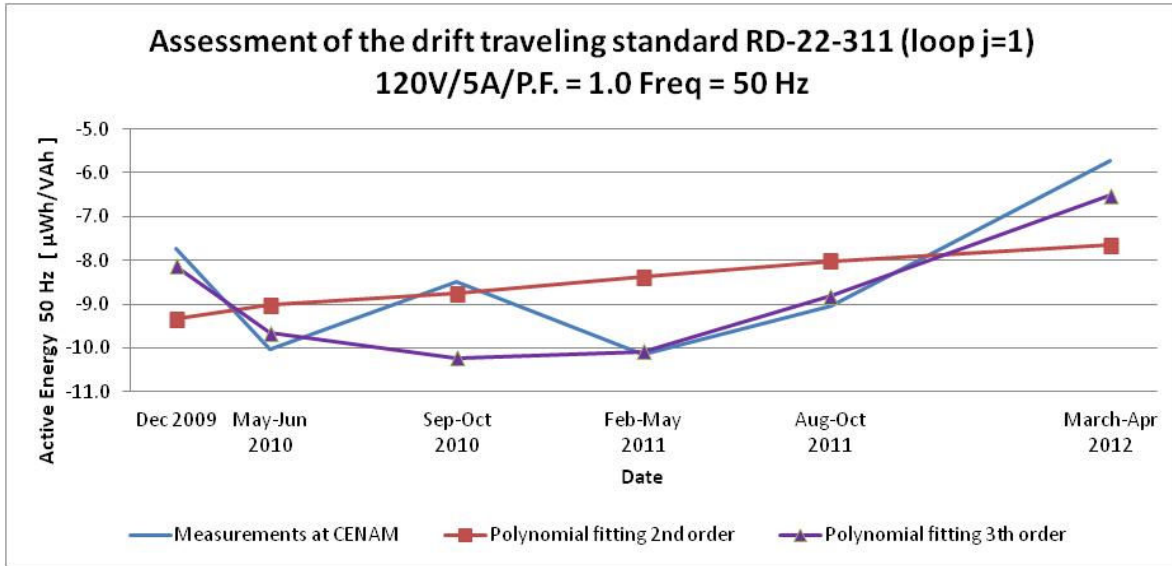
**Table 8.** Regression coefficients for loop  $j = 2$ , reference standard RD-23-432.

Frequency [ Hz ]	Power Factor	Polynomial coefficients (parts in $10^6$ )		Standard deviation of residuals (parts in $10^6$ )
		B	C	
50 Hz	<b>Active Energy</b>			
	1.0	-1.417 5	+0.000 7	1.1
	0.5 lead	+1.088 1	-0.000 5	0.8
	0.5 lag	-2.396 1	+0.001 2	1.8
	<b>Reactive Energy</b> <sup>NOTE 6</sup>			
	30° lead	---	---	
	30° lag	---	---	
	90° lead	---	---	
	90° lag	---	---	
53 Hz	<b>Active Energy</b>			
	1.0	-1.413 9	+0.000 7	1.1
	0.5 lead	+1.165 3	-0.000 6	0.9
	0.5 lag	-2.385 0	+0.001 2	1.8
	<b>Reactive Energy</b> <sup>NOTE 6</sup>			
	30° lead	---	---	
	30° lag	---	---	
	90° lead	---	---	
	90° lag	---	---	
60 Hz	<b>Active Energy</b>			
	1.0	-1.352 7	+0.000 7	1.1
	0.5 lead	+1.560 2	-0.000 8	1.1
	0.5 lag	-2.483 5	+0.001 2	1.8
	<b>Reactive Energy</b>			
	30° lead	---	---	
	30° lag	---	---	
	90° lead	+1.435 7	-0.000 7	1.1
	90° lag	-1.506 1	+0.000 8	1.1

**Note 6.**

It may be noticed that on loop  $j = 2$ , the participating laboratories did not report measurements of reactive energy at frequencies of 50 Hz and 53 Hz. Measurements of reactive energy were not reported a 30° lead-lag at 60 Hz.

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. Tables B.1 to B.8 in Appendix B show 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 30 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  $\bar{x}_{i,m}$  (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:

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

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

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

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  $I_j \times 3$ , whose elements in the first column are all equal to one and the other  $(k,n)$  elements ( $k = 1, 2, \dots, I_j$  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:

$$\bar{D}_{CENAM}(m) = \frac{\sum_{k=1}^{I_j} [x_{CENAM,k}(m) - x_{P,CENAM,k}(m)]}{I_j}, \quad (5)$$

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:

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

The key comparison reference values  $X_{KCRV}(m)$  for each of the twenty one test points  $m = 1, 2 \dots 21$  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  $D_i(m)$ :

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

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  $\bar{x}_{i,m}$  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:

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

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, with maximum value of 1.8 parts in  $10^6$ .

Tables 9.A and 9.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 9.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°	1.6	1.8	1.0	4.7	4.8	4.6
120 V / 5 A / +60°	-1.0	0.6	3.1	4.8	4.9	5.0
120 V / 5 A / -60°	2.8	-2.6	1.0	5.3	5.4	5.5
120 V / 5 A / +90°	2.2	2.2	0.2	5.6	5.9	5.6
120 V / 5 A / -90°	7.2	9.2	9.7	5.6	5.9	5.6
120 V / 5 A / +30°	-4.9	0.0	-1.0	5.6	5.7	5.7
120 V / 5 A / -30°	-7.1	-9.7	-7.6	5.8	5.8	5.8

**Table 9.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	0.0	0.0	6.1	6.1	5.8
120 V / 5 A / +60°	0.0	0.0	0.0	6.1	6.1	5.9
120 V / 5 A / -60°	0.0	0.0	0.0	6.2	6.2	6.1
120 V / 5 A / +90°	---	---	0.0	---	---	6.1
120 V / 5 A / -90°	---	---	0.0	---	---	6.1
120 V / 5 A / +30°	---	---	---	---	---	---
120 V / 5 A / -30°	---	---	---	---	---	---

### 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  $j = 1, 2$ :

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

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

$$u_{D_{i,KCRV}}^2(m) = [1 - 2w_i(m)]u_{D_i(m)}^2 + u_{KCRV}^2(m) - 2s_r^2(m) \sum_{k \neq 1, k=2}^j w_k(m) [\tilde{t}_i (T'_{CENAM} T_{CENAM})^{-1} \tilde{t}'_k]. \quad (11)$$

When the laboratory is the pilot, its difference with the  $X_{KCRV}(m)$  value is:

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

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

where  $w_1$  is the corresponding weight for CENAM.

For any of the  $m = 1$  to 21 testing points, Tables 10 and 11 show the differences between the  $i$ th laboratory including CENAM and the  $X_{KCRV}(m)$ . Tables 10.A and 10.B stand for the measurement results of active and reactive power in loop  $j = 1$ , whereas Tables 11.A and 11.B stand for the corresponding measurement results for loop  $j = 2$ .

**Table 10.A.** Loop  $j = 1$ , Active Energy. Difference between the  $i$ th laboratory and the  $X_{KCRV}(m)$  value and its associated uncertainty, expressed in  $\mu Wh/VAh$ .

Active Energy Reference Standard RD-22-311		Difference with $X_{KCRV}(m)$			Uncertainty ( $k=2$ )		
		0°	+60°	-60°	0°	+60°	-60°
50 Hz	CENAM	-1.6	1.0	-2.8	20	20	20
	NIST	3.4	4.0	-0.8	8	8	8
	INMETRO	4.0	9.7	-5.5	22	26	26
	NRC	-2.4	-5.2	4.0	7	7	7
	UTE	4.3	1.3	7.0	20	40	40
53 Hz	CENAM	-1.8	-0.6	2.6	20	20	20
	NIST	2.9	0.8	0.7	8	8	8
	INMETRO	0.6	5.0	-4.1	22	26	26
	NRC	-2.8	-0.6	-3.9	7	7	8
	UTE	12.8	0.8	13.3	20	40	40
60 Hz	CENAM	-1.0	-3.1	-1.0	20	20	20
	NIST	3.6	0.4	2.1	8	8	9
	INMETRO	2.3	5.1	-2.1	22	26	26
	NRC	-2.8	2.7	0.9	7	7	8
	UTE	4.0	-7.9	12.1	19	40	40

**Table 10.B.** Loop  $j = 1$ , Reactive Energy. Difference between the  $i$ th laboratory and the  $X_{KCRV}(m)$  value and its associated uncertainty, expressed in  $\mu\text{varh}/\text{VAh}$ .

Reactive Energy Reference Standard RD-22-311		Difference with $X_{KCRV}(m)$				Uncertainty ( $k=2$ )			
		+90°	-90°	+30°	-30°	+90°	-90°	+30°	-30°
50 Hz	CENAM	-2.2	-7.2	4.9	7.1	19	19	19	19
	NIST	----	----	----	----	----	----	----	----
	INMETRO	-7.4	-1.4	0.1	4.6	21	21	26	26
	NRC	3.3	7.4	-4.8	-7.9	6	6	6	6
	UTE	----	----	----	----	----	----	----	----
53 Hz	CENAM	-2.2	-9.2	0.0	9.7	19	19	19	19
	NIST	----	----	----	----	----	----	----	----
	INMETRO	-5.4	-5.6	-0.1	6.6	21	21	26	26
	NRC	3.6	12.2	0.0	-11.5	7	7	6	6
	UTE	----	----	----	----	----	----	----	----
60 Hz	CENAM	-0.2	-9.7	1.0	7.6	19	19	19	19
	NIST	----	----	----	----	----	----	----	----
	INMETRO	-4.4	-4.9	2.0	5.6	21	21	26	26
	NRC	0.8	10.3	-1.2	-8.5	6	6	6	6
	UTE	----	----	----	----	----	----	----	----

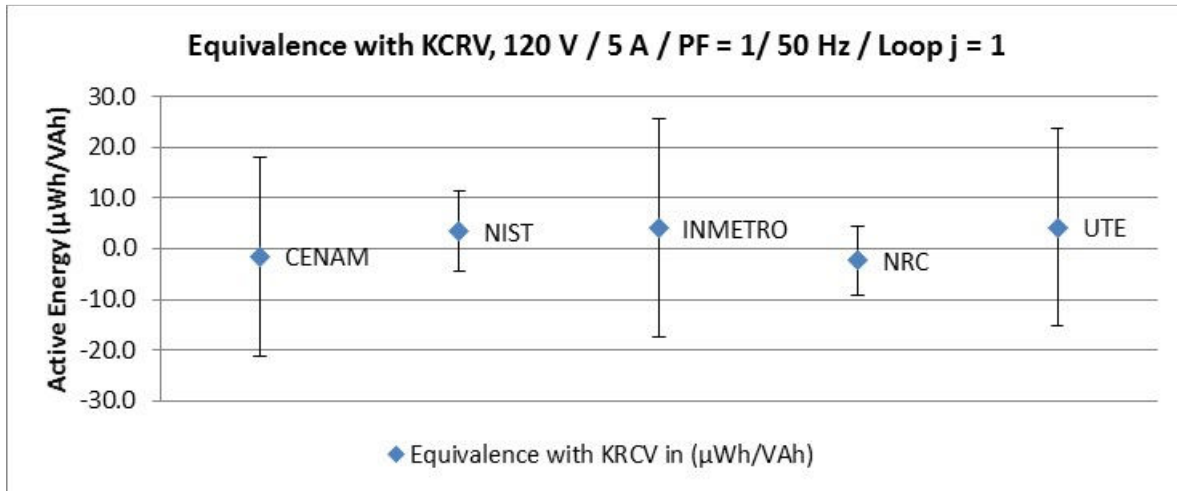
**Table 11.A.** Loop  $j = 2$ , Active Energy. Difference between the  $i$ th laboratory and the  $X_{KCRV}(m)$  value and its associated uncertainty, expressed in  $\mu\text{Wh}/\text{VAh}$ .

Active Energy Reference Standard RD-23-432		Difference with $X_{KCRV}(m)$			Uncertainty ( $k=2$ )		
		0°	+60°	-60°	0°	+60°	-60°
50 Hz	CENAM	0.0	0.0	0.0	19	19	19
	CENAMEP	3.9	-8.7	-6.5	58	90	90
	INM	18.6	0.0	23.0	110	110	110
	ICE	---	---	---	---	---	---
	SMN-INDECOPI	---	---	---	---	---	---
	LCPN-ME	6.0	-7.3	15.7	110	110	110
53 Hz	CENAM	0.0	0.0	0.0	19	19	19
	CENAMEP	42.1	29.0	2.0	58	90	90
	INM	21.6	-3.7	10.6	110	110	110
	ICE	---	---	---	---	---	---
	SMN-INDECOPI	---	---	---	---	---	---
	LCPN-ME	1.0	-18.9	13.2	110	110	110
60 Hz	CENAM	0.0	0.0	0.0	19	19	19
	CENAMEP	51.7	64.7	18.8	58	90	90
	INM	-1.0	-30.1	26.4	93	93	94
	ICE	6.3	27.5	-3.7	103	202	202
	SNM-INDECOPI	-9.2	8.5	-12.7	133	70	70
	LCPN-ME	-7.6	-33.5	26.1	110	110	110

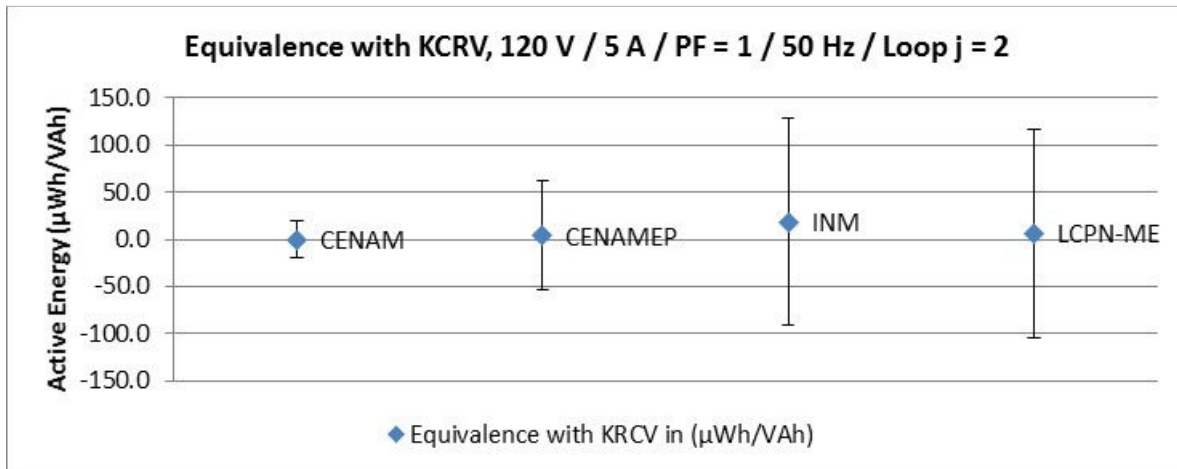
**Table 11.B.** Loop  $j = 2$ , Reactive Energy. Difference between the  $i$ th laboratory and the  $X_{KCRV}(m)$  value and its associated uncertainty, expressed in  $\mu\text{varh}/\text{VAh}$ .

Reactive Energy Reference Standard		Difference with $X_{KCRV}(m)$				Uncertainty ( $k=2$ )			
		+90°	-90°	+30°	-30°	+90°	-90°	+30°	-30°
60 Hz	CENAM	0	0	---	---	19	19	---	---
	ICE	17	17	---	---	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.



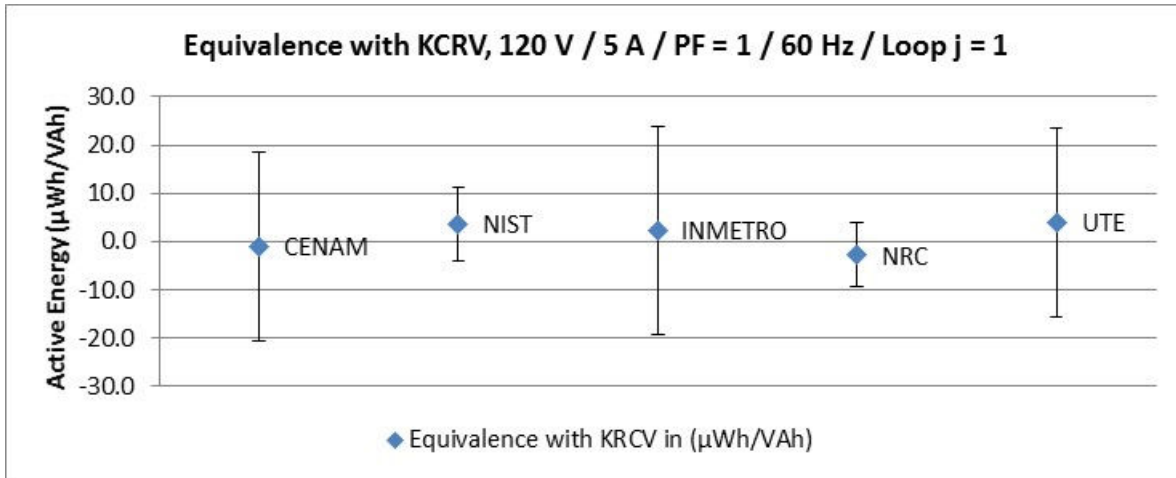


Figure 5.A. Difference between the KCRV and the results of the laboratories of loop  $j = 1$ , at  $pf = 1$ , 60 Hz.

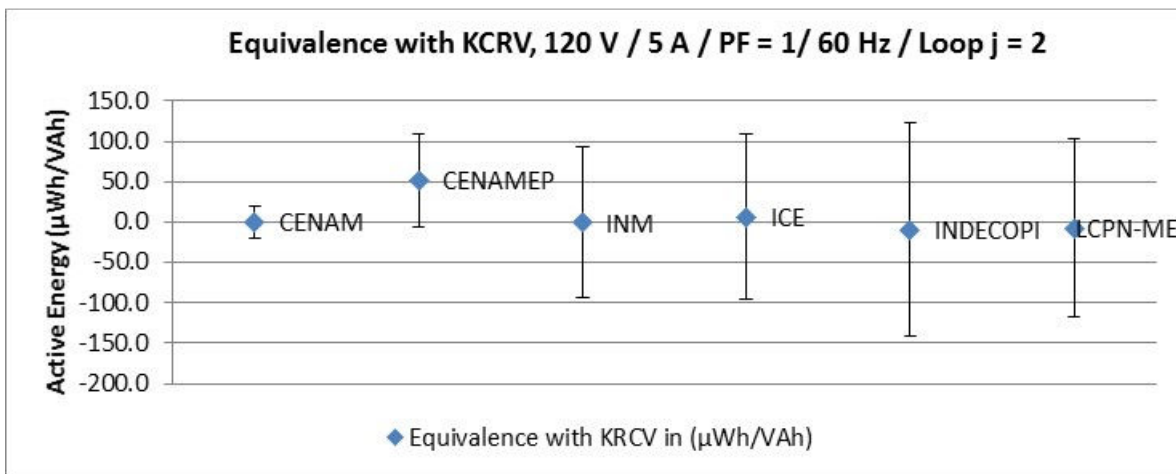


Figure 5.B. Difference between the KCRV and the results of the laboratories of loop  $j = 2$ , at  $pf = 1$ , 60 Hz.

#### 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

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

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

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

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

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

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

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

#### 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:

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

## 7. Conclusions

Measurements of active and reactive energy were included in this regional supplementary comparison.

The regression fitting on the measurements of the pilot laboratory provides a robust estimate of the supplementary comparison reference value. A second order polynomial was used for the regression fitting resulting in a standard deviation of the residuals lower than 2 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 6.2 above, a regression fitting on the measurements of CENAM was carried out in order to estimate the predicted values of its measurement results  $\bar{x}_{i,m}$ . 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 7 and 8, 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 1.8 parts in  $10^6$  for all the  $m = 21$  testing points. The contribution from the correlation is lower than  $0.1 \mu\text{Wh}/\text{VAh}$ .

The small 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 energy 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 energy measurement are acknowledged.

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 energy in the scope of this 50/60 Hz key comparison of power. The results of this SIM.EM-S7 comparison in reactive energy support very well the capabilities of modern measurement technologies of energy which offer the simultaneous measurement of active and reactive energy in the same measurement standards.

It is important to mention that many of the participating laboratories in the SIM.EM-S7 supplementary comparison energy also participated at the same time in the key comparison SIM.EM-K5 of power, 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-S7 supplementary comparison 50/60 Hz energy, and to the SIM.EM-k5 key comparison 50/60 Hz power, for the provision of the traveling standards RD-22-311 and RD-23-432.

## 8. References

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3. CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons. CCEM, 21 Mar. 2007.
4. SIM.EM-S7 Supplementary Comparison 50/60 Hz Energy Protocol, May 2010.
5. Mary G. Natrella, Experimental Statistics, National Bureau of Standards Handbook 91, Aug. 1963.

## 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 energy 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-S7 supplementary comparison, CENAM used a reference watt-hour-meter traceable to the national measurement standard of electrical energy.

**Table A1.** *Reference watt-hour-meter.*

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

This reference was measured during the comparison with a transfer standard every week since the beginning of the Comparison. 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 used in this supplementary comparison.

**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 RADIANT were used for this SIM.EM-S7 supplementary comparison of energy. 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, 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 auxiliary 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 reference standards 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:  $(23 \pm 1.0) ^\circ\text{C}$
- Laboratory relative humidity:  $(50 \pm 30) \% \text{RH}$ .

#### 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.



**Table A5.** Active energy: uncertainties type A and B.

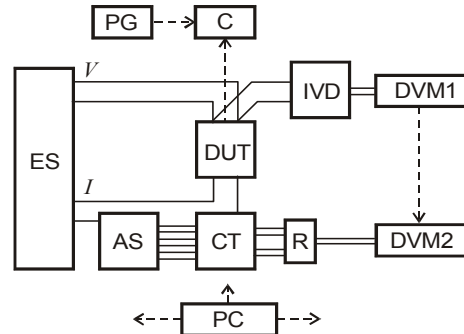
Voltage	Current	Frequency	Power Factor	Type A k = 1.0	Type B k = 1.0	Expanded k = 2.0
( V )	( A )	( Hz )	( $\lambda$ )	( $\mu\text{Wh} / \text{VAh}$ )	( $\mu\text{Wh} / \text{VAh}$ )	( $\mu\text{Wh} / \text{VAh}$ )
120	5	50	1.0	< 1	10	20
			0.5 lead	< 1	10	20
			0.5 lag	< 1	10	20
			1.0	< 1	10	20
			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 energy: uncertainties type A and B.

Voltage	Current	Frequency	Power Factor	Type A k = 1	Type B k = 1	Expanded k = 2.0
( V )	( A )	( Hz )	( $\lambda$ )	( $\mu\text{varh} / \text{VAh}$ )	( $\mu\text{varh} / \text{VAh}$ )	( $\mu\text{varh} / \text{VAh}$ )
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
			0 lead	< 1	10	20
			0 lag	< 1	10	20
		60	0.866 lead	< 1	10	20
			0.866 lag	< 1	10	20
			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 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.  $2 \times 10$  ohms or  $2 \times 20$  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.



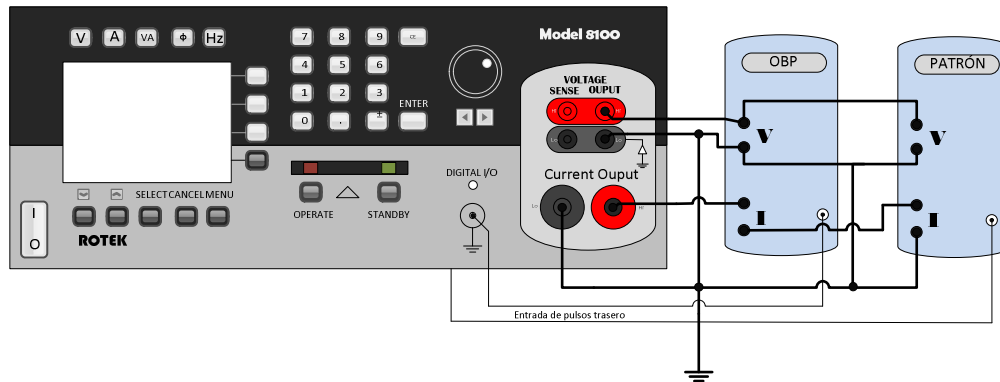
### A.3 Measurement standard at ICE, Costa Rica.

#### A.3.1 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.3.2 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.3.3 Traceability.

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

**A.4 Measurement standard at CENAMEP AIP, Panama.****A.4.1 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.4.2 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.4.3 Traceability**

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

**A.5 Measurement standard at SNM-INDECOPI, Peru.****A.5.1 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.5.2 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.5.3 Used Equipment.**

Local standard radian RD-21-332

**A.5.4 Traceability.**

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

## A.6 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<sup>1</sup>. The system uses a differential sampling technique<sup>4,2</sup> to relate the amplitudes and phases of two, sinusoidal, spectrally-pure voltage signals,  $V_V$  and  $V_I$ , which are scaled versions of the voltage and current signals applied to the meter under test (MUT), to a single, piecewise-approximated voltage signal,  $V_J$ , generated using a programmable Josephson voltage standard (PJVS)<sup>3</sup>. 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  $V_V$  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<sup>4</sup>. 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<sup>5</sup>, T1, is used to measure the output voltage of the current shunt in the presence of large common-mode voltages.

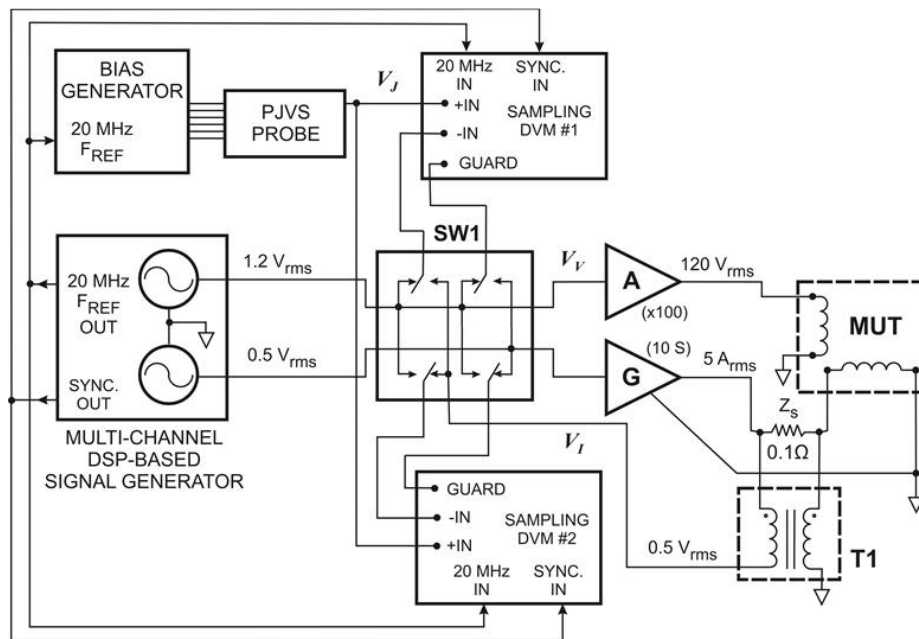


Fig. A.7.1. Simplified diagram of the NIST power generation system.

<sup>1</sup> B. Waltrip, B. Gong, T. Nelson, Y. Wang, C. Burroughs, A. Rufenacht, 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.

<sup>2</sup> A. Rufenacht 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.

<sup>3</sup> 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 MoSi<sub>2</sub> barrier junctions," *IEEE Trans. Appl. Supercon.*, vol. 15, no. 2, pp. 461-464, Jun. 2005.

<sup>4</sup> O. Laug, T. Souders, B. Waltrip, "A Four-Terminal Current Shunt with Calculable AC Response," NIST Tech. Note 1462, August 2004.

<sup>5</sup> 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.

### A.7 Measurement standard at NRC, Canada

#### Description of NRC Power Bridge

In the NRC power bridge<sup>6</sup>, 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  $\mu\text{W}/\text{VA}$  and 5 to 8  $\mu\text{VARh}/\text{VAh}$ , 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<sup>7</sup>, its output was measured using a digital voltmeter (Agilent 3458A) running with Swerlein Algorithm<sup>8</sup>.

The current was measured with a Current - Voltage Transducer.

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.

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<sup>6</sup> 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  $\mu\text{W}/\text{VA}$  ( $k = 1$ )," IEEE Trans. Instrum. Meas., vol. IM-62, no. 6, pp. 1704–1709, June 2013.

<sup>7</sup> 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.

<sup>8</sup> 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

**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 energy are expressed in terms of  $\mu\text{Wh}/\text{VAh}$ , whereas those for reactive energy are expressed in terms of  $\mu\text{varh}/\text{VAh}$ .

As shown in the tables below, some participants did not carried out measurements at all the testing points as shown in Table 9.B and 10.A. A blank cell shows that the participating laboratory did not submit its measurement results.

**Table B.1.** *Measurement results of Active Energy. Loop j=1 in  $\mu\text{Wh/VAh}$ .*

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 [ $\mu\text{Wh/VAh}$ ]			Error [ $\mu\text{Wh/VAh}$ ]			Error [ $\mu\text{Wh/VAh}$ ]			
1	CENAM	29/12/2009	2009.99	-7.7	-7.5	-6.2	1.4	1.8	-3.3	-9.6	-3.9	-4.8
2	CENAM	24/05/2010 10/06/2010	2010.42	-10.0	-10.0	-9.9	-4.3	-4.2	-9.9	-6.2	-0.1	-0.5
3	NIST	02/07/2010 13/08/2010	2010.56	-3.9	-3.9	-3.8	0.6	-0.9	-4.3	-4.9	-2.8	1.5
4	CENAM	01/09/2010 27/10/2010	2010.75	-8.5	-8.4	-8.8	-4.2	-4.3	-10.0	-4.5	1.3	0.7
5	INMETRO	06/12/2010 17/12/2010	2010.97	-3.0	-6.0	-5.0	6.0	3.0	0.0	-9.0	-7.0	-2.0
6	CENAM	25/02/2011 16/05/2011	2011.27	-10.1	-9.6	-10.0	-4.5	-4.4	-10.2	-5.7	0.2	-0.2
7	NRC	25/05/2011 05/06/2011	2011.43	-9.0	-9.0	-10.0	-9.1	-3.0	-2.9	1.2	-6.1	0.0
8	CENAM	25/08/2011 24/10/2011	2011.75	-9.1	-8.8	-9.0	-3.4	-3.4	-9.1	-5.7	0.2	-0.3
9	UTE	15/12/2011 21/12/2011	2011.97	-2.0	7.0	-3.0	-3.0	-2.0	-14.0	5.0	12.0	14.0
10	CENAM	15/03/2012 02/04/2012	2012.22	-5.7	-5.6	-5.8	-1.5	-1.5	-7.3	-4.7	1.4	1.0

**Table B.2.** Expanded uncertainty ( $p=95.45\%$ ) in Active Energy. Loop  $j=1$  in  $\mu\text{Wh/VAh}$ .

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 [ $\mu\text{Wh/VAh}$ ]			U [ $\mu\text{Wh/VAh}$ ]			U [ $\mu\text{Wh/VAh}$ ]			
1	<b>CENAM</b>	29/12/2009	2009.99	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
2	<b>CENAM</b>	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	<b>NIST</b>	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
4	<b>CENAM</b>	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
5	<b>INMETRO</b>	06/12/2010 17/12/2010	2010.97	22.0	22.0	22.0	26.2	26.3	26.3	26.3	26.3	26.3
6	<b>CENAM</b>	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
7	<b>NRC</b>	25/05/2011 05/06/2011	2011.43	8.0	8.1	8.0	8.0	8.4	8.0	8.0	8.3	8.0
8	<b>CENAM</b>	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
9	<b>UTE</b>	15/12/2011 21/12/2011	2011.97	20.0	20.0	20.0	40.0	40.0	40.0	40.0	40.0	40.0
10	<b>CENAM</b>	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



Table B.3. Measurement results of Reactive Energy. Loop  $j=1$  in  $\mu\text{varh}/\text{VAh}$ .

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 [ $\mu\text{varh}/\text{VAh}$ ]			Error [ $\mu\text{varh}/\text{VAh}$ ]			Error [ $\mu\text{varh}/\text{VAh}$ ]			Error [ $\mu\text{varh}/\text{VAh}$ ]			
1	CENAM	29/12/2009	2009.99	-4.9	-4.8	-4.1	-12.6	-12.4	-12.6	-0.7	-4.6	-1.0	7.0	5.6	-0.4
2	CENAM	24/05/2010 10/06/2010	2010.42	-2.4	-2.4	-1.7	-15.3	-15.0	-15.0	2.0	-1.9	1.8	7.1	5.7	-0.2
3	NIST	02/07/2010 13/08/2010	2010.56	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
4	CENAM	01/09/2010 27/10/2010	2010.75	-4.0	-3.8	-2.5	-13.6	-13.5	-14.0	0.3	-3.3	0.8	7.1	5.7	-0.4
5	INMETRO	06/12/2010 17/12/2010	2010.97	-9.0	-7.0	-7.0	-8.0	-10.0	-9.0	-4.0	-3.0	2.0	5.0	3.0	-2.0
6	CENAM	25/02/2011 16/05/2011	2011.27	-2.4	-2.4	-1.5	-15.0	-14.9	-15.1	1.6	-2.2	1.7	6.9	5.4	-0.6
7	NRC	25/05/2011 05/06/2011	2011.43	1.3	1.7	-2.1	1.1	8.1	6.4	-8.7	-2.6	-0.9	-6.9	-14.6	-15.6
8	CENAM	25/08/2011 24/10/2011	2011.75	-3.1	-3.0	-1.9	-14.5	-14.4	-14.7	1.7	-1.9	2.0	7.7	6.2	0.2
9	UTE	15/12/2011 21/12/2011	2011.97	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
10	CENAM	15/03/2012 02/04/2012	2012.22	-6.9	-6.6	-5.6	-10.9	-10.9	-11.2	0.7	-3.0	0.8	10.2	8.7	2.6

**Table B.4.** Expanded uncertainty ( $p=95.45\%$ ) in Reactive Energy. Loop  $j=1$  in  $\mu\text{varh/VAh}$ .

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 [ $\mu\text{varh/VAh}$ ]			U [ $\mu\text{varh/VAh}$ ]			U [ $\mu\text{varh/VAh}$ ]			U [ $\mu\text{varh/VAh}$ ]			
1	<b>CENAM</b>	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	<b>CENAM</b>	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	<b>NIST</b>	02/07/2010 13/08/2010	2010.56	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
4	<b>CENAM</b>	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	<b>INMETRO</b>	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	<b>CENAM</b>	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	<b>NRC</b>	25/05/2011 05/06/2011	2011.43	8.1	8.9	8.0	8.1	9.0	8.0	8.0	8.2	8.0	8.0	8.3	8.0
8	<b>CENAM</b>	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	<b>UTE</b>	15/12/2011 21/12/2011	2011.97	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
10	<b>CENAM</b>	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

**Note:** Cells in blank on Tables B.1 to B.4 correspond to null measurements of the participants.

**Table B.5.** Measurement results of Active Energy. Loop  $j=2$  in  $\mu\text{Wh}/\text{VAh}$ .

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 [ $\mu\text{Wh}/\text{VAh}$ ]			Error [ $\mu\text{Wh}/\text{VAh}$ ]			Error [ $\mu\text{Wh}/\text{VAh}$ ]			
1	CENAM	29/12/2009	2009.99	-27.7	-22.0	-6.8	-15.5	-13.0	-10.9	-12.5	-3.1	4.8
2	CENAM	24/05/2010 10/06/2010	2010.42	-27.4	-21.1	-4.8	-19.2	-16.4	-14.6	-8.6	0.9	9.1
3	LCPN-ME	14/07/2010 27/07/2010	2010.55	-20.0	-19.0	-12.0	-24.0	-33.0	-46.0	6.0	13.0	34.0
4	INDECOPI	31/08/2010 13/09/2010	2010.68	-----	-----	-13.4	-----	-----	-4.1	-----	-----	-4.5
5	INM	30/10/2010 01/11/2010	2010.83	-7.0	2.0	-5.0	-17.0	-18.0	-43.0	14.0	11.0	35.0
6	CENAM	15/12/2010 26/01/2011	2011.02	-23.2	-17.5	-2.0	-16.1	-13.6	-12.5	-7.6	1.8	10.2
7	CENAM	03/02/2011 25/02/2011	2011.12	-22.3	-16.3	-0.7	-14.8	-12.3	-11.0	-8.0	1.4	9.6
8	CENAM	04/03/2011 08/04/2011	2011.22	-25.6	-19.0	-3.4	-17.5	-14.7	-13.1	-8.2	1.2	9.5
9	ICE	11/05/2011 17/05/2011	2011.37	-----	-----	3.0	-----	-----	13.7	-----	-----	6.3
10	CENAMEP	16/06/2011 23/06/2011	2011.47	-20.9	23.4	48.6	-26.5	13.8	50.8	-14.0	4.0	29.0
11	CENAM	13/10/2011 28/10/2011	2011.81	-25.2	-19.3	-3.8	-19.3	-16.9	-16.1	-6.3	3.1	11.5
12	CENAM	04/11/2011 25/11/2011	2011.87	-25.1	-19.4	-4.2	-18.2	-16.0	-15.3	-7.5	2.1	10.5
13	CENAM	02/12/2011 23/12/2011	2011.95	-24.3	-18.4	-3.0	-17.6	-15.1	-13.9	-7.4	2.0	10.1
14	CENAM	06/01/2012 26/01/2012	2012.04	-25.8	-19.7	-4.2	-19.2	-16.6	-15.4	-7.0	2.4	10.5
15	CENAM	02/02/2012 24/02/2012	2012.12	-24.6	-18.6	-2.8	-20.3	-17.7	-16.5	-4.8	4.6	13.0
16	CENAM	01/03/2012 23/03/2012	2012.2	-21.6	-15.5	0.1	-16.8	-14.2	-12.9	-5.3	4.2	12.4
17	CENAM	02/04/2012	2012.25	-23.8	-17.8	-2.1	-16.8	-14.3	-12.7	-7.4	1.9	9.9

**Table B.6.** Expanded uncertainty ( $p=95.45\%$ ) in Active Energy. Loop  $j=2$  in  $\mu W/VA$ .

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 [ $\mu Wh/VAh$ ]			U [ $\mu Wh/VAh$ ]			U [ $\mu Wh/VAh$ ]			
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	LCPN-ME	14/07/2010 27/07/2010	2010.55	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0
4	INDECOPI	31/08/2010 13/09/2010	2010.68	---	---	133.0	---	---	70.0	---	---	70.0
5	INM	30/10/2010 01/11/2010	2010.83	110.0	110.0	94	110.0	110.0	94	110.0	110.0	94
6	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
7	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
8	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
9	ICE	11/05/2011 17/05/2011	2011.37	---	---	103.0	---	---	202.0	---	---	202.0
10	CENAMEP	16/06/2011 23/06/2011	2011.47	58.0	58.0	58.0	90.0	90.0	90.0	90.0	90.0	90.0
11	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
12	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
13	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
14	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
15	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
16	CENAM	01/03/2012 23/03/2012	2012.2	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
17	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 Energy. Loop  $j=2$  in  $\mu\text{var}/\text{VA}$ .

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 [ $\mu\text{varh}/\text{VAh}$ ]			Error [ $\mu\text{varh}/\text{VAh}$ ]			Error [ $\mu\text{varh}/\text{VAh}$ ]			Error [ $\mu\text{varh}/\text{VAh}$ ]			
1	CENAM	29/12/2009	2009.99	14.5	8.8	-5.3	-37.7	-31.3	-14.6	3.8	-3.8	-7.7	-10.9	-9.6	-8.3
2	CENAM	24/05/2010 10/06/2010	2010.42	13.0	6.6	-8.9	-34.6	-28.4	-12.6	2.2	-5.2	-10.4	-10.1	-8.9	-7.6
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	9.0	3.3	-11.7	-30.3	-24.6	-9.2	1.2	-6.1	-11.4	-6.9	-6.3	-5.4
6	CENAM	03/02/2011 25/02/2011	2011.12	8.1	2.3	-12.5	-29.0	-23.3	-8.0	1.8	-5.6	-10.6	-5.2	-4.5	-3.6
7	CENAM	04/03/2011 08/04/2011	2011.22	11.4	5.1	-10.1	-32.3	-26.1	-10.6	1.9	-5.4	-10.5	-8.1	-7.2	-6.1
8	ICE	11/05/2011 17/05/2011	2011.37	----	----	7.4	----	----	6.3	----	----	----	----	----	----
9	CENAMEP	16/06/2011 23/06/2011	2011.47	----	----	----	----	----	----	----	----	----	----	----	----
10	CENAM	13/10/2011 28/10/2011	2011.81	11.3	5.7	-8.9	-32.1	-26.4	-11.4	0.7	-6.6	-11.9	-9.4	-8.8	-8.5
11	CENAM	04/11/2011 25/11/2011	2011.87	11.5	5.8	-8.9	-32.4	-26.6	-11.7	1.5	-5.8	-11.1	-8.8	-8.1	-7.9
12	CENAM	02/12/2011 23/12/2011	2011.95	10.3	4.6	-10.3	-31.3	-25.4	-10.2	1.2	-6.0	-11.0	-8.0	-7.1	-6.3
13	CENAM	06/01/2012 26/01/2012	2012.04	11.5	5.7	-9.4	-32.4	-26.5	-11.2	0.8	-6.3	-11.4	-9.5	-8.5	-7.7
14	CENAM	02/02/2012 24/02/2012	2012.12	10.8	5.1	-10.0	-31.8	-25.9	-10.5	-1.2	-8.4	-13.6	-10.9	-9.9	-9.2
15	CENAM	01/03/2012 23/03/2012	2012.2	7.6	1.8	-13.3	-28.6	-22.6	-7.3	-0.7	-8.1	-13.2	-7.2	-6.4	-5.5
16	CENAM	02/04/2012	2012.25	9.7	3.8	-11.2	-30.6	-24.5	-9.2	1.7	-5.4	-10.2	-6.7	-5.6	-4.6

**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 Energy. Loop  $j=2$  in  $\mu\text{var}/\text{VA}$ .

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 [ $\mu\text{varh}/\text{VAh}$ ]			U [ $\mu\text{varh}/\text{VAh}$ ]			U [ $\mu\text{varh}/\text{VAh}$ ]			U [ $\mu\text{varh}/\text{VAh}$ ]			
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	---	---	116.0	---	---	116.0	---	---	---	---	---	---
9	CENAMEP	16/06/2011 23/06/2011	2011.47	---	---	---	---	---	---	---	---	---	---	---	---
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	2012.2	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 Energy, Loop  $j = 1$ .**

