International Comparison of AC-DC Current Transfer Standards EURAMET.EM-K12

Final Report

Appendix 2:
"EURAMET.EM-K12: Reports of the institutes"

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Key comparison EUROMET.EM-K12 "AC-DC CURRENT TRANSFER"

Report of CMI

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Content

1. Describing of the Measuring Method

1.1. Traceability chart and the reference standard of CMI

The traceability chart for AC-DC current transfer difference is on Figure No. 1. For AC-DC difference measurements.
In the first step two working standards (10mA/1V/90Ω PMJTCs) are characterized by a reference standard (10mA/1V/90Ω PMJTC), calibrated in PTB. By using these two working PMJTCs and current shunts the whole AC-DC current difference scale up to 20 A is derived.

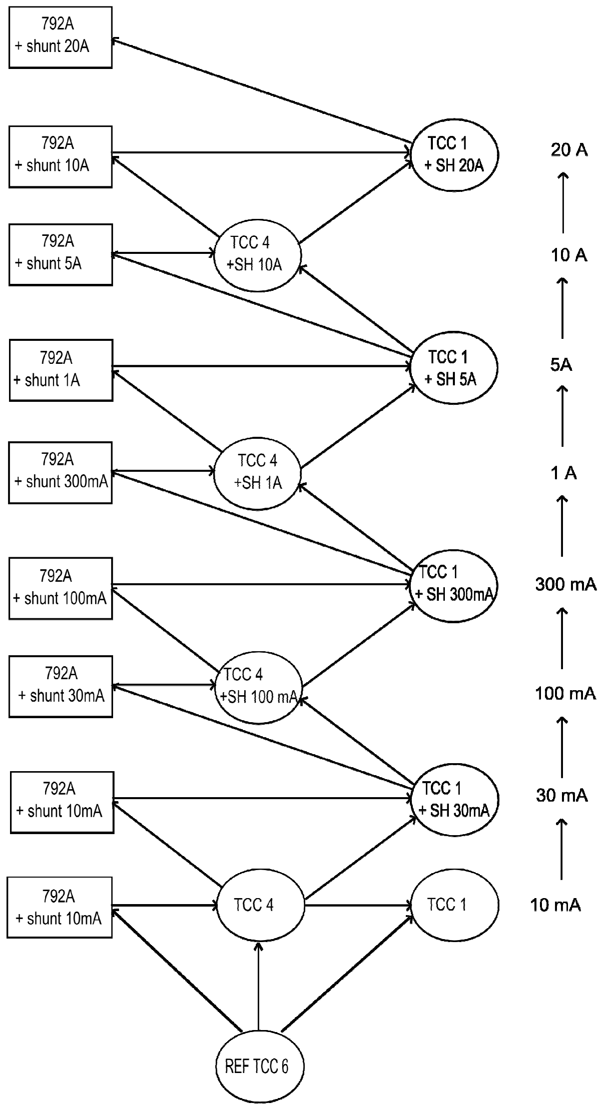


Fig. 1 CMI's traceability chart for AC-DC current transfer

Our reference standard is planar multijunction thermal converter 1V/10mA/90Ω produced by IPHT Jena, Serial No. 6 PTB/IPHT 1996. Its last calibration was at PTB in 2008.

1.2. AC-DC current transfer difference calibration of the travelling standard at 10 mA

The reference standard (REF) and the travelling standard (device under test, DUT) were connected in series using CMI made series T connector (see Fig. 2).

The reference standard was at high potential and the travelling standard was at low potential. Both the input and the output of the travelling standard were earthed. The output of the reference standard was earthed.

The AC and DC currents of 10 mA were supplied directly by AC and DC voltage calibrators and switched by an automatic switch. The switch was made in METAS, Switzerland. Two digital nanovoltmeters were used for measurement of TCCs output voltages.

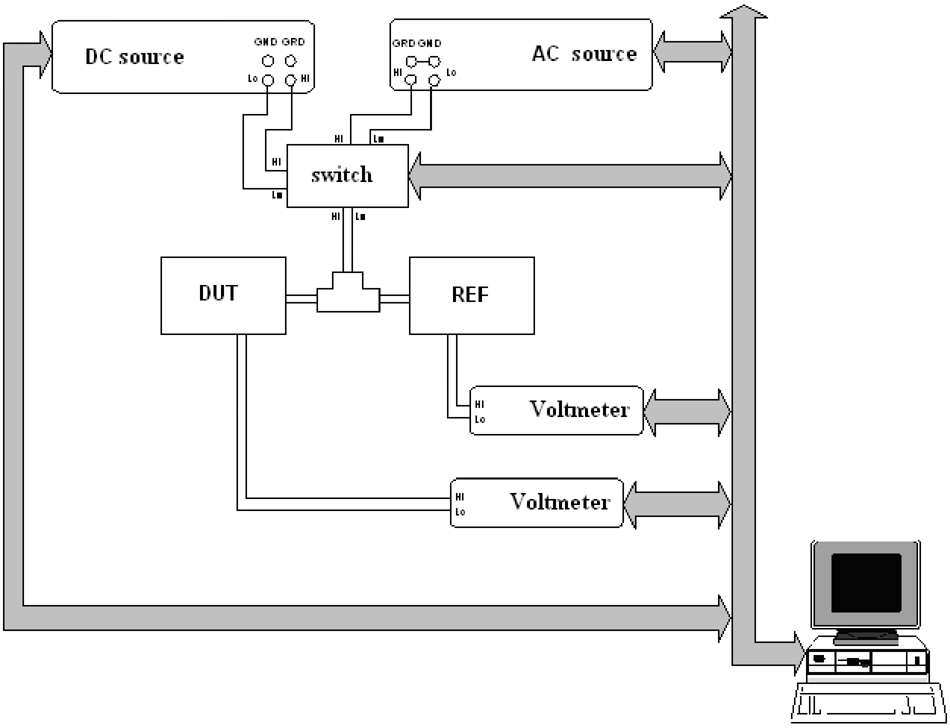


Fig. 2 Measurement system for 10 mA

The sequence of the measurements was: AC, DC+, AC, DC-, AC with the time delay of 40 second between switching of an AC/DC voltage (current) on the switch and the reading of TCCs output voltages. Averaging of the output voltages for dc and ac results was made. Taking the differences of the output voltages at AC and DC for the reference (REF) and travelling (DUT) standard, the ac-dc difference between these two standards δ_{MEAS} was calculated:

$$\delta_{MEAS} = \frac{U_{O\_REF\_AC} - U_{O\_REF\_DC}}{n_{REF} U_{O\_REF\_DC}} - \frac{U_{O\_DUT\_AC} - U_{O\_DUT\_DC}}{n_{DUT} U_{O\_DUT\_DC}}$$

The AC-DC transfer difference of travelling standard at 10 mA δ_{10mA} was got after adding the known ac-dc transfer difference of the reference standard δ_{REF} :

$$\delta_{10mA} = \delta_{MEAS} + \delta_{REF} .$$

Each measurement sequence for one frequency was repeated 10 times and the mean value and standard deviation were calculated.

1.3. AC-DC current transfer difference calibration of the travelling standard at 5 A

The standards were connected in series using CMI made series T connector. The AC a DC currents were applied through the transconductance amplifier which was alternately connected to the DC and AC voltage source using automated switch OFMET (see Fig. 3).

In step up procedure up to 5 A (see Fig. 1) two measurements were done for each current step. First, the reference standard was placed at high potential and calibrated standard at low potential. Second, the positions of reference and calibrated standard were interchanged. Final value of AC-DC current difference of calibrated standard was calculated as average of these two measurements. During the measurements the input and the output of the standard at low position were earthed and also the output of the standard at high position was earthed.

At 5 A was the travelling standard compared with the reference standard as follows: The reference standard was at high potential and the travelling standard was at low potential. Both the input and the output of the travelling standard were earthed. The output of the reference standard was earthed.

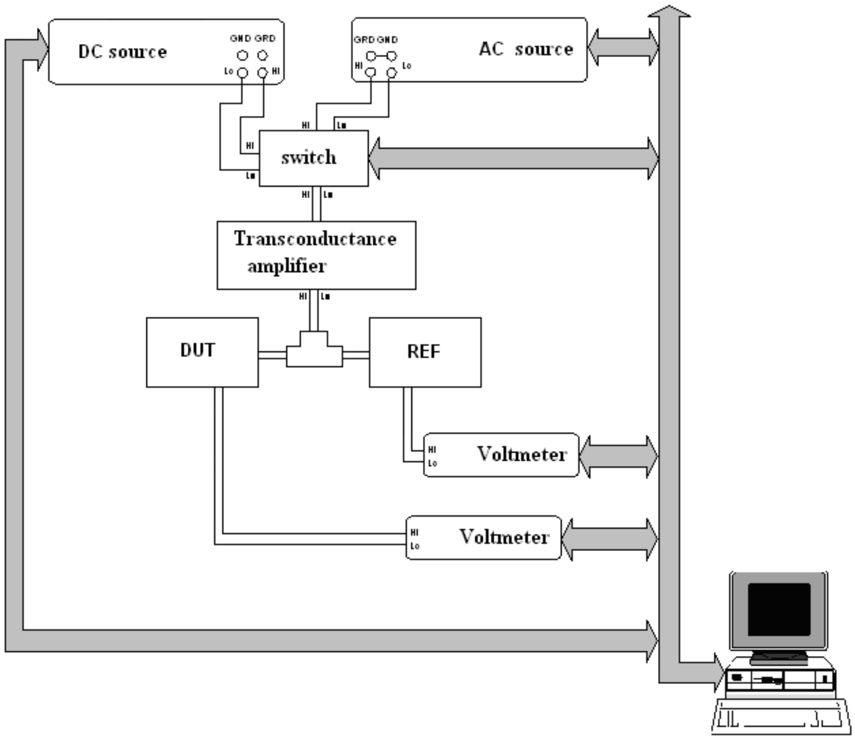


Fig. 3 Measurement system up to 5 A

The sequence of one measurement was: AC, DC+, AC, DC-, AC with the time delay of 40 second between switching of an AC/DC voltage on the switch and the output voltage of PMJTCs measurement. Averaging of the output voltages for ac and dc results was made. Taking the differences of the output voltages at AC and DC for the reference (REF) and calibrated (DUT) standard, the ac-dc difference between these two standards was calculated:

$$\delta_{MEAS} = \frac{U_{O\_REF\_AC} - U_{O\_REF\_DC}}{n_{REF} U_{O\_REF\_DC}} - \frac{U_{O\_DUT\_AC} - U_{O\_DUT\_DC}}{n_{DUT} U_{O\_DUT\_DC}} .$$

The AC-DC transfer difference of tested standard δ_{DUT} (for low or high potential position) was got after adding the known ac-dc transfer difference of the reference standard δ_{REF} :

$$\delta_{DUT} = \delta_{MEAS} + \delta_{REF}$$

Each measurement sequence for one frequency was repeated 10 times, the mean value and standard deviation were calculated.

2. Ambient Conditions of the Measurement

	Min	Max
Ambient temperature / ºC	22,4	23,4
Relative humidity / %	48	59
Pressure / hPa	963	986

3. Other Influence Parameters

Frequency of the measuring signal:

	Nominal frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Measuring frequency	10,000 05	55,000 3	1,000 006	10,000 060	20,000 12	50,000 30	100,000 60
Expanded uncertainty	0,000 05	0,000 3	0,000 003	0,000 002	0,000 02	0,000 02	0,000 02

4. Detailed Uncertainty Budget

Combined uncertainty for the calibration at 10 mA is given by the following equation:

$$u^2(\delta_{10mA}) = u^2(\delta_{REF}) + u^2(\delta_{S\_DUT}) + u^2(\delta_{SET-UP}) + u^2(\delta_{CONN})$$
$$+ u^2(\delta_{FREQ}) + u^2(\delta_{TEMP}),$$

where $u^2(\delta_{REF})$ is contribution of reference standard (PMJTC),

$u^2(\delta_{S\_DUT})$ is contribution of reproducibility of measured DUT's AC-DC difference (standard deviation),

$u^2(\delta_{SET-UP})$ is contribution of measuring set-up,

$u^2(\delta_{CONN})$ is influence of used connectors,

$u^2(\delta_{FREQ})$ is contribution of frequency dependence,

$u^2(\delta_{TEMP})$ is contribution of temperature dependence.

Uncertainty budget for the calibration at 10 mA is calculated in Table 1.

Table 1 Uncertainty budget for the calibration at 10 mA

Contribution of	frequency (kHz)							Type A/B	Distribution
	0,01	0,055	1	10	20	50	100		
reference standard	1,5	1,5	1,5	1,5	1,5	1,5	1,5	B	Normal
reproducibility	0,5	0,5	0,5	0,5	0,5	0,5	0,5	A	Normal
frequency	0	0	0	0	0	0	0,1	B	Normal
temperature	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Rectangular
connectors	0,2	0,2	0,2	0,2	0,2	0,2	0,2	B	Normal
measuring set-up	1	1	1	1	1,5	2	2	B	Normal
combined uncertainty (k=1)	*2,0*	*2,0*	*2,0*	*2,0*	*2,2*	*2,6*	*2,6*		
expanded uncertainty (k=2)	**4,0**	**4,0**	**4,0**	**4,0**	**4,4**	**5,2**	**5,2**		

Combined uncertainty for the calibration of DUT at 30 mA, 100 mA, 300 mA, 1 A and 5 A (see the step-up scheme on Fig.1) is given by the following equation:

$$u^2(\delta_{DUT}) = u^2(\delta_{REF}) + u^2(\delta_{S\_DUT}) + u^2(\delta_{SET-UP}) + u^2(\delta_{LEVEL}) + u^2(\delta_{CONN}) + u^2(\delta_{FREQ}) + u^2(\delta_{TEMP}),$$

where $u^2(\delta_{REF})$ is contribution of reference standard,
$u^2(\delta_{S\_DUT})$ is contribution of reproducibility of measured AC-DC difference (standard deviation),
$u^2(\delta_{SET-UP})$ is contribution of measuring set-up,
$u^2(\delta_{LEVEL})$ is contribution of level dependence,
$u^2(\delta_{CONN})$ is influence of used connectors,
$u^2(\delta_{FREQ})$ is contribution of frequency dependence,
$u^2(\delta_{TEMP})$ is contribution of temperature dependence.

Uncertainty budget for the step-up procedure is calculated in Table 2.

Table 2 Uncertainty budget for the step-up procedure up to 5 A

Current	Reference standard	Calibrated standard	Contribution of	frequency (kHz) 0,01	0,055	1	10	20	50	100	Type A/B	Distribution
10mA	PMJTC n. 6	PMJTC n.1 with 30 mA shunt	reference standard	1,5	1,5	1,5	1,5	1,5	1,5	1,5	B	Normal
			reproducibility	3	1,7	1,7	1,7	1,7	1,7	1,7	A	Normal
			level dependence	0	0	0	0	0	0	0	B	Normal
			frequency	0	0	0	0	0	0	0,1	B	Normal
			temperature	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Rectangular
			connectors	2	1,5	1,5	1,5	1,5	1,5	2	B	Normal
			measuring set-up	1	1	1	1	2	3	8	B	Normal
			combined uncertainty (k=1)	*4,1*	*2,9*	*2,9*	*2,9*	*3,4*	*4,1*	*8,6*		
			expanded uncertainty (k=2)	**8**	**6**	**6**	**6**	**7**	**8**	**17**		
Current	Reference standard	Calibrated standard	Contribution of	frequency (kHz) 0,01	0,055	1	10	20	50	100	Type A/B	Distribution
30mA	PMJTC n.1 with 30 mA shunt	PMJTC n.4 with 100 mA shunt	reference standard	4,1	2,9	2,9	2,9	3,4	4,1	7,6	B	Normal
			reproducibility	3	1,7	1,7	1,7	1,7	1,7	2	A	Normal
			level dependence	2	2	2	2	2	2	2	B	Normal
			frequency	0	0	0	0	0	0	0,1	B	Normal
			temperature	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Rectangular
			connectors	2	1,5	1,5	1,5	1,5	1,5	2	B	Normal
			measuring set-up	1	1	1	1	2	3	8	B	Normal
			combined uncertainty (k=1)	*5,9*	*4,4*	*4,4*	*4,4*	*5,0*	*5,9*	*12,2*		
			expanded uncertainty (k=2)	**12**	**9**	**9**	**9**	**10**	**12**	**24**		
Current	Reference standard	Calibrated standard	Contribution of	frequency (kHz) 0,01	0,055	1	10	20	50	100	Type A/B	Distribution
100mA	PMJTC n.4 with 100 mA shunt	PMJTC n.1 with 300 mA shunt	reference standard	5,9	4,4	4,4	4,4	5,0	5,9	10,9	B	Normal
			reproducibility	1,7	1,7	1,7	1,7	1,7	1,7	1,7	A	Normal
			level dependence	2	2	2	2	2	2	2	B	Normal
			frequency	0	0	0	0	0	0	0,1	B	Normal
			temperature	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Rectangular
			connectors	2	1,5	1,5	1,5	1,5	1,5	2	B	Normal
			measuring set-up	1	1	1	1	2	3	8	B	Normal
			combined uncertainty (k=1)	*6,8*	*5,4*	*5,4*	*5,4*	*6,2*	*7,3*	*15,0*		
			expanded uncertainty (k=2)	**14**	**11**	**11**	**11**	**12**	**15**	**30**		

Current	Reference standard	Calibrated standard	Contribution of	frequency (kHz)							Type A/B	Distribution
				0,01	0,055	1	10	20	50	100		
			reference standard	6,8	5,4	5,4	5,4	6,2	7,3	13,4	B	Normal
300mA	PMJTC n.1	PMJTC n.4	reproducibility	5	1,5	1,5	1,5	1,5	1,5	1,5	A	Normal
	with	with	level dependence	2	2	2	2	2	2	2	B	Normal
	300 mA	1 A	frequency	0	0	0	0	0	0	0,1	B	Normal
	shunt	shunt	temperature	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Rectangular
			connectors	2	1,5	1,5	1,5	1,5	1,5	2	B	Normal
			measuring set-up	1	1	1	1	2	3	8	B	Normal
			combined uncertainty (k=1)	*9,0*	*6,3*	*6,3*	*6,3*	*7,2*	*8,4*	*17,3*		
			expanded uncertainty (k=2)	**18**	**13**	**13**	**13**	**14**	**17**	**35**		
Current	Reference standard	Calibrated standard	Contribution of	frequency (kHz)							Type A/B	Distribution
				0,01	0,055	1	10	20	50	100		
			reference standard	9,0	6,3	6,3	6,3	7,2	8,4	15,5	B	Normal
1A	PMJTC n.4	PMJTC n.1	reproducibility	7	4	4	4	4	4	4	A	Normal
	with	with	level dependence	2	2	2	2	2	2	2	B	Normal
	1 A	5 A	frequency	0	0	0	0	0	0	0,1	B	Normal
	shunt	shunt	temperature	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Rectangular
			connectors	2	1,5	1,5	1,5	1,5	1,5	2	B	Normal
			measuring set-up	1	1	1	1	2	3	8	B	Normal
			combined uncertainty (k=1)	*11,8*	*7,9*	*7,9*	*7,9*	*8,8*	*10,1*	*19,7*		
			expanded uncertainty (k=2)	**24**	**16**	**16**	**16**	**18**	**20**	**39**		
Current	Reference standard	Calibrated standard	Contribution of	frequency (kHz)							Type A/B	Distribution
				0,01	0,055	1	10	20	50	100		
			reference standard	11,8	7,9	7,9	7,9	8,8	10,1	17,7	B	Normal
5A	PMJTC n.1	Travelling	reproducibility	2	2	2	2	2	2	2	A	Normal
	with	standard	level dependence	2	2	2	2	2	2	2	B	Normal
	5 A		frequency	0	0	0	0	0	0	0,1	B	Normal
	shunt		temperature	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Rectangular
			connectors	2	1,5	1,5	1,5	1,5	1,5	2	B	Normal
			measuring set-up	1	1	1	1	2	3	8	B	Normal
			combined uncertainty (k=1)	*12,4*	*8,6*	*8,6*	*8,6*	*9,6*	*11,1*	*21,5*		
			expanded uncertainty (k=2)	**25**	**17**	**17**	**17**	**19**	**22**	**43**		

5. Results of the Measurements

Measuring result:

Current	Measured ac-dc current difference / 10^{-6} at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	5,7	-0,1	0,7	1,0	1,7	2,7	7,5
5 A	2	0	-2	-12	-23	-46	-70

Expanded uncertainty:

Current	Expanded uncertainty / 10^{-6} at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	4,0	4,0	4,0	4,0	4,4	5,2	5,2
5 A	25	17	17	17	19	22	43

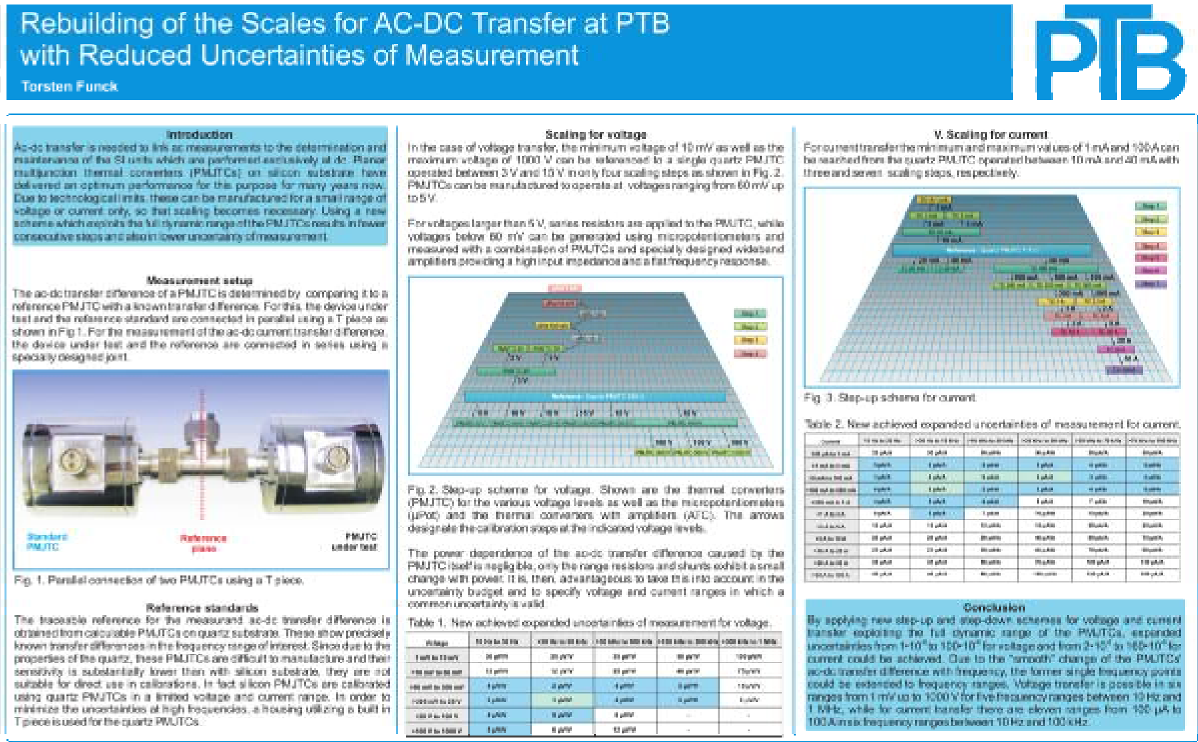
EURAMET Key International Comparison
of AC-DC Current Transfer Standards

EURAMET.EM-K12

Measurement Report of PTB

Measurement setup

The measurement setup and the build-up of the scales is described in detail in:
T. Funck, “Rebuilding of the Scales for AC-DC Transfer at PTB with Reduced Uncertainties of Measurement” CPEM 2012 digest, July 2012.



The transfer standard was connected in series with an appropriate PTB standard for ac-dc current transfer difference using a special T-joint. This series connection was alternately supplied with alternating current and direct current of different polarity. The output voltages of both standards were recorded and the ac-dc current transfer difference of the transfer standard was calculated.

The PTB standard used is described in detail in:
L. Scarioni, M. Klonz, and T. Funck “Quartz Planar Multijunction Thermal Converter as a New AC–DC Current Transfer Standard Up to 1 MHz,” IEEE Trans. Instrum. Meas., vol. 54, no. 2, pp 799 - 802, April 2005.

Definition of the measurand

The measurand is ac-dc current transfer difference δ, which is defined as

$$\delta = \frac{I_{\mathrm{ac}} - I_{\mathrm{dc}}}{I_{\mathrm{dc}}}$$

where I_{ac} is an rms ac current, and I_{dc} is a dc current which, when reversed, produces the same mean output response as the rms ac current.
Ac-dc current transfer differences are expressed in microamperes per ampere (µA/A) and a positive sign indicates that an ac current larger than the dc current was required to produce the same output response.

Measurement procedure

The measurement procedure using potential driven guarding is described in detail in:
T. Funck and M. Klonz "Improved Ac-dc Current Transfer Step-Up with New Current Shunts and Potential Driven Guarding" IEEE Trans. Instrum. Meas., vol. 56, no. 2, pp 361 - 364, April 2007

Reference standard

The reference standard used is considered to be a primary standard. This is described in detail in:
L. Scarioni, M. Klonz, and T. Funck "Quartz Planar Multijunction Thermal Converter as a New AC–DC Current Transfer Standard Up to 1 MHz," IEEE Trans. Instrum. Meas., vol. 54, no. 2, pp 799 - 802, April 2005.

Measurement results

Measurement Results of PTB:

	Measured ac-dc current difference at frequency						
	10 Hz	**55 Hz**	**1 kHz**	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
10 mA	+6,6 µA/A	-0,0 µA/A	-0,1 µA/A	+0,4 µA/A	+1,0 µA/A	+0,9 µA/A	+2,3 µA/A
5 A	+1 µA/A	+0 µA/A	-0 µA/A	-10 µA/A	-20 µA/A	-40 µA/A	-50 µA/A

Expanded Uncertainties of PTB:

	Expanded uncertainty at frequency						
	10 Hz	**55 Hz**	**1 kHz**	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
10 mA	1,8 µA/A	1,0 µA/A	0,7 µA/A	0,8 µA/A	0,9 µA/A	1,3 µA/A	2,0 µA/A
5 A	6 µA/A	5 µA/A	5 µA/A	6 µA/A	7 µA/A	11 µA/A	17 µA/A

Measurement Frequencies of PTB:

	Nominal frequency						
	10 Hz	**55 Hz**	**1 kHz**	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
Measured frequency	10,00 Hz	55,00 Hz	1,000 kHz	10,00 kHz	20,00 kHz	50,00 kHz	100,0 kHz
Expanded uncertainty	0,02 Hz	0,02 Hz	0,002 kHz	0,02 kHz	0,02 kHz	0,02 kHz	0,2 kHz

Ambient conditions

Environmental parameters:

	Min	Max	Remarks
Ambient temperature	21,5 °C	24,8 °C	*U* = 0,2 °C
Relative humidity	45,0 %	59,8 %	*U* = 2 %
Atmospheric pressure	991,8 hPa	1021,2 hPa	*U* unknown

Uncertainty budgets

The sources of uncertainty are described in detail in:
T. Funck, "Rebuilding of the Scales for AC-DC Transfer at PTB with Reduced Uncertainties of Measurement" CPEM 2012 digest, July 2012.

At 10 mA the sources of uncertainty are:

- the uncertainty of the calculable standard
- the uncertainty of the comparison
- the standard deviation of measurements
- the deviation between different measurement setups

At 5 A the sources of uncertainty are:

- the uncertainty of the step-up, i.e. of the 5-A-standard
- the uncertainty of the comparison
- the standard deviation of measurements
- the deviation between different measurement setups

The detailed uncertainty budgets according to the "ISO Guide to the Expression of Uncertainty in Measurement" look like this:

Uncertainty budgets for 10 mA

10 Hz

Parameter X_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
d_Q	0,3 µA/A	normal	0,30 µA/A	1	0,30 µA/A	0,090 (µA/A)^2	50	1,620E-4 (µA/A)^4
d_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)^2	50	3,200E-5 (µA/A)^4
Standard deviation	1,8 µA/A	normal	0,52 µA/A	1	0,52 µA/A	0,270 (µA/A)^2	11	6,627E-3 (µA/A)^4
Max.dev. from mean	1,0 µA/A	rectangular	0,58 µA/A	1	0,58 µA/A	0,333 (µA/A)^2	10.000	1,111E-5 (µA/A)^4
					0,86 µA/A	0,733 (µA/A)^2	**79**	6,832E-3 (µA/A)^4
					1,71 µA/A	***k* = 2**		

55 Hz

Parameter X_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
d_Q	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)^2	50	2,000E-6 (µA/A)^4
d_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)^2	50	3,200E-5 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)^2	11	1,516E-4 (µA/A)^4
Max.dev. from mean	0,6 µA/A	rectangular	0,35 µA/A	1	0,35 µA/A	0,120 (µA/A)^2	10.000	1,440E-6 (µA/A)^4
					0,46 µA/A	0,211 (µA/A)^2	**238**	1,870E-4 (µA/A)^4
					0,92 µA/A	***k* = 2**		

1000 Hz

Parameter X_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
d_Q	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)^2	50	2,000E-6 (µA/A)^4
d_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)^2	50	3,200E-5 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)^2	11	1,516E-4 (µA/A)^4
Max.dev. from mean	0,2 µA/A	rectangular	0,12 µA/A	1	0,12 µA/A	0,013 (µA/A)^2	10.000	1,778E-8 (µA/A)^4
					0,32 µA/A	0,104 (µA/A)^2	**58**	1,856E-4 (µA/A)^4
					0,65 µA/A	***k* = 2**		

10.000 Hz

Parameter X_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
d_Q	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)^2	50	2,000E-6 (µA/A)^4
d_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)^2	50	3,200E-5 (µA/A)^4
Standard deviation	0,2 µA/A	normal	0,06 µA/A	1	0,06 µA/A	0,003 (µA/A)^2	11	1,010E-6 (µA/A)^4
Max.dev. from mean	0,5 µA/A	rectangular	0,29 µA/A	1	0,29 µA/A	0,083 (µA/A)^2	10.000	6,944E-7 (µA/A)^4
					0,37 µA/A	0,137 (µA/A)^2	**523**	3,570E-5 (µA/A)^4
					0,74 µA/A	***k* = 2**		

20.000 Hz

Parameter X_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
d_Q	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)^2	50	2,000E-6 (µA/A)^4
d_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)^2	50	3,200E-5 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)^2	11	1,516E-4 (µA/A)^4
Max.dev. from mean	0,5 µA/A	rectangular	0,29 µA/A	1	0,29 µA/A	0,083 (µA/A)^2	10.000	6,944E-7 (µA/A)^4
					0,42 µA/A	0,174 (µA/A)^2	**163**	1,863E-4 (µA/A)^4
					0,83 µA/A	***k* = 2**		

50.000 Hz

Parameter X_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
d_Q	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)^2	50	1,250E-3 (µA/A)^4
d_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)^2	50	3,200E-5 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)^2	11	1,516E-4 (µA/A)^4
Max.dev. from mean	0,5 µA/A	rectangular	0,29 µA/A	1	0,29 µA/A	0,083 (µA/A)^2	10.000	6,944E-7 (µA/A)^4
					0,64 µA/A	0,414 (µA/A)^2	**120**	1,434E-3 (µA/A)^4
					1,29 µA/A	***k* = 2**		

100.000 Hz

Parameter X_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
d_Q	0,7 µA/A	normal	0,70 µA/A	1	0,70 µA/A	0,490 (µA/A)^2	50	4,802E-3 (µA/A)^4
d_C	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)^2	50	1,250E-3 (µA/A)^4
Standard deviation	1,5 µA/A	normal	0,43 µA/A	1	0,43 µA/A	0,188 (µA/A)^2	11	3,196E-3 (µA/A)^4
Max.dev. from mean	0,5 µA/A	rectangular	0,29 µA/A	1	0,29 µA/A	0,083 (µA/A)^2	10.000	6,944E-7 (µA/A)^4
					1,01 µA/A	1,011 (µA/A)^2	**110**	9,249E-3 (µA/A)^4
					2,01 µA/A	***k* = 2**		

Uncertainty budgets for 5 A

10 Hz

Parameter x_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
Stepup	2,8 µA/A	normal	2,80 µA/A	1	2,80 µA/A	7,840 (µA/A)²	50	1,229E+0 (µA/A)^4
d_c	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)²	50	1,250E-3 (µA/A)^4
Standard deviation	1,7 µA/A	normal	0,49 µA/A	1	0,49 µA/A	0,241 (µA/A)²	11	5,273E-3 (µA/A)^4
Max.dev. from mean	0,7 µA/A	rectangular	0,40 µA/A	1	0,40 µA/A	0,163 (µA/A)²	10.000	2,668E-6 (µA/A)^4
					2,91 µA/A	8,494 (µA/A)²	**58**	1,236E+0 (µA/A)^4
					5,83 µA/A	***k* = 2**		

55 Hz

Parameter x_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
Stepup	2,2 µA/A	normal	2,20 µA/A	1	2,20 µA/A	4,840 (µA/A)²	50	4,685E-1 (µA/A)^4
d_c	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)²	50	1,250E-3 (µA/A)^4
Standard deviation	1,7 µA/A	normal	0,49 µA/A	1	0,49 µA/A	0,241 (µA/A)²	11	5,273E-3 (µA/A)^4
Max.dev. from mean	0,4 µA/A	rectangular	0,23 µA/A	1	0,23 µA/A	0,053 (µA/A)²	10.000	2,844E-7 (µA/A)^4
					2,32 µA/A	5,384 (µA/A)²	**61**	4,750E-1 (µA/A)^4
					4,64 µA/A	***k* = 2**		

1000 Hz

Parameter x_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
Stepup	2,2 µA/A	normal	2,20 µA/A	1	2,20 µA/A	4,840 (µA/A)²	50	4,685E-1 (µA/A)^4
d_c	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)²	50	1,250E-3 (µA/A)^4
Standard deviation	1,7 µA/A	normal	0,49 µA/A	1	0,49 µA/A	0,241 (µA/A)²	11	5,273E-3 (µA/A)^4
Max.dev. from mean	1,2 µA/A	rectangular	0,69 µA/A	1	0,69 µA/A	0,480 (µA/A)²	10.000	2,304E-5 (µA/A)^4
					2,41 µA/A	5,811 (µA/A)²	**71**	4,751E-1 (µA/A)^4
					4,82 µA/A	***k* = 2**		

10.000 Hz

Parameter x_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
Stepup	2,2 µA/A	normal	2,20 µA/A	1	2,20 µA/A	4,840 (µA/A)²	50	4,685E-1 (µA/A)^4
d_c	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)²	50	1,250E-3 (µA/A)^4
Standard deviation	3,5 µA/A	normal	1,01 µA/A	1	1,01 µA/A	1,021 (µA/A)²	11	9,474E-2 (µA/A)^4
Max.dev. from mean	1,7 µA/A	rectangular	0,98 µA/A	1	0,98 µA/A	0,963 (µA/A)²	10.000	9,280E-5 (µA/A)^4
					2,66 µA/A	7,074 (µA/A)²	**89**	5,646E-1 (µA/A)^4
					5,32 µA/A	***k* = 2**		

20.000 Hz

Parameter x_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
Stepup	3,1 µA/A	normal	3,10 µA/A	1	3,10 µA/A	9,610 (µA/A)²	50	1,847E+0 (µA/A)^4
d_c	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)²	50	1,250E-3 (µA/A)^4
Standard deviation	3,5 µA/A	normal	1,01 µA/A	1	1,01 µA/A	1,021 (µA/A)²	11	9,474E-2 (µA/A)^4
Max.dev. from mean	1,8 µA/A	rectangular	1,04 µA/A	1	1,04 µA/A	1,080 (µA/A)²	10.000	1,166E-4 (µA/A)^4
					3,46 µA/A	11,961 (µA/A)²	**74**	1,943E+0 (µA/A)^4
					6,92 µA/A	***k* = 2**		

50.000 Hz

Parameter x_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
Stepup	4,6 µA/A	normal	4,60 µA/A	1	4,60 µA/A	21,160 (µA/A)²	50	8,955E+0 (µA/A)^4
d_c	0,5 µA/A	normal	0,50 µA/A	1	0,50 µA/A	0,250 (µA/A)²	50	1,250E-3 (µA/A)^4
Standard deviation	7,0 µA/A	normal	2,02 µA/A	1	2,02 µA/A	4,083 (µA/A)²	11	1,516E+0 (µA/A)^4
Max.dev. from mean	3,4 µA/A	rectangular	1,96 µA/A	1	1,96 µA/A	3,853 (µA/A)²	10.000	1,485E-3 (µA/A)^4
					5,42 µA/A	29,347 (µA/A)²	**82**	1,047E+1 (µA/A)^4
					10,83 µA/A	***k* = 2**		

100.000 Hz

Parameter x_i	Dx_i or s_i	Distribution	$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$	$n_{eff\ i}$	$u_i^4(y)/\nu_{eff\ i}$
Stepup	7,5 µA/A	normal	7,50 µA/A	1	7,50 µA/A	56,250 (µA/A)²	50	6,328E+1 (µA/A)^4
d_c	1,0 µA/A	normal	1,00 µA/A	1	1,00 µA/A	1,000 (µA/A)²	50	2,000E-2 (µA/A)^4
Standard deviation	11 µA/A	normal	3,18 µA/A	1	3,18 µA/A	10,083 (µA/A)²	11	9,243E+0 (µA/A)^4
Max.dev. from mean	3,6 µA/A	rectangular	2,08 µA/A	1	2,08 µA/A	4,320 (µA/A)²	10.000	1,866E-3 (µA/A)^4
					8,46 µA/A	71,653 (µA/A)²	**71**	7,255E+1 (µA/A)^4
					16,93 µA/A	***k* = 2**		

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Object	**EURAMET.EM-K12** Key International Comparison Of AC-DC Current Transfer Standards. Multi Junction Thermal Converter, PTP/IPHT Serial Nr. PMJTC 17 Current Shunt, BEV Serial Nr. B3A
Order	Determination of the current AC-DC difference at 10 mA and 5 A and frequencies of 10Hz, 55Hz, 1kHz, 10kHz, 20kHz, 50kHz and 100kHz
Applicant	BEV, Bundesamt für Eichung- und Vermessungswesen Arltgasse 35 A-1160 Vienna Austria
Traceability	The reported measurement values are traceable to national standards and thus to internationally supported realizations of the SI-units.
Date of Calibration	10.09.2012 (10 mA standard) and 19.09.2012 (5A standard)
Marking	none

CH-3003 Bern-Wabern, 31 October 2012

For the Measurements	Sector Electricity
Dr. Alessandro Mortara	Dr. Beat Jeckelmann, Head of sector

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Extent of the Calibration

The AC-DC current difference was measured at the following frequencies: 10 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz. The measuring current was 10 mA for the multi junction thermal converter alone and 5 A for the multi-junction thermal converter plus current shunt assembly. Both measurements have been done with earthed device under test ("low" position in the series assembly)

Measurement Procedure

At 10 mA, the travelling thermal converter was connected in series with a reference planar multi-junction thermal converter (PMJTC) previously calibrated by a primary laboratory (BEV). This converter is the basis for a step up procedure leading to the determination of the AC-DC difference of a current standard suitable for measurements at 5A. This standard was used for the calibration of the travelling device at the 5A level. The standards for the step-up consist of 2 PMJTCs used in conjunction with a set of shunts manufactured by the Swedish National Metrology Laboratory (SP). The setup measures the following quantity:

$$\delta_2 = \delta_1 + \frac{1}{n_2} \times \frac{\frac{V_{DC2+} + V_{DC2-}}{2} - V_{AC2}}{\frac{V_{DC2+} + V_{DC2-}}{2}} - \frac{1}{n_1} \times \frac{\frac{V_{DC1+} + V_{DC1-}}{2} - V_{AC1}}{\frac{V_{DC1+} + V_{DC1-}}{2}}$$

Where:

δ_2 and δ_1 are, respectively, the AC/DC current difference of the UUT and reference converters,
V_{DC2+} and V_{DC1+} are, respectively, the output voltages responses of the UUT and reference converters to equal positive current inputs,
V_{DC2-} and V_{DC1-} are, respectively, the output voltages responses of the UUT and reference converters to equal negative current inputs,
V_{AC2} and V_{AC1} are, respectively, the output voltages responses of the UUT and reference converters to equal AC current inputs,
n_2 and n_1 are respectively, the exponent of the input-output characteristic of the UUT and reference converters.

The nominal magnitudes and rms value of, respectively, the DC and AC current inputs are the same. The measurand, δ_2 ,as defined above can be shown to be equivalent to the definition given in the technical protocol of the comparison.

The output voltages were measured with two voltmeters using the potential-driven output circuit technique to reduce reversal errors. A 2µF capacitor was connected at the input of the voltmeter measuring the reference output (the UUT had a built-in capacitor at its voltage output).The measurement at the 10mA level was performed in voltage mode, applying an appropriate voltage to the reference and travelling standard, connected in series using a current-tee. At the 5A level, a transconductance amplifier was used to generate the input current.

The frequencies were measured at the voltage output of the calibrator using a calibrated universal counter and found to be nominal to better than ±0.1%.

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Measurement Conditions

The temperature was measured using a calibrated thermometer with the probe placed in close proximity of the UUT. The humidity was measured with a probe mounted in a fixed location of the room where the measurements were carried out. The measurement conditions were as follows:

Current	Mean temperature (T), humidity (H) and measurement date		
	T (°C)	H (%)	date
10 mA	23.4	39.4	10.09.2012
5 A	23.5	38.4	19.09.2012

The distribution of ambient temperature and relative humidity are assumed to be uniform about the mean value within ±0.5 °C and ±5% respectively.

Current Measurement Results

Current	Measured ac-dc current difference (μA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	7.1	0.6	0.4	0.6	0.7	1.6	2.5
5 A	1.5	0.0	2.0	-8.0	-18.9	-40.9	-51.7

Current Uncertainty of Measurement

Current	Expanded uncertainty (μA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	8.3	8.3	8.3	8.3	8.3	8.3	9.4
5 A	12.4	9.9	9.2	10.4	12.3	21.2	31.4

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Frequency Measurement Results

	Measured frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
measured	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
expanded uncertainty	0.01 Hz	0.06 Hz	1 Hz	10 Hz	20 Hz	50 Hz	100 Hz

Uncertainty budget:

			frequency in Hz						
			10	55	1000	10000	20000	50000	100k
	current (A)	0.01							
	ref. std. uncertainty including drift		**4**	**4**	**4**	**4**	**4**	**4**	**4**
	current (A)	0.01							
ref: TFMJ2	pooled st. dev.	A, N	0.2	0.1	0.1	0.1	0.1	0.1	0.1
	leakage currents	B, R	0.6	0.3	0.8	0.4	0.4	0.2	0.2
UUT:PTC 17	"n" factor	B, R	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	level dep. of ref. TVC	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	frequency	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N	0.1	0.0	0.0	0.0	0.0	0.1	0.3
	Std. uncertainty		**4.1**	**4.0**	**4.1**	**4.0**	**4.0**	**4.0**	**4.1**
	U_{95}		**8.3**	**8.3**	**8.3**	**8.3**	**8.3**	**8.3**	**9.4**

			frequency in Hz						
			10	55	1000	10000	20000	50000	100k
	current (A)	5							
	ref. std. uncertainty		**5.8**	**4.9**	**4.6**	**4.8**	**5.2**	**7.4**	**9.9**
	current (A)	5							
ref: TFMJ2 shunt 5A SP	pooled st. dev.	A, N	0.3	0.4	0.3	0.5	0.3	0.2	0.2
	leakage currents	B, R	0.8	0.3	0.2	1.6	1.5	6.5	9.7
UUT: PTC 17 +	"n" factor	B, R	1.0	1.0	1.0	1.0	1.0	1.0	1.0
shunt 5A BEV	level dep. of ref. TVC	B, R	2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N	0.1	0.2	0.1	0.4	0.6	0.3	0.4
	Std. uncertainty		**6.0**	**4.9**	**4.6**	**5.1**	**5.5**	**9.9**	**13.9**
	U_{95}		**12.4**	**9.9**	**9.2**	**10.4**	**12.3**	**21.2**	**31.4**

Notes: in the above tables, A, N means type A with normal distribution, B, R means type B with rectangular distribution. U_{95} is computed multiplying the standard uncertainty with the coverage factor.

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The effective degrees of freedom for each uncertainty component and the coverage factors are shown in the following tables.

		frequency in Hz						
		10	55	1000	10000	20000	50000	100k
current (A)	0.01							
pooled st. dev.	A, N	30	30	30	30	30	30	30
leakage currents	B, R	∞	∞	∞	∞	∞	∞	∞
"n" factor	B, R	∞	∞	∞	∞	∞	∞	∞
level dep. of TVC	B, R	∞	∞	∞	∞	∞	∞	∞
frequency	B, R	∞	∞	∞	∞	∞	∞	∞
reproductibility of setup	A, N	5	5	5	5	5	5	5
Effective degrees of freedom		**35**	**33**	**35**	**34**	**35**	**31**	**8**
Coverage factor		**2.04**	**2.04**	**2.04**	**2.04**	**2.04**	**2.04**	**2.31**

		frequency.in Hz						
		10	55	1000	10000	20000	50000	100k
current (A)	5							
pooled st. dev.	A, N	18	54	54	54	36	36	36
leakage currents	B, R	∞	∞	∞	∞	∞	∞	∞
"n" factor	B, R	∞	∞	∞	∞	∞	∞	∞
voltage dep. of ref. TVC	B, R	∞	∞	∞	∞	∞	∞	∞
frequency	B, R	∞	∞	∞	∞	∞	∞	∞
reproductibility of setup	A, N	3	9	9	9	6	6	6
Effective degrees of freedom		**21**	**52**	**63**	**40**	**9**	**14**	**9**
Coverage factor		**2.08**	**2.01**	**2.00**	**2.02**	**2.26**	**2.15**	**2.26**

The reported uncertainty of measurement is stated as the combined standard uncertainty multiplied by a coverage factor as specified. The measured value (*y*) and the associated expanded uncertainty (*U*) represent the interval ($y \pm U$) which contains the value of the measured quantity with a probability of approximately 95 %. The uncertainty was estimated following the guidelines of the ISO (GUM:1995).

The measurement uncertainty contains contributions originating from the measurement standard, from the calibration method, from the environmental conditions and from the object being calibrated. The long-term characteristic of the object being calibrated is not included.

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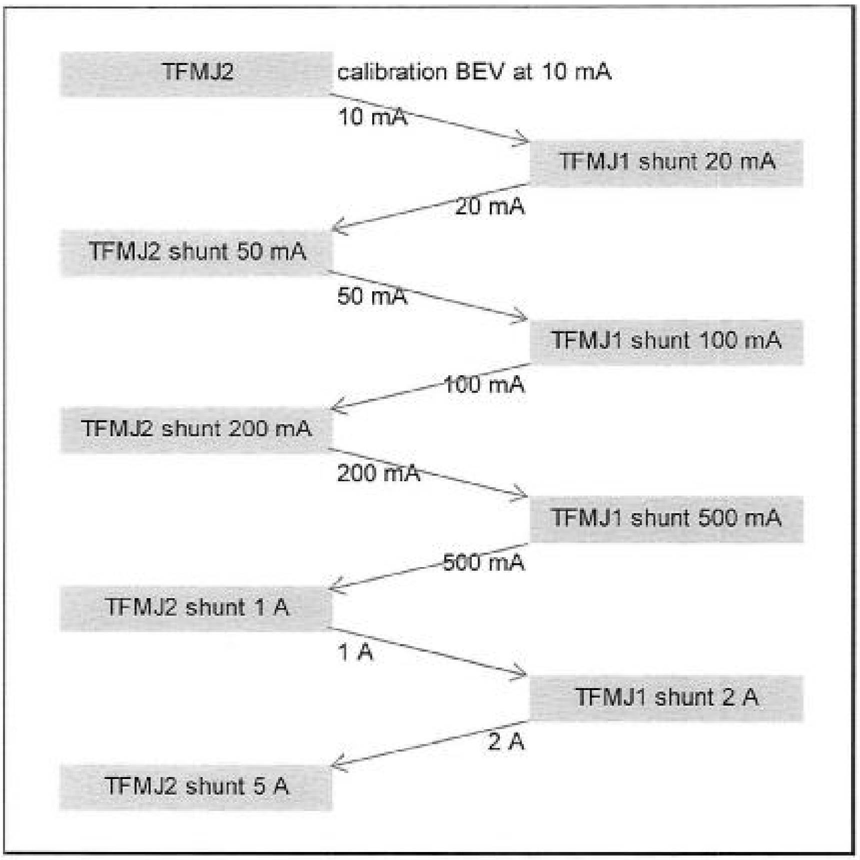
Appendix 1: Stepping procedure



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Appendix 2: Uncertainty budget for the stepping procedure

			Frequency in Hz						
			10	55	1000	10000	20000	50000	100k
from BEV calibration	current (A)	0.01							
standard: TFMJ2	standard uncertainty		**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**
Step n. 1	current (A)	0.01							
ref: TFMJ2	pooled st. dev.	A, N	0.6	0.5	0.4	0.4	0.4	0.5	0.3
UUT: TFMJ1 shunt 20 mA	leakage currents	B, R	0.3	0.2	0.5	0.2	0.3	0.1	0.1
	"n" factor	B, R	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R	2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N	0.2	0.3	0.3	0.2	0.2	0.1	0.1
	standard uncertainty		**4.2**	**4.1**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**
	U_{95}		**8.4**	**8.1**	**8.1**	**8.1**	**8.1**	**8.1**	**8.0**

			Frequency in Hz						
			10	55	1k	10k	20k	50k	100k
previous step:	current (A)	0.01							
	standard uncertainty		**4.2**	**4.1**	**4.0**	**4.0**	**4.0**	**4.0**	**4.0**
Step n. 2	current (A)	0.02							
ref: TFMJ1 shunt 20 mA	pooled st. dev.	A, N	1.0	1.4	0.8	0.7	0.7	0.9	0.5
UUT: TFMJ2 shunt 50 mA	leakage currents	B, N	0.6	0.4	0.4	0.8	0.7	1.5	2.0
	"n" factor	B, R	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R	2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N	0.4	0.3	0.2	0.6	0.4	1.1	1.6
	standard uncertainty		**4.5**	**4.4**	**4.1**	**4.2**	**4.1**	**4.4**	**4.5**
	U_{95}		**9.1**	**8.7**	**8.3**	**8.3**	**8.3**	**8.8**	**9.0**

			Frequency in Hz						
			10	55	1k	10k	20k	50k	100k
previous step:	current (A)	0.02							
	standard uncertainty		**4.5**	**4.4**	**4.1**	**4.2**	**4.1**	**4.4**	**4.5**
Step n. 3	current (A)	0.05							
ref: TFMJ2 shunt 50 mA	pooled st. dev.	A, N	0.8	0.4	0.5	0.4	0.4	0.4	0.4
UUT: TFMJ1	leakage currents	B,N	0.3	0.4	0.3	0.8	1.7	3.5	5.5
shunt 100 mA	"n" factor	B, R	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R	2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N	0.3	0.3	0.3	0.6	1.5	2.6	4.1
	standard uncertainty		**4.8**	**4.4**	**4.2**	**4.3**	**4.5**	**5.5**	**6.9**
	U_{95}		**9.5**	**8.8**	**8.4**	**8.5**	**9.1**	**11.0**	**13.7**

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				Frequency in Hz						
				10	55	1k	10k	20k	50k	100k
previous step:	current (A)	0.05								
	standard uncertainty			**4.8**	**4.4**	**4.2**	**4.3**	**4.5**	**5.5**	**6.9**
Step n. 4	current (A)	0.1								
ref: TFMJ1 shunt 100 mA	pooled st. dev.	A, N		0.7	0.6	0.6	0.6	0.6	0.6	0.5
UUT: TFMJ2	leakage currents	B,N		0.3	0.1	0.3	1.1	1.5	2.8	4.0
shunt 200 mA	"n" factor	B, R		0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R		2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R		0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N		0.2	0.3	0.3	0.8	0.9	1.6	2.3
	standard uncertainty			**5.0**	**4.5**	**4.3**	**4.4**	**4.8**	**6.0**	**7.6**
	U_{95}			**9.9**	**8.9**	**8.5**	**8.9**	**9.5**	**12.0**	**15.2**

				Frequency in Hz						
				10	55	1k	10k	20k	50k	100k
previous step:	current (A)	0.1								
	standard uncertainty			**5.0**	**4.5**	**4.3**	**4.4**	**4.8**	**6.0**	**7.6**
Step n. 5	current (A)	0.2								
ref: TFMJ2 shunt 200 mA	pooled st. dev.	A, N		0.6	0.6	0.9	0.9	0.8	0.8	1.0
UUT: TFMJ1	leakage currents	B,N		0.1	0.7	0.5	0.5	0.5	1.1	0.3
shunt 500 mA	"n" factor	B, R		0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R		2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R		0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N		0.3	0.4	0.3	0.4	0.6	0.8	0.6
	standard uncertainty			**5.1**	**4.6**	**4.4**	**4.6**	**4.9**	**6.1**	**7.7**
	U_{95}			**10.3**	**9.1**	**8.8**	**9.1**	**9.8**	**12.3**	**15.4**

				Frequency in Hz						
				10	55	1k	10k	20k	50k	100k
previous step:	current (A)	0.2								
	standard uncertainty			**5.1**	**4.6**	**4.4**	**4.6**	**4.9**	**6.1**	**7.7**
Step n. 6	current (A)	0.5								
ref: TFMJ1 shunt 500 mA	pooled st. dev.	A, N		0.4	0.4	0.5	0.5	0.4	0.5	0.4
UUT: TFMJ2 shunt 1 A	leakage currents	B,N		0.3	0.8	0.3	0.3	0.3	0.6	1.4
	"n" factor	B, R		0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R		2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R		0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N		0.2	0.5	0.4	0.2	0.2	0.4	0.9
	standard uncertainty			**5.3**	**4.6**	**4.5**	**4.6**	**4.9**	**6.2**	**7.8**
	U_{95}			**10.6**	**9.3**	**8.9**	**9.2**	**9.8**	**12.4**	**15.6**

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			Frequency in Hz						
			10	55	1k	10k	20k	50k	100k
previous step:	current (A)	0.5							
	standard uncertainty		**5.3**	**4.6**	**4.5**	**4.6**	**4.9**	**6.2**	**7.8**
Step n. 7	current (A)	1							
ref: TFMJ2 shunt 1 A	pooled st. dev.	A, N	1.2	0.3	0.5	0.5	0.7	0.5	0.6
UUT: TFMJ1 shunt 2 A	leakage currents	B,N	0.3	0.8	0.1	0.5	0.9	1.1	0.9
	"n" factor	B, R	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R	2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N	0.3	0.4	0.2	0.4	0.7	0.8	1.3
	standard uncertainty		**5.6**	**4.7**	**4.5**	**4.7**	**5.0**	**6.3**	**8.0**
	U_{95}		**11.1**	**9.4**	**9.0**	**9.4**	**10.1**	**12.6**	**15.9**

			Frequency in Hz						
			10	55	1k	10k	20k	50k	100k
previous step:	current (A)	1							
	standard uncertainty		**5.6**	**4.7**	**4.5**	**4.7**	**5.0**	**6.3**	**8.0**
Step n. 8	current (A)	2							
ref: TFMJ1 shunt 2 A	pooled st. dev.	A, N	0.9	1.0	0.6	0.9	0.8	0.8	0.6
UUT: TFMJ2 shunt 5 A	leakage currents	B,N	0.4	0.2	0.1	0.9	1.1	4.6	6.9
	"n" factor	B, R	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	level dep. of TVC	B, R	2.0	0.5	0.0	0.0	0.0	0.0	0.0
	frequency	B, R	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	reproductibility of setup	A, N	0.3	0.4	0.2	0.5	0.6	2.8	4.3
	standard uncertainty		**5.8**	**4.9**	**4.6**	**4.8**	**5.2**	**7.4**	**9.9**
	U_{95}		**11.6**	**9.7**	**9.1**	**9.7**	**10.4**	**14.9**	**19.8**

Report on measurement results from JV measurements on the EURAMET-K.12 AC-DC difference audit devices.

Definition of Measurand

AC-DC current transfer difference is defined as

$$\delta = \frac{I_{ac} - I_{dc}}{I_{dc}},$$

where I_{ac} is the rms ac current, and I_{dc} is a dc current which, when reversed, produces the same mean output response as the rms ac current. Differences are expressed in µA/A, and a positive sign signifies that more ac than dc current was required for the same output response.

Description of the measurement setup

In the measurement setup in Figure 1, a current shunt, a Thermal Voltage Converter (TVC) or a combination of a current shunt and a TVC can be compared to the AC-DC current transfer difference of either a reference shunt, a reference TVC or a combination of the two.

The main components of the measurement setup are

- A DC voltage source, typically a Fluke 5700A calibrator
- An AC voltage source, typically a Fluke 5700A calibrator
- A relay switch with relay driver unit and GPIB interface
- A Clarke-Hess 8100 transconductance amplifier
- Two HP/Agilent 3458A Digital Multimeters (DMM) to read the DC output of the TVCs
- Common Mode Rejection (CMR) filters to stop AC noise from entering the DMMs
- Shunt and TVC as reference
- “Tee” for series connection of reference and Object under test
- Two isolation power transformers in cascade to reduce the common mode capacitance of the “High” side of the setup to the surroundings
- A high-frequency isolation transformer and two GPIB extenders to provide an isolated GPIB to the “High” DMM
- A commercially available PC with GPIB interface, running a LabView program to control the whole measurement setup, including initialization, parameter setup, timing between readings, reading data, computing the AC-DC difference and writing results to a log file.

Guarding and grounding scheme is essential in the setup. The front panel of the transconductance amplifier is connected to the guards of the voltage sources, which are operated in external guard mode.

On the “Low” side of the setup, the guard of the “Low” DMM is connected to the “Low” side of the “Tee”, using the cable shields and housing of CMR filter in a “daisy-chain” fashion as illustrated in Figure 1. The chassis of the "Low” DMM is grounded via the power cord ground conductor and the GPIB cable shield. The input LO side of the DMM is connected to the DMM guard using front panel button “Guard to LO”.

On the “High” side of the setup, the guard of the “High” DMM is connected in the same way to the “High” side of the “Tee”. In addition, the chassis of the “High” DMM, is connected to the guard of this DMM. Total capacitance between “High” DMM chassis and surroundings is approximately 100 pF, as opposed to the higher capacitance between guard and chassis of the DMM. AC current leakage between DMM input and the chassis+guard of the DMM is in this way reduced to approximately the same level as on the “Low” side of the setup. This improves the setup symmetry. The input LO side of the DMM is connected to the DMM guard using front panel button “Guard to LO”.

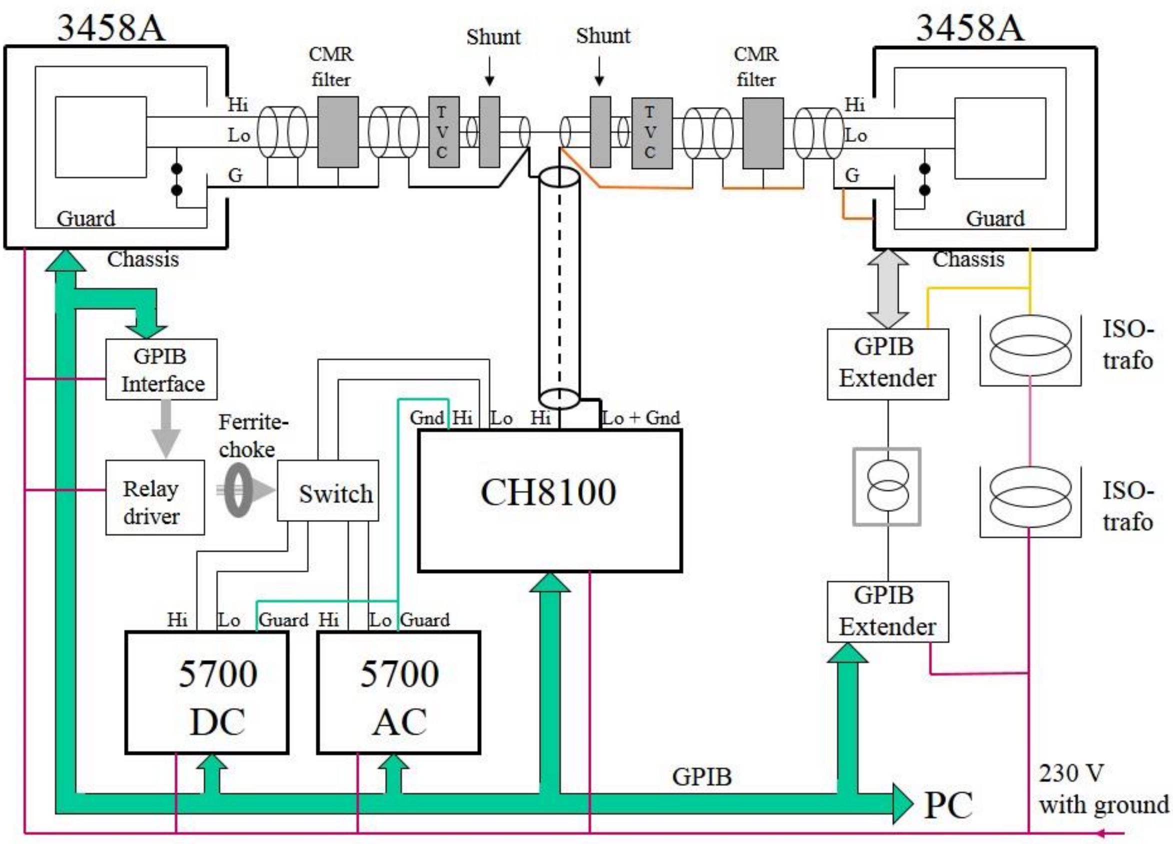

Figure 1: A schematic description of the measurement setup.

Reference standards

Three 90 Ω Planar Multi-junction Thermal Voltage Converters (TVC 21, TVC 14 and TVC 18) were operated in the measurements. In the case of the 10 mA measurements, a self-made 30 mA nominal current radial shunt (JV30mA), with calculable AC-DC difference was connected to the reference TVC. For the 5 A measurements, a self-made 5 A current shunt (JV5A), with an AC-DC difference determined in a step-up calibration from the reference shunt JV30mA, was operated in combination with the reference TVC.

Statement of traceability

TVC 21 and TVC 14 were calibrated by PTB in January - February 2011.

Description of the measurement procedure

10 mA

The PTC 17 traveling standard for 10 mA was measured in the setup described in the previous section. On the "high" side of the setup, a 90 Ω TVC is connected to the JV30mA shunt, so that the reference TVC is in voltage mode. The PTC 17 TVC, positioned at the "low" side, is connected in series to the combination of shunt and TVC on the "high" side, thereby operating in current mode. Measurements from two separate reference TVCs was compared and averaged in the reported values.

5 A

The combination of PTC 17 and B3A 5A current shunt was compared against the same TVCs as for the 10 mA standard, with the reference standards in the "high" position. A self-made 5A nominal current shunt (JV5A) is connected to the reference TVC so that the TVC operates in voltage mode. As a consistency check, an additional TVC (TVC 18) was calibrated in voltage mode against one of the calibrated TVCs (TVC 14), and then used in combination with JV5A to measure on the traveling standard. This gave the same result as for the two separate measurements with the two calibrated TVCs. The reported value, is an average of these three different measurement setups.

Details for the measurement procedure

The procedure is essentially the same as that described in detail by Knight/Legg/Martin [1],[2] and Rydler [3],[4].

The measurement starts by determining the scale factors, which describes the sensitivity for variations in input current for the reference and the test device. This is done by performing a series of measurements at 1 kHz AC current, where the current is varied ±0.5% in relation to the nominal measuring current. A series of 13 measurements are performed and a curve-fitting algorithm is applied to compensate for temperature drift and offset in the detectors. The scale factor is applied to convert the measured (DC) signal to input currents (AC_{rms}).

Further, for each frequency, the AC current is adjusted to within 100 ppm of the DC current measured with the TVCs. The magnitude of the AC-DC difference is measured in a series of 13 measurements with equal waiting times between the measurements, typically 60 s. The sequence of the 13 measurements are AC, DC+, AC, DC-,…,AC

For each measurement, the reading from the detectors is triggered at the same time. The 13 measurements are converted into input currents with the scale factors. Subsequently, the difference between the readings. The same curve-fitting, as mentioned above, is applied to these 13 differences and the magnitude of the AC-DC difference between the reference standard and the test device is calculated for the respective frequency.

The 13 pairs of readings results in many degrees of freedom in the determination of the AC-DC difference. Thus, a standard deviation in this difference can be determined. The absolute AC-DC difference of the test device is finally calculated from the measured AC-DC difference and the known AC-DC difference of the reference standard.

Ambient conditions

The temperature was kept at 23±1°C with a relative humidity of 43±5%.

Measurements Results

The data are as shown in the tables below:

Measurement current 10 mA				**Measurement current 5 A**		
	AC-DC diff.	Exp. Uncert.			AC-DC diff.	Exp. Uncert.
Frequency Hz	µA/A	µA/A		Frequency Hz	µA/A	µA/A
10	9	5		10	1	11
55	1	3		55	0	7
1000	0	3		1000	0	7
10000	1	3		10000	-8	7
20000	1	3		20000	-17	7
50000	1	3		50000	-35	8
100000	1	5		100000	-45	11

Expanded uncertainties are calculated uncertainties (k=2). The most important contributions to uncertainties are the TVCs uncertainty, its power dependency, the reference shunt's uncertainty, and for 5 A, the accumulated step-up uncertainty.

Detailed uncertainties

The two tables below, show the specific contributions to the expanded uncertainties in the results above. A detailed description of the components is given in the appended uncertainty budget. All of the components consist of type B uncertainties, except the standards deviation *s,* which is of type A uncertainty.

To simplify the tables, the proper notation of e.g. $u(\delta_{TVC})$, $u(\delta_{JVR30mA})$, etc. was omitted. The expanded uncertainty in the result is the root of the sum of squares for all the individual components in the tables, for their respective frequency and current.

10 mA

Frequency (Hz)	TVC	JVR30mA	s	T	sf	DMMnoise	CMRR	KMR	lin	dist	x	ind
10	1	0.5	0.37	0.1	0.4	1	0.1	0.1	1.5	0.2	1	0.1
55	0.5	0.1	0.34	0.1	0.4	1	0.1	0.1	0.5	0.2	0.3	0.1
1000	0.5	0.1	0.32	0.1	0.4	1	0.1	0.1	0.3	0.2	0.3	0.1
10000	0.5	0.2	0.33	0.1	0.4	1	0.1	0.1	0.3	0.2	0.3	0.1
20000	0.5	0.3	0.30	0.1	0.4	1	0.1	0.1	0.3	0.2	0.3	0.1
50000	0.5	0.4	0.40	0.2	0.4	1	0.1	0.1	0.3	0.2	0.4	0.1
100000	1.5	0.6	0.33	0.2	0.4	1	0.1	0.1	0.4	0.2	0.6	0.1

5A

Frequency (Hz)	TVC14	JV5A	s	T	sf	DMMnoise	CMRR	KMR	lin	dist	x	ind
10	1	4.6	0.14	0.1	0.4	1	0.1	0.1	1.5	0.2	1	0.1
55	0.5	3.0	0.12	0.1	0.4	1	0.1	0.1	0.5	0.2	0.3	0.1
1000	0.5	2.9	0.38	0.1	0.4	1	0.1	0.1	0.3	0.2	0.3	0.1
10000	0.5	2.9	0.17	0.1	0.4	1	0.1	0.1	0.3	0.2	0.3	0.1
20000	0.5	3.1	0.20	0.1	0.4	1	0.1	0.1	0.3	0.2	0.3	0.1
50000	0.5	3.5	0.17	0.2	0.4	1	0.1	0.1	0.3	0.2	0.4	0.1
100000	1.5	4.8	0.20	0.2	0.4	1	0.1	0.1	0.3	0.2	0.6	0.1

[1] Knight, R.B.D.; Legg, D.J. and Martin, P.: "Digital "bridge" for comparison of AC-DC transfer instruments", IEE Proc., 138(3), pp.169-175, 1991.

[2] Martin, P. and Knight, R.B.D.: "Components and systems for AC/DC transfer at the ppm level", IEEE Trans. Instr. Meas., IM-32, pp.63-72, 1983.

[3] Rydler, Karl-Erik: "Automatiserat mätsystem för kalibrering av termoomvandlare", SP Rapport 1991:37, SP, Fysik och Elteknik, Box 857, S-501 15 Borås, Sverige.

[4] Rydler, Karl-Erik: ”Nogrann mätning av växelström” 1994

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Model equation and uncertainty in AC step-up with JV current shunts

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April 30, 2014

Measurement function

The AC-DC difference δ for an object at step N and frequency j can be expressed as:

$$\delta_{objN,j} = \delta_{ref1,j} + \sum_{i=1}^{N} \delta_{Ti,j} + \sum_{i=1}^{N} \delta_{KMRi,j} + \sum_{i=1}^{N} \delta_{lini,j} + \sum_{i=1}^{N} \delta_{linSi,j} + \sum_{i=1}^{N} \delta_{sfi,j} + \sum_{i=1}^{N} \delta_{DMMnoisei,j} + \sum_{i=1}^{N} \delta_{CMRRi,j} + \sum_{i=1}^{N} \delta_{disti,j} + \sum_{i=1}^{N} \delta_{indi,j} + \sum_{i=1}^{N} \delta_{xi,j} \quad (1)$$

where all of the components are described below. All partial derivatives are equal to 1, e.g.

$$\frac{\partial \delta_{objN,j}}{\partial \delta_{ref1,j}} = 1, \frac{\partial \delta_{objN,j}}{\partial \delta_{Ti,j}} = 1 \quad (2)$$

as all the separate parts in the function are assumed to be independent. All expectation values are 0, except from $\delta_{ref1,j}$ and $\delta_{KMRi,j}$. The combined uncertainty at step N and frequency j can then be expressed as:

$$u^2_{\delta_{objN,j}} = u^2_{\delta_{ref1,j}} + \sum_{i=1}^{N} u^2_{\delta_{Ti,j}} + \sum_{i=1}^{N} u^2_{\delta_{KMRi,j}} + \sum_{i=1}^{N} u^2_{\delta_{lini,j}} + \sum_{i=1}^{N} u^2_{\delta_{linSi,j}} + \sum_{i=1}^{N} u^2_{\delta_{sfi,j}} + \sum_{i=1}^{N} u^2_{\delta_{DMMnoisei,j}} + \sum_{i=1}^{N} u^2_{\delta_{CMRRi,j}} + \sum_{i=1}^{N} u^2_{\delta_{disti,j}} + \sum_{i=1}^{N} u^2_{\delta_{indi,j}} + \sum_{i=1}^{N} u^2_{\delta_{xi,j}} + \sum_{i=1}^{N} s^2_{i,j} \quad (3)$$

Specific contributions

$u(\delta_{ref})$ – Uncertainty in the reference (TVC + shunt).

The AC-DC current difference is deduced from the AC-DC voltage difference, and the value is set to 3 ppm based on this.[1] If it is only the current shunt, which is characterized, the contribution is reduced by interchanging the position of the TVCs, such that it is only the calculated AC-DC difference of the reference shunt, which contributes. The remaining contribution from the TVC is related to linearity, and is thus covered in $\delta_{lini,j}$.

$u(\delta_{T})$ – Uncertainty related to AC leakage in the "T-piece".

As there is a non symmetrical current leak from the "T-piece", there is an uncertainty related to the determination of the AC-DC difference. This contribution can, after extensive investigations, be quantified to 0.1 ppm in all steps for frequencies $\leq$ 20 kHz. By interchanging the "high" and "low" position, this can be reduced to $<$ 0.5 ppm at 100 kHz, where it is proportional to the frequency in the rage $50 - 300$ kHz.[2]

$u(\delta_{KMR})$ – Uncertainties from Knight-Martin-Rydlers method for curve fitting.

This contribution is considered to be less than 0.1 ppm.

$u(\delta_{lin})$ – Uncertainty from linearity/power dependency in the TVC.

Planar multi-junction thermal converters are used within 20 - 100 % of its current level, with a contribution of less than 0.1 ppm. At frequencies below 300 Hz, and down to 10 Hz, the contribution increases inversely proportional to the frequency. This leads to contributions of 1.5 ppm, 1 ppm and 0.5 ppm at 10 Hz, 20 Hz and 45/55 Hz, respectively. At 300 Hz, and above, the contribution is set to 0.3 ppm.

$u(\delta_{linS})$ – Uncertainty from the linearity/power dependency of the reference current shunt

Contribution from the power dependency of the reference current shunt during step-up calibration. Funck and Klonz[3] have shown that the power dependency of the JV shunts are below 0.3 ppm from 3:1 steps at 100 mA and 100 kHz, decreasing with frequency. At a 5:1 step, (5 A against 1 A) the JV shunts were estimated to have a 3.5 ppm uncertainty at 100 kHz.

$u(\delta_{sf})$ – Uncertainty from scale factor of the TVC.

This contribution is considered to be 0.4 ppm.

$u(\delta_{DMMnoise})$ – Uncertainty related to noise, drift and non linearity in the DMM and measurement setup.

Based on experience, this contribution is considered to be 1 ppm.

$u(\delta_{CMRR})$ – Uncertainty due to a finite Common-mode suppression of the DMM.

This contribution is considered to be less than 0.1 ppm.

$u(\delta_{dist})$ – Uncertainty from distortion of the AC curve shape.

This contribution has been calculated to be 0.2 ppm at 2 A and 5 kHz, proportional to frequency and current by applying a calibrator as the current source. When operating a CH8100 transconductance amplifier below 200 % of its range up to 100 kHz, and below 100 % up to 300 kHz, this constitutes less than 0.2 ppm.

[1] M. Klonz, dr.- ing. Thesis 1987. Entwicklung von Vielfachtermokonvertern zur genauen Rückführung von Wechselgrössen auf äquivalente Gleichgrössen

[2] K. Lind, J. H. Espedalen, and H. Slinde. "Optimizing the Series Connection of Thermal Converters For AC-DC Current Difference Calibration-Improved Model." Precision Electromagnetic Measurements Digest, 2004 Conference on. IEEE, 2004.

[3] Torsten Funck and Manfred Klonz. "Improved AC–DC current transfer step-up with new current shunts and potential driven guarding." Instrumentation and Measurement, IEEE Transactions on 56.2 (2007): 361-364.

$u(\delta_{ind})$ – *Contribution from mutual induction from current to voltage side.*

When operating our self-designed JV current shunts, this contribution is less than 0.1 ppm for all frequencies.

$u(\delta_x)$ – *Step-up uncertainty related to non symmetric stray current in the measurement setup.*

This contribution has been considered to be < 0.5 ppm up to 50 kHz, < 1 ppm at 100 kHz and < 2 ppm at 300 kHz. By interchanging "high" and "low" position in the measurement setup, this will be partly canceled out. The contributions will then be < 0.2 ppm, < 0.5 ppm and 1 ppm, respectively.

s – *Standard deviation for a measurement series.*

The measurement program calculates a standard deviation for each frequency in a measurement series, from the Knight-Martin-Rydlers method for curve fitting. The standard deviation of all measurement series, at the same frequency, is then averaged and compared to the a calculated standard deviation of the AC-DC difference result of the measurement series. The largest of these two numbers is then divided by the square root of the number of measurement series, and is used as $s_{i,j}$.

Report of EURAMET.EM-K12

EURAMET Key International Comparison
of AC-DC Current Transfer Standards

TÜBİTAK UME Voltage Laboratory

1. SCOPE

Comparison of AC-DC current transfer standards at 10 mA and 5 A currents and frequencies 10 Hz, 55 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz. Parameter to be measured is the ac-dc transfer difference that is defined as:

$$d = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

Where I_{ac} is ac current and I_{dc} is dc current which, when reversed, produces the same mean output response as the rms ac current I_{ac}.

2. PERIOD OF MEASUREMENTS

The measurements have been performed at TÜBİTAK UME in the period of 09.11.2012–05.12.2012.

3. TRAVELING STANDARDS

The travelling standard for the current of 10 mA is a Planar Multi-Junction Thermal Converter (PMJTC), manufactured by IPHT Jena with the following nominal parameters:
Rated Input Current: 10 mA
Heater Resistance: 90 Ω
Thermocouple Resistance: 7.6 kΩ
Output Voltage at Rated Current: approx. 100 mV

The 5 A travelling standard comprises a 147 mΩ coaxial shunt (Serial No B3A) connected in parallel to the PMJTC described above. The shunt has been manufactured at BEV.
The main parameters are as follows:
Current Shunt, Serial No B3A:
Nominal Resistance 147 mΩ
Input Connector type N (female)
Output Connector type N (male)

4. AMBIENT CONDITIONS

The comparison measurements have been performed in TÜBİTAK UME Voltage Laboratory which has the environmental conditions given below:

Temperature	:	(23 ± 1) °C
Relative Humidity	:	(45 ± 10) %

During the comparison measurement, the environmental temperature and relative humidity have been measured by UME temperature-humidity monitoring system.

5. MEASUREMENTS PRECAUTIONS

- The traveling standard has been allowed to stabilize in laboratory conditions, which is under control for one day after their arrival to Voltage Laboratory of TÜBİTAK UME.

- Traveling standards were measured for the “Lo” position. Both input and output of the traveling standards were earthed during measurements.
- After application of the current, minimum 25 minutes were allowed for stabilization.

6. AC-DC CURRENT TRANSFER SYSTEM of TÜBİTAK UME

Ac-dc current transfer system of TÜBİTAK UME is based on PMJTCs and ac-dc current shunts. Primary group consists of four PMJTC with heater resistance of 90 OHM and nominal current of 10 mA. One of the converters is calibrated in PTB and used to check other standards in the group. Higher currents are established through a step up procedure by using suitable PMJTC – ac-dc shunt combinations. Used ac-dc shunts are homemade and commercial and are attached to the PMJTCs with heater of the 90 OHM. Step-up measurements scheme is given in Figure 1.

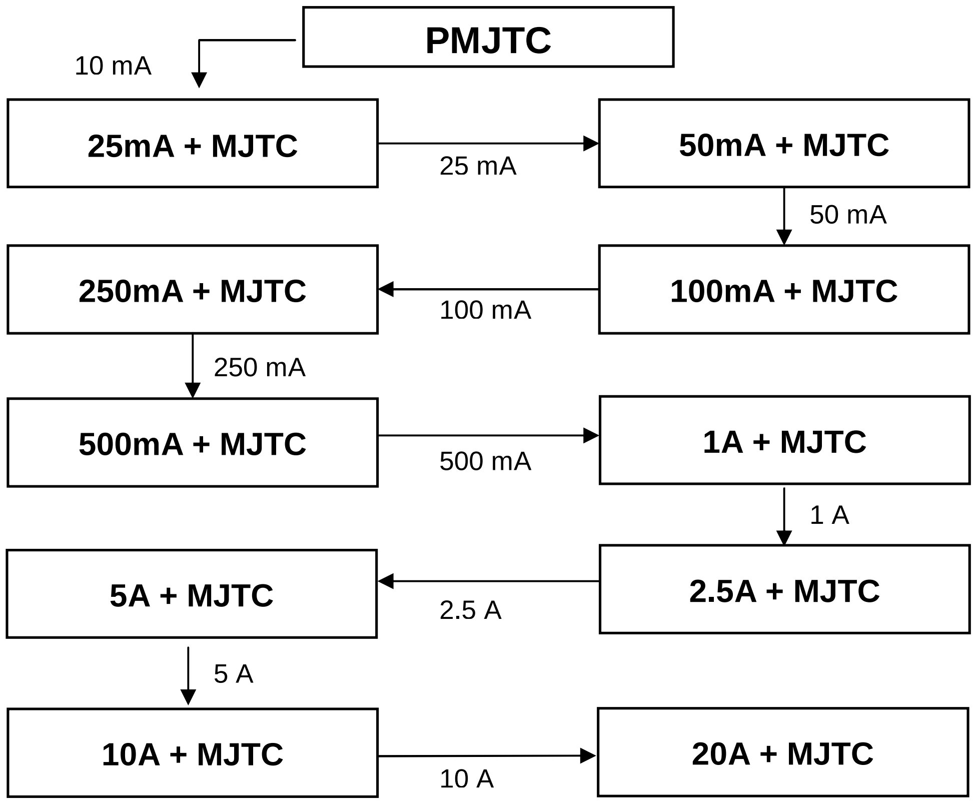

Figure 1. Ac-dc current transfer step-up measurements in TÜBİTAK UME

7. MEASUREMENT SET-UP of TÜBİTAK UME

Measurement set-up used in TÜBİTAK UME for ac-dc current transfer is shown in Figure 2.

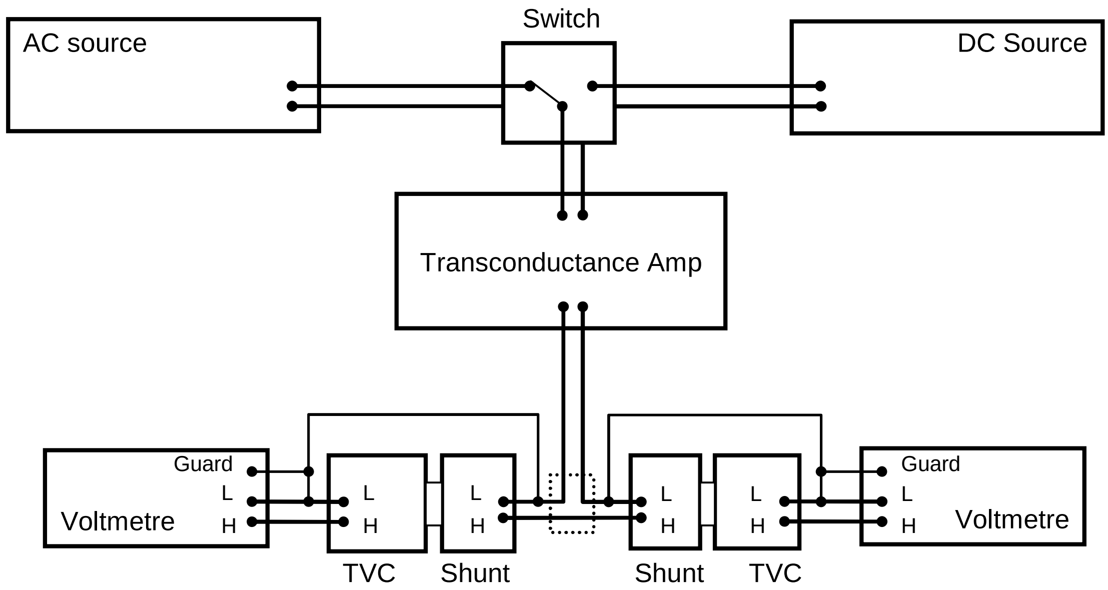

Figure 2. Measurement set-up for ac-dc current measurements in TÜBİTAK UME

AC and DC calibrators (Fluke 5700A) are used to produce voltages delivered through a fast switch to a transconductance amplifier (CH 8100) and converted to the necessary currents. Outputs of the standards are monitored with nanovoltmeters, Keithley 182, which are modified to have a guard and connected in order to drive guards at the potentials of the ac-dc standards. Measurements are performed automatically using a PC and homemade software.

8. MEASUREMENT METHOD

Measurement procedure begins with warming up and determination of the sensitivity coefficients of the transfer standards at working current. Then, ac and dc currents, adjusted to produce the same (within 50 ppm tolerance) output of test converter, are applied in ac, dc-, ac, dc+, ac sequence and outputs of both converters are measured with nanovoltmeters. Each current is applied for 90 seconds period before reading the outputs of the converters.

AC-DC difference of the test device at each cycle is calculated by using formula bellow:

$$d_t = d_s + \frac{E_{dcs} - E_{acs}}{n_s \cdot E_{dcs}} - \frac{E_{dct} - E_{act}}{n_t \cdot E_{dct}}$$

Where;

δ_t ac-dc transfer difference of the test transfer standard

δ_s ac-dc transfer difference of the reference transfer standard

E_{acs} output emf of the reference transfer standard when applied AC current

E_{dcs} average output emf of the reference transfer standard when applied forward and reverse DC current

E_{act} output emf of the test transfer standard when applied AC current

E_{dct} average output emf of the test transfer standard when applied forward and reverse DC current

n_s, n_t sensitivity parameters of reference and test transfer standard

At each frequency twelve measurements of ac-dc transfer difference are performed and final result is given as mean value of these measurements.

9. MEASUREMENT RESULTS

Ac-dc transfer difference:

Current	Measured ac-dc current difference (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	6.9	0.1	0.1	0.2	0.3	1.6	3.0
5 A	-1	0	0	-11	-21	-43	-65

Expanded Uncertainty:

Current	Expanded Uncertainty (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	4.7	3.3	3.3	3.3	3.3	4.0	6.0
5 A	12	8	8	8	9	12	21

Measurement Frequency:

Current	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. Frequency	9.99985 Hz	54.9991 Hz	999.984 Hz	9.99984 kHz	19.9997 kHz	49.9992 kHz	99.9984 kHz
Expanded Uncertainty	10 µHz/Hz						

Environmental parameters:

	Minimum	Maximum	Remarks
Ambient temperature (ºC)	23.10	23.87	
Relative humidity (%)	38.2	51.0	

10. UNCERTAINTY BUDGET

Model function of the measurements is

$$\delta_t = \delta_{diff} + \delta_{drift} + \delta_{ref} + \delta_{rep} + \delta_{con} + \delta_{sys}$$

where;

δ_t	AC-DC transfer difference of test transfer standard
δ_{ref}	AC-DC transfer difference of reference transfer standard
δ_{drift}	AC-DC transfer difference due to drift of reference transfer standard
δ_{diff}	AC-DC transfer difference between test and reference transfer standard
δ_{rep}	AC-DC transfer difference due to the repeatability during comparison
δ_{con}	AC-DC transfer difference due to the connectors and connections
δ_{sys}	AC-DC transfer difference due to the measurement system

Uncertainty Budget for 10 mA

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference Standard, k=1	2.0	1.5	1.5	1.5	1.5	1.5	2.0	Type B	Normal
Drift of the Standard	0.3	0.2	0.2	0.2	0.2	0.5	0.8	Type B	Rect.
Standard Deviation	0.5	0.5	0.5	0.5	0.5	0.5	0.5	Type A	Normal
Repeatability	1.0	0.3	0.3	0.3	0.3	0.5	1.5	Type A	Normal
Measurement System	1.0	0.5	0.5	0.5	0.5	0.8	1.0	Type B	Rect.
Connectors	0	0	0	0	0	0,5	1.0	Type B	Rect.

Standard Uncertainty, k=1	2.3	1.6	1.6	1.6	1.6	1.6	3.0
Expanded Uncertainty	**4.7**	**3.3**	**3.3**	**3.3**	**3.3**	**4.0**	**6.0**
Eff. deg. of freedom:	70	62	62	62	65	71	73

Uncertainty Budget for 5 A

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference Standard, k=1	5.0	3.5	3.5	3.5	3.5	5.0	10.0	Type B	Normal
Drift of the Standard	0.5	0.5	0.5	0.5	0.5	1.0	2.0	Type B	Rect.
Standard Deviation	1.0	0.8	0.8	0.8	0.8	0.8	0.8	Type A	Normal
Repeatability	1.0	0.5	0.5	0.5	1.0	2.0	3.0	Type A	Normal
Measurement System	1.0	0.5	0.5	0.5	0.5	0.8	1.0	Type B	Rect.
Connectors	0	0	0	0	0	0.5	1.0	Type B	Rect.

Standard Uncertainty, k=1	6	4	4	4	4	6	10
Expanded Uncertainty	**12**	**8**	**8**	**8**	**9**	**12**	**21**
Eff. deg. of freedom:	56	55	55	55	57	57	58

EURAMET Key International Comparison
of AC-DC Current Transfer Standards

EURAMET.EM - K12

Report of the measurements at GUM
7 - 22 January 2013

Acronym of Institute: GUM
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Date: 25. Feb. 2013
Measurements performed in January 2013

General Information

This report describes the method and the results of the measurements performed at GUM from the 7th January to the 23th January 2013 as part of the EURAMET Key International Comparison of AC-DC Current Transfer Standard.
The measured parameter is the AC-DC transfer difference of traveling standard.
The travelling standard for the current of 10 mA is a Planar Multi-Junction Thermal Converter Type PTP/IPHT Serial Number PTC 17 manufactured by IPHT Jena.
The travelling standard for the current of 5 A is the converter described above and 147 mΩ coaxial shunt Serial Number B3A manufactured at BEV connected in parallel to it.

The Reference Standard and Statement of Traceability

The GUM reference standard is 1 Volt Thermal Voltage Converter Model 84506, Serial Number 0943500001688, and connected in parallel to it Primary Alternating Current Shunts: Model HCS-1A P/N 81554 and Model HCS-1E P/N 81668-001, used respectively for the current of 10 mA and the current of 5 A.
They all are manufactured by Holt Instrument Laboratories.

The GUM reference standard 1 Volt Thermal Voltage Converter Model 84506 and Primary Alternating Current Shunts Model HCS-1 were calibrated in PTB in 2012 year – Calibration Certificate of 25-10-2012, calibration mark 20080PTB12 to 20086PTB12.

Definition of Measurand

AC-DC current transfer difference of travelling standard is defined as:

$$\Delta_M = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

where
Iac is an rms ac current, and
Idc is a dc current which produces the same mean output response as the rms ac current.
Differences are expressed in microampers per ampere (μA/A) and a positive sign signifies that more ac than dc current was required for the same output response.

Measurement setup

Calibrator Fluke 5720A was the current source of the system in case of 10 mA for frequencies 10 Hz, 55 Hz, 1 kHz and 10 kHz and in case of 5 A for frequencies 55 Hz, 1 kHz and 10 kHz.
Calibrator Fluke 5220A was the current source of the system in case of 10 mA for frequency 10 kHz, and in case of 5 A for frequency 10 Hz.
Output EMF of the traveling standard was measured by the Datron 1281 digital multimeter.
Output EMF of GUM reference standard was measured by the Keithley 2182 nanovoltmeter.
The AC-DC transfer difference was measured for the “L_O” position of the travelling standard.
The input of the travelling standard has been connected in series with input of the GUM reference standard by means of a serial T-connector.
Schemes of measurement system and its connections are shown at Fig. 1 and Fig. 2.

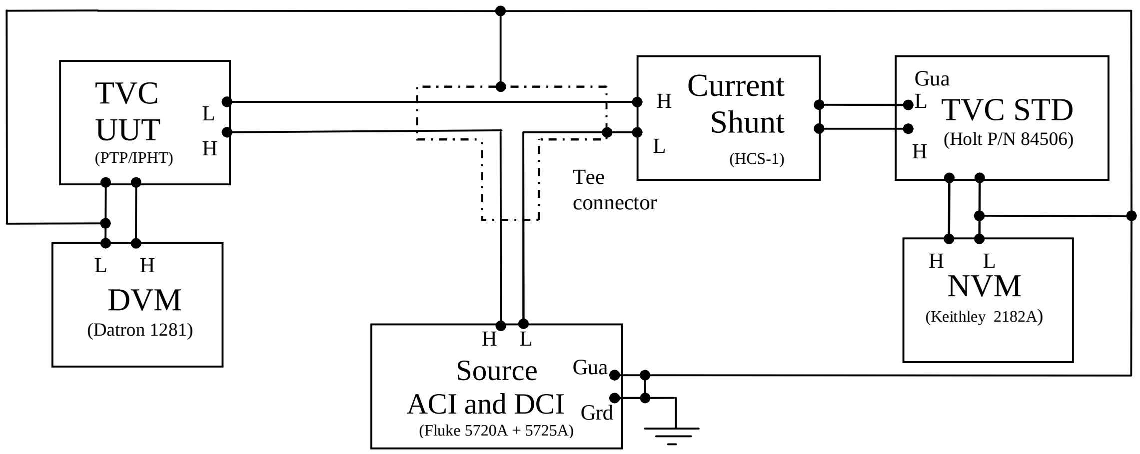

Fig. 1. Scheme of measurement system and its connections for 10 mA.

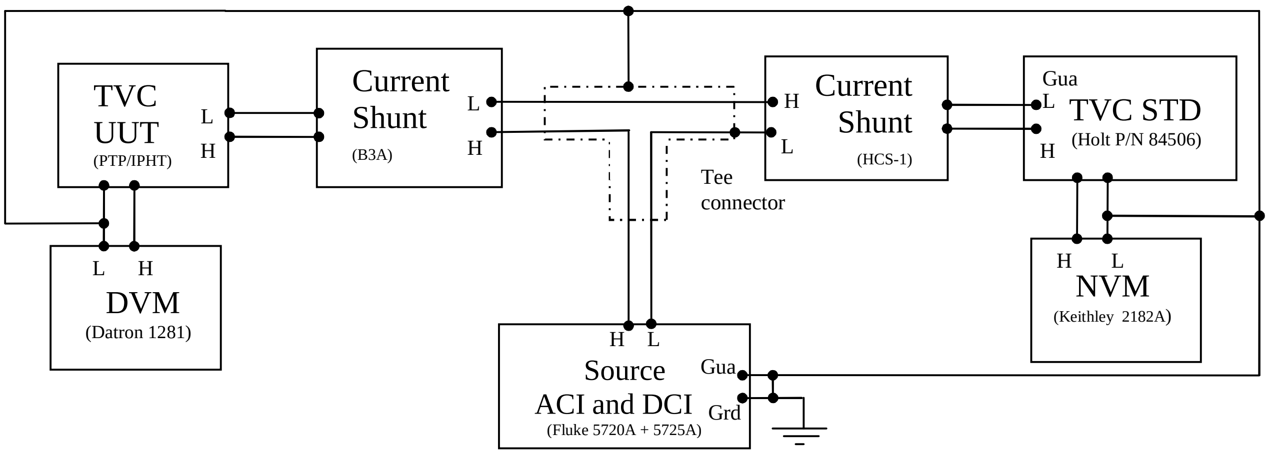

Fig. 2. Scheme of measurement system and its connections for 5A.

Measurement Procedure

In order to run comparison the dual-channel method was used.
Measurement was automated using LabView program and was performed as 16 sequences for every current value for every frequency.
The input of the travelling standard has been connected in series with input of the GUM reference standard by means of a serial T-connector. AC and DC currents in the proper sequence have been applied to standards. Every sequence contains 5 steps (signals from calibrator) in the following order: I_{AC}, $+I_{DC}$, I_{AC}, $-I_{DC}$, I_{AC}. Each step lasted 60 seconds.
Averages of modules of output values both compared standards have been calculated for each sequence and inserted into the formula which defines the AC-DC transfer difference of the traveling standard Δ_M

$$\Delta_{\mathrm{M}} = \Delta_1 + \Delta_2 + \Delta_3 = \frac{E_{\mathrm{SAC}} - E_{\mathrm{SDC}}}{n_{\mathrm{S}} \cdot E_{\mathrm{SDC}}} - \frac{E_{\mathrm{XAC}} - E_{\mathrm{XDC}}}{n_{\mathrm{X}} \cdot E_{\mathrm{XDC}}} + \Delta_2 + \Delta_3$$

where:

E_{XAC} – output voltage value of calibrated converter when input AC input signal is given,

E_{XDC} – output voltage value of calibrated converter when input DC input signal is given,
E_{SAC} – output voltage value of reference standard converter when input AC signal is given,
E_{SDC} – output voltage value of reference standard converter when input DC signal is given,
n_X – characteristic parameter of calibrated converter,
n_S – characteristic parameter of reference standard converter,
Δ_1 – measurement difference as a result obtained on measurement setup,
Δ_2 – correction from not reproducible results of series of measurements,
Δ_3 – AC-DC transfer difference of GUM standard (standard converter correction).

The measurements were carried out for both serial T-connector positions. The same number of repeats were performed for every of both positions. The final result is considered as average for both positions and uncertainty component from serial T-connector is eliminated.

Table 1. The Measurements Results

Current	Measured AC-DC current difference (µA/A) at frequency				
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz
10 mA	8,3	0,5	0,8	-3,3	3,9
5 A	-2,5	-2,4	-4,5	-20,3	-

Current	Expanded Uncertainty (µA/A) at frequency				
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz
10 mA	4,7	3,8	3,9	4,5	4,4
5 A	12,4	12.3	12,5	12,6	-

Current	Eff. deg. of freedom:				
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz
10 mA	439	248	211	239	100
5 A	11483	22068	16216	16825	-

Current	Nominal Frequency at 10 mA				
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz
Meas. Frequency	9,999917	54,999565	0,9999920	9,999921	19,999998
Expanded Uncertainty	0,000010	0,000050	0,0000011	0,000011	0,000022

Current	Nominal Frequency at 5 A				
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz
Meas. Frequency	9,999931	54,999565	0,9999920	9,999921	-
Expanded Uncertainty	0,000010	0,000050	0,0000011	0,000011	-

The Ambient Conditions of the Measurement

The measurements have been performed in a shielded cage at the temperature from 22,1 °C to 23,4 °C (except 5 A for 55 Hz to 10 kHz where limits of temperature were from 21,6 °C to 23,2 °C) with uncertainty ± 0,1 °C and relative humidity from 44,1 % to 57,7 % with uncertainty ± 0,4 %. Ambient conditions were measured every 5 minutes during the converters measurements.
The values of these parameters were recorded during the period of the measurements.

The Uncertainty Budget

Three uncertainty contributions are taken under account:

$$u(\Delta_M) = \sqrt{u(\Delta_1)^2 + u(\Delta_2)^2 + u(\Delta_3)^2}$$

$u(\Delta_M)$ – uncertainty of measurement,
$u(\Delta_1)$ – contribution from measuring set-up calculated by type B evaluation,
$u(\Delta_2)$ - contribution from reproducibility calculated by type A evaluation,
$u(\Delta_3)$ - contribution from reference standard (calibration certificate) calculated by type B evaluation,

Because

$$\Delta_1 = \frac{E_{SAC} - E_{SDC}}{n_S \cdot E_{SDC}} - \frac{E_{XAC} - E_{XDC}}{n_X \cdot E_{XDC}}$$

then $u(\Delta_1)$ could be presented as

$$u(\Delta_1) = \sqrt{c_1^2 \cdot u(E_{SAC})^2 + c_2^2 \cdot u(E_{SDC})^2 + c_3^2 \cdot u(n_S)^2 + c_4^2 \cdot u(E_{XAC})^2 + c_5^2 \cdot u(E_{XDC})^2 + c_6^2 \cdot u(n_X)^2}$$

where $c_1 \div c_6$ - sensitivity coefficients.

Then uncertainty of measurement:

$$u(\Delta_M) = \sqrt{c_7^2 \cdot u(\Delta_2)^2 + c_1^2 \cdot u(E_{SAC})^2 + c_2^2 \cdot u(E_{SDC})^2 + c_3^2 \cdot u(n_S)^2 + c_4^2 \cdot u(E_{XAC})^2 + c_5^2 \cdot u(E_{XDC})^2 + c_6^2 \cdot u(n_X)^2 + c_8^2 \cdot u(\Delta_3)^2}$$

where $c_7 \div c_8$ - sensitivity coefficients

Table 2. Uncertainty budget

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
D_2	d_2	$u(d_2)$	normal	$c_7 = 1$	$c_7 \cdot u(d_2)$
E_{SAC}	e_{SAC}	$u(e_{SAC})$	trapezoidal	$c_1 = \frac{1}{n_S \cdot E_{SDC}}$	$c_1 \cdot u(e_{SAC})$
E_{SDC}	e_{SDC}	$u(e_{SDC})$	trapezoidal	$c_2 = \frac{E_{SAC}}{n_S}\left(-\frac{1}{E_{SDC}^2}\right)$	$c_2 \cdot u(e_{SDC})$
n_S	n_s	$u(n_s)$	normal	$c_3 = \frac{E_{SAC} - E_{SDC}}{E_{SDC}}\left(-\frac{1}{n_S^2}\right)$	$c_3 \cdot u(n_s)$
E_{XAC}	e_{XAC}	$u(e_{XAC})$	trapezoidal	$c_4 = -\frac{1}{n_X \cdot E_{XDC}}$	$c_4 \cdot u(e_{XAC})$
E_{XDC}	e_{XDC}	$u(e_{XDC})$	trapezoidal	$c_5 = \frac{E_{XAC}}{n_X}\left(\frac{1}{E_{XDC}^2}\right)$	$c_5 \cdot u(e_{XDC})$
n_X	n_x	$u(n_x)$	normal	$c_6 = \frac{E_{XAC} - E_{XDC}}{E_{XDC}}\left(\frac{1}{n_X^2}\right)$	$c_6 \cdot u(n_x)$
D_3	Δ_3	$u(\delta_3)$	normal	$c_8 = 1$	$c_8 \cdot u(\delta_3)$
D_M	Δ_M				$u(\delta_M)$

Table 3. Uncertainty budget (10 mA, 10 Hz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 μA/A	9,3E-07 A/A	normal	1	$9{,}3\cdot10^{-7}$ A/A
E_{SAC}	1,71371722E-02 V	1,5E-08 V	trapezoidal	31,815 1/V	$4{,}8\cdot10^{-7}$ V/V
E_{SDC}	1,71381674E-02 V	1,5E-08 V	trapezoidal	-31,813 1/V	$-4{,}8\cdot10^{-7}$ V/V
n_S	1,83401 V/V	4,3E-03 V/V	normal	1,727E-05 V/V	$7{,}4\cdot10^{-8}$ V/V
E_{XAC}	8,51040897E-02 V	4,8E-08 V	trapezoidal	-5,81 1/V	$-2{,}8\cdot10^{-7}$ V/V
E_{XDC}	8,51365296E-02 V	4,8E-08 V	trapezoidal	5,81 1/V	$2{,}8\cdot10^{-7}$ V/V
n_X	2,020768 V/V	8,3E-04 V/V	normal	-9,331E-05 V/V	$-7{,}7\cdot10^{-8}$ V/V
D_3	6 μA/A	2 E-06 A/A	normal	1	$2\cdot10^{-6}$ A/A
D_M	**8,3** (average of both positions) μA/A				**2,3** μA/A

Table 4. Uncertainty budget (10 mA, 55 Hz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 μA/A	8,7E-07 A/A	normal	1	$8{,}7\cdot10^{-7}$ A/A
E_{SAC}	1,71395385E-02 V	1,5E-08 V	trapezoidal	31,812 1/V	$4{,}8\cdot10^{-7}$ V/V
E_{SDC}	1,71398779E-02 V	1,5E-08 V	trapezoidal	-31,811 1/V	$-4{,}8\cdot10^{-7}$ V/V
n_S	1,83401 V/V	4,3E-03 V/V	normal	5,887E-06 V/V	$2{,}53\cdot10^{-8}$ V/V
E_{XAC}	8,52787577E-02 V	4,8E-08 V	trapezoidal	-5,803 1/V	$-2{,}79\cdot10^{-7}$ V/V
E_{XDC}	8,52793821E-02 V	4,8E-08 V	trapezoidal	5,803 1/V	$2{,}79\cdot10^{-7}$ V/V
n_X	2,020768 V/V	8,3E-04 V/V	normal	-1,793E-06 V/V	$-1{,}49\cdot10^{-9}$ V/V
D_3	-5 μA/A	1,5E-06 A/A	normal	1	$1{,}5\cdot10^{-6}$ A/A
D_M	**0,5** (average of both positions) μA/A				**1,9** μA/A

Table 5. Uncertainty budget (10 mA, 1 kHz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 μA/A	9,2E-07 A/A	normal	1	$9{,}2\cdot10^{-7}$ A/A
E_{SAC}	1,714109E-02 V	1,5E-08 V	trapezoidal	31,809 1/V	$4{,}8\cdot10^{-7}$ V/V
E_{SDC}	1,714121E-02 V	1,5E-08 V	trapezoidal	-31,809 1/V	$-4{,}8\cdot10^{-7}$ V/V
n_S	1,83401 V/V	4,3E-03 V/V	normal	2,222E-06 V/V	$9{,}6\cdot10^{-9}$ V/V
E_{XAC}	8,528192E-02 V	4,8E-08 V	trapezoidal	-6,393 1/V	$-3{,}1\cdot10^{-7}$ V/V
E_{XDC}	8,528329E-02 V	4,8E-08 V	trapezoidal	6,393 1/V	$3{,}1\cdot10^{-7}$ V/V
n_X	2,020768 V/V	8,3E-04 V/V	normal	-4,773E-06 V/V	$-4\cdot10^{-9}$ V/V
D_3	-4 μA/A	1,5E-06 A/A	normal	1	$1{,}5\cdot10^{-6}$ A/A
D_M	**0,8** (average of both positions) μA/A				**1,9** μA/A

Table 6. Uncertainty budget (10 mA, 10 kHz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 μA/A	9,9E-07 A/A	normal	1	$9{,}9\cdot10^{-7}$ A/A
E_{SAC}	1,712562E-02 V	1,5E-08 V	trapezoidal	31,810 1/V	$4{,}8\cdot10^{-7}$ V/V
E_{SDC}	1,714070E-02 V	1,5E-08 V	trapezoidal	-31,782 1/V	$-4{,}8\cdot10^{-7}$ V/V
n_S	1,83401 V/V	4,3E-03 V/V	normal	2,616E-04 V/V	$1{,}1\cdot10^{-6}$ V/V
E_{XAC}	8,520028E-02 V	4,8E-08 V	trapezoidal	-5,803 1/V	$-2{,}8\cdot10^{-7}$ V/V
E_{XDC}	8,527825E-02 V	4,8E-08 V	trapezoidal	5,80 1/V	$2{,}8\cdot10^{-7}$ V/V
n_X	2,020768 V/V	8,3E-04 V/V	normal	-2,24E-04 V/V	$1{,}9\cdot10^{-7}$ V/V
D_3	-1 μA/A	1,5E-06 A/A	normal	1	$1{,}5\cdot10^{-6}$ A/A
D_M	**-3,3** (average of both positions) μA/A				**2,3** μA/A

Table 7. Uncertainty budget (10 mA, 20 kHz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 μA/A	1,3E-06 A/A	normal	1	$1{,}3\cdot10^{-6}$ A/A
E_{SAC}	1,715324E-02 V	1,5E-08 V	trapezoidal	31,886 1/V	$4{,}8\cdot10^{-7}$ V/V
E_{SDC}	1,714758E-02 V	1,5E-08 V	trapezoidal	-31,897 1/V	$-4{,}8\cdot10^{-7}$ V/V
n_S	5,5E-03 V/V	5,5E-03 V/V	normal	-9,866E-05 V/V	$-5{,}4\cdot10^{-7}$ V/V
E_{XAC}	8,540050E-02 V	4,8E-08 V	trapezoidal	-6,405 1/V	$-3{,}1\cdot10^{-7}$ V/V
E_{XDC}	8,537166E-02 V	4,8E-08 V	trapezoidal	6,407 1/V	$3{,}1\cdot10^{-7}$ V/V
n_X	1,1E-03 V/V	1,1E-03 V/V	normal	1,010E-04 V/V	$1{,}1\cdot10^{-7}$ V/V
D_3	3 μA/A	1,5E-06 A/A	normal	1	$1{,}5\cdot10^{-6}$ A/A
D_M	**3,9** (average of both positions) μA/A				**2,2** μA/A

Table 8. Uncertainty budget (5A, 10 Hz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 μA/A	1,1E-06 A/A	normal	1	$1{,}1\cdot10^{-6}$ A/A
E_{SAC}	1,6923E-02 V	1,5E-08 V	trapezoidal	33,105 1/V	$5\cdot10^{-7}$ V/V
E_{SDC}	1,6920E-02 V	1,5E-08 V	trapezoidal	-33,111 1/V	$-5\cdot10^{-7}$ V/V
n_S	1,78526 V/V	6,1E-03 V/V	normal	-5,869E-05 V/V	$-3{,}6\cdot10^{7}$ V/V
E_{XAC}	4,8695E-02 V	4,5E-08 V	trapezoidal	-10,822 1/V	$-4{,}9\cdot10^{-7}$ V/V
E_{XDC}	4,8670E-02 V	4,5E-08 V	trapezoidal	10,831 1/V	$4{,}9\cdot10^{-7}$ V/V
n_X	1,898502 V/V	3,2E-03 V/V	normal	1,423E-04 V/V	$4{,}6\cdot10^{-7}$ V/V
D_3	14 μA/A	6E-06 A/A	normal	1	$6\cdot10^{-6}$ A/A
D_M	**-2,5** (average of both positions) μA/A				**12,4** μA/A

Table 9. Uncertainty budget (5A, 55kHz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 µA/A	9,2E-07 A/A	normal	1	$9{,}2\cdot10^{-7}$ A/A
E_{SAC}	1,6930785E-02 V	1,5E-08 V	trapezoidal	33,083 1/V	$5\cdot10^{-7}$ V/V
E_{SDC}	1,693079E-02 V	1,5E-08 V	trapezoidal	-33,082 1/V	$-5\cdot10^{-7}$ V/V
n_S	1,78526 V/V	6,1E-03 V/V	normal	8,812E-06 V/V	$5{,}4\cdot10^{-8}$ V/V
E_{XAC}	4,8683908E-02 V	4,5E-08 V	trapezoidal	-10,823 1/V	$4{,}9\cdot10^{-7}$ V/V
E_{XDC}	4,8669945E-02 V	4,5E-08 V	trapezoidal	10,83 1/V	$-4{,}9\cdot10^{-7}$ V/V
n_X	1,898502 V/V	3,2E-03 V/V	normal	7,960E-05 V/V	$2{,}5\cdot10^{-7}$ V/V
D_3	-4 µA/A	6E-06 A/A	normal	1	$6\cdot10^{-6}$ A/A
D_M	**-2,4** (average of both positions) µA/A				**6,2** µA/A

Table 10. Uncertainty budget (5A, 1kHz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 µA/A	1,0E-06 A/A	normal	1	$1\cdot10^{-6}$ A/A
E_{SAC}	1,695E-02 V	1,5E-08 V	trapezoidal	33,065 1/V	$5\cdot10^{-7}$ V/V
E_{SDC}	1,694E-02 V	1,5E-08 V	trapezoidal	-33,074 1/V	$-5\cdot10^{-7}$ V/V
n_S	1,78526 V/V	6,1E-03 V/V	normal	-9,004E-05 V/V	$5{,}5\cdot10^{-7}$ V/V
E_{XAC}	4,869E-02 V	4,5E-08 V	trapezoidal	-10,820 1/V	$-4{,}9\cdot10^{-7}$ V/V
E_{XDC}	4,868E-02 V	4,5E-08 V	trapezoidal	10,082 1/V	$4{,}9\cdot10^{-7}$ V/V
n_X	1,898502 V/V	3,2E-03 V/V	normal	6,942E-05 V/V	$2{,}1\cdot10^{-7}$ V/V
D_3	-4 µA/A	6E-06 A/A	normal	1	$6\cdot10^{-6}$ A/A
D_M	**-4,5** (average of both positions) µA/A				**6,2** µA/A

Table 11. Uncertainty budget (5A, 10kHz)

Quantity X_i	Estimate x_i	Std. uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(y)$
Δ_2	0 µA/A	1E-06 A/A	normal	1	$1\cdot10^{-6}$ A/A
E_{SAC}	1,695E-02 V	1,5E-08 V	trapezoidal	33,064 1/V	$5\cdot10^{-7}$ V/V
E_{SDC}	1,694E-02 V	1,5E-08 V	trapezoidal	-33,085 1/V	$-5\cdot10^{-7}$ V/V
n_S	1,785260 V/V	6,1E-03 V/V	normal	-1,983E-04 V/V	$1{,}2\cdot10^{-6}$ V/V
E_{XAC}	4,873E-02 V	4,5E-08 V	trapezoidal	-10,816 1/V	$-4{,}9\cdot10^{-7}$ V/V
E_{XDC}	4,870E-02 V	4,5E-08 V	trapezoidal	10,816 1/V	$4{,}9\cdot10^{-7}$ V/V
n_X	1,898502 V/V	3,2E-03 V/V	normal	2,088E-04 V/V	$6{,}7\cdot10^{-7}$ V/V
D_3	17 µA/A	6E-06 A/A	normal	1	$6\cdot10^{-6}$ A/A
D_M	**-20,3** (average of both positions) µA/A				**6,3** µA/A

Notes:

1. *u*(e_{SAC}), *u*(e_{SAC}), *u*(e_{SAC}), *u*(e_{SAC}) – any of these uncertainties has trapezoidal distribution obtained by convolution of the two rectangular distributions (resolution and short term stability components).

2. *u*(n_s), *u*(n_s) - any of these uncertainties has normal distribution obtained by convolution of the two rectangular distributions (resolution and short term stability components) and one dominant normal distribution (reproducibility component).

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EURAMET Key International Comparison of AC-DC Current Standards

EURAMET.EM-K12

Report of the Portuguese Measurements

April 2013
Isabel Godinho

CONTENTS

1. Introduction

The measurement procedure used at IPQ, described in this report, was performed in agreement with the instructions provided in the comparison technical protocol and according to the best measurement uncertainties. Values of AC-DC current transfer differences of each standard are presented only up to 20 kHz, because at 5 A level that's laboratory limit capability and at 10 mA level, at the time of measurements, it was not possible to make all the necessary build up above 20 kHz.

2. Travelling Standards

The circulating AC-DC transfer standard used for this comparison at the current of 10 mA was a Planar Multi-Junction Thermal Converter, type PTP/IPHT, serial number PTC 17, from IPHT Jena, with following nominal parameters:

Rated input current:	10 mA
Heater resistance:	90 Ω
Thermocouple resistance:	7.6 kΩ
Output voltage at rated current:	≈ 100 mV

The circulating AC-DC transfer standard used for this comparison at the current of 5 A includes a 147 mΩ coaxial shunt connect in parallel to the PMJTC. This shunt was manufactured at BEV with serial number B3A and has the following parameters:

Nominal resistance:	147 Ω
Input connector:	type N (female)
Output connector:	type N (male).

3. Measurement Conditions

The AC-DC current transfer difference of each standard is defined as:

$$\delta = \frac{I_{AC} - I_{DC}}{I_{DC}}$$

where: I_{AC} – is the rms AC current

I_{DC} – is the DC current which when reversed produces the same mean output voltage of the thermal standard as the I_{AC}.

The travelling standards were measured at several frequencies, aiming at our lowest uncertainty level and corresponding to the goal of the comparison.

The measurements were performed in a thermo regulated laboratory. The ambient conditions were monitored during the measurements and the temperature and humidity limits are indicated in Table 1 and graphically presented in Figure 1.

Table 1 - Temperature and humidity limits:

	Min	Max	Expanded uncertainty
Ambient Temperature (°C)	20,10	22,51	0,03
Relative Humidity (%)	44,5	57,8	0,2

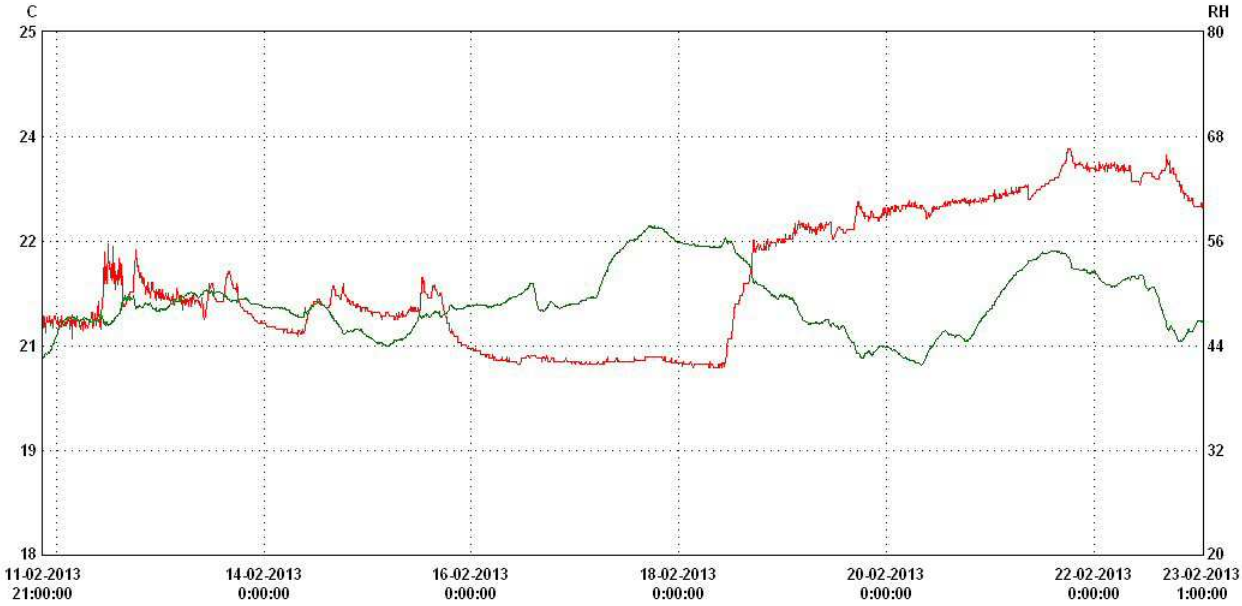

Figure 1 - Ambient conditions monitored during the measurements
(RED line: temperature - GREEN line: relative humidity).

4. Measurement Set-up, Procedure and Traceability Scheme

The travelling standards were compared with the standards which constitute IPQ's primary and reference set of standards for AC-DC current transfer.

The primary standards are 10 mA Multifunction's Thermal Converters MJTC's, built into brass housings and traceable to PTB.

The reference standards are formed with several MJTC's and SJTC's mounted in a similar way and each of them associated to a commercial shunt (Fluke model A40 or A40A), covering ranges up to 20 A.

The IPQ measurements were carried out with a comparator, whose simplified schematic diagram is represented in Figure 2. With this comparator and allowing at least a half-an-hour for the stabilization of all the equipment, the difference in the AC-DC differences of the transfer standards was measured for each test current and at each frequency value. Each measurement cycle follows the sequence of applying AC,

DC^+, AC, DC^- and AC. When the current is switched from AC to DC or vice-versa, the output of the transconductance amplifier is short circuited.

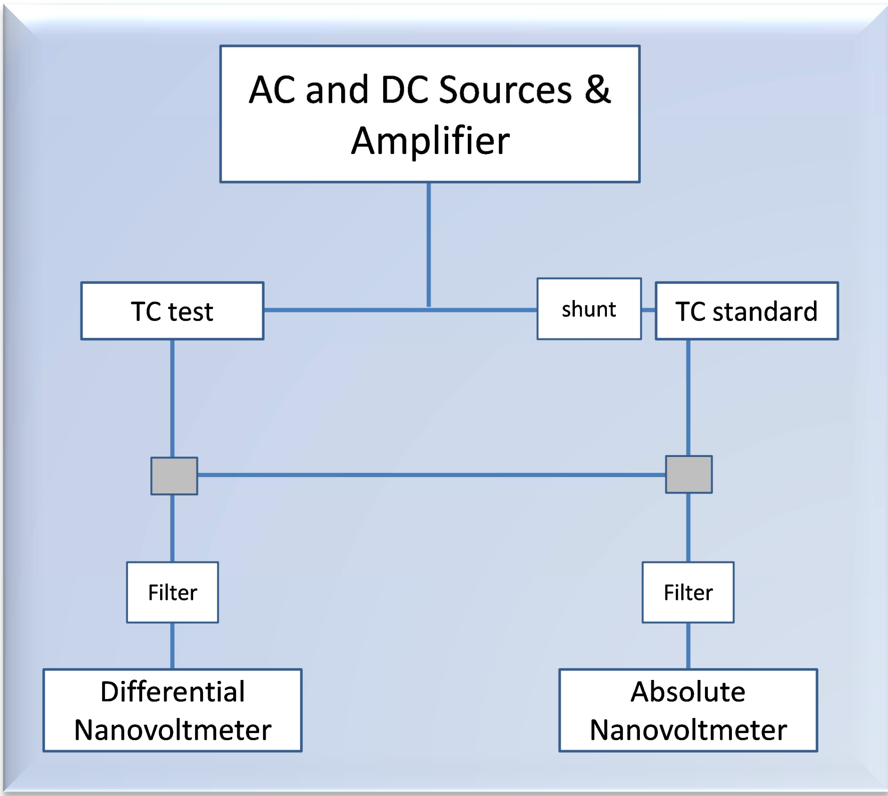

Figure 2 – IPQ AC-DC measuring setup.

Applied frequency signal was characterised to monitor the deviations from the nominal values and the frequency stability of the AC Source. The corresponding values and the Allan deviation stability are indicated in Table 2.

Table 2 – Frequency values:

Current	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Measurement Frequency (Hz)	9,999 937	55,000 400	0,999 976	9,999 76	19,999 5		
Allan Deviation - τ = 64 s	6,6E-05	6,7E-05	4,0E-05	1,9E-04	2,1E-03		

5. Results and Uncertainties of the Measurements

The results of the series of measurements provided by the several comparisons between the travelling standards and our reference standards are given in Table 3 and the corresponding expanded uncertainty is presented in Table 4.

Table 3 – Measurement results:

Current	Measured AC-DC current difference (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	-4	-14	-12	-1	29		
5A	-4	-3	-26	-209	-239		

Table 4 – Expanded uncertainty:

Current	Expanded Uncertainty (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	40	18	16	17	18		
5A	61	31	32	35	31		

The detailed uncertainty budget in accordance with the principles of ISO Guide to the Expression of Uncertainty in Measurement - GUM, including the evaluation and distribution for every component and an evaluation of the coverage factor is presented in Table 5 and Table 6. The standard uncertainty is the combined type A and type B uncertainties.

Table 5 – Uncertainty budget calculated for the nominal current value of 10 mA:

Contribution of:	Standard Uncertainty (µA/A) at frequency					Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz		
Reference standard: TC at nominal current	20	8	8	8	8	B	Gaussian
Setup procedure	1,7	1,2	0,8	0,9	0,8	B	Rectangular
Standard deviation of measurements	0,8	4,3	1,2	1,6	3,9	A	Gaussian
Dependence with current level	2	0,5	0,5	0,5	0,5	B	Rectangular
Dependence with potential of the housing	1	1	1	1	1	B	Rectangular
Standard unc:	20	9	8	8	9		
Expanded unc:	**40**	**18**	**16**	**17**	**18**		
Coverage factor *k*:	2	2	2	2	2		

Table 6 – Uncertainty budget calculated for the nominal current value of 5 A:

Contribution of:	Standard Uncertainty (µA/A) at frequency					Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz		
Reference standard: TC at nominal current	30	15	15	15	15	B	Gaussian
Setup procedure	1,7	1,2	0,8	0,9	0,8	B	Rectangular
Standard deviation measurements	3,8	3,7	4,8	8,4	3,8	A	Gaussian
Dependence with current level	3	2	2	2	2	B	Rectangular
Dependence with potential of the housing	1	1	1	1	1	B	Rectangular

Standard unc:	30	16	16	17	16
Expanded unc:	**61**	**31**	**32**	**35**	**32**
Coverage factor k:	2	2	2	2	2

Appendix 1: Summary of Results

EURAMET Key international Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Institute: Portuguese Institute for Quality
Date of measurements: from 12th to 22th February 2013

Measurement Results:

Current	Measured AC-DC current difference (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	-4	-14	-12	-1	29		
5A	-4	-3	-26	-209	-239		

Expanded Uncertainty:

Current	Expanded Uncertainty (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	40	18	16	17	18		
5A	61	31	32	35	31		

Measurement Frequency:

Current	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Measurement Frequency (Hz)	9,999 937	55,000 400	0,999 976	9,999 76	19,999 5		
Allan Deviation - τ = 64 s	6,6E-05	6,7E-05	4,0E-05	1,9E-04	2,1E-03		

Environmental Parameters during the measurements:

	Min	Max	Expanded uncertainty
Ambient Temperature (°C)	20,10	22,51	0,03
Relative Humidity (%)	44,5	57,8	0,2

Appendix 2: Summary of Uncertainty Budget

EURAMET Key international Comparison of AC-DC Current Transfer Standards
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Institute: Portuguese Institute for Quality
Date of measurements: from 12th to 22th February 2013

Measurement Current: 10 mA

Contribution of:	Standard Uncertainty (µA/A) at frequency					Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz		
Reference standard: TC at nominal current	20	8	8	8	8	B	Gaussian
Setup procedure	1,7	1,2	0,8	0,9	0,8	B	Rectangular
Standard deviation of measurements	0,8	4,3	1,2	1,6	3,9	A	Gaussian
Dependence with current level	2	0,5	0,5	0,5	0,5	B	Rectangular
Dependence with potential of the housing	1	1	1	1	1	B	Rectangular

Standard unc:	20	9	8	8	9
Expanded unc:	**40**	**18**	**16**	**17**	**18**
Coverage factor k:	2	2	2	2	2

Measurement Current: 5 A

Contribution of:	Standard Uncertainty (µA/A) at frequency					Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz		
Reference standard: TC at nominal current	30	15	15	15	15	B	Gaussian
Setup procedure	1,7	1,2	0,8	0,9	0,8	B	Rectangular
Standard deviation measurements	3,8	3,7	4,8	8,4	3,8	A	Gaussian
Dependence with current level	3	2	2	2	2	B	Rectangular
Dependence with potential of the housing	1	1	1	1	1	B	Rectangular

Standard unc:	30	16	16	17	16
Expanded unc:	**61**	**31**	**32**	**35**	**32**
Coverage factor k:	2	2	2	2	2

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EURAMET Key International Comparison of AC-DC Current Transfer Standards EURAMET.EM-K12

CEM MEASURENT REPORT

DATE: 14th MARCH 2013

Authors	Signature
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1. Measurement setup and reference standard

The travelling standards have been compared with the CEM reference standards. The comparison has been made comparing the outputs of the reference and the travelling standard applying the same ac and dc current to both by means of series connection to a current source. For 10 mA measurements a voltage source was adjusted to provide 10 mA. For the 5A measurements a transconductance amplifier was used to provide the nominal 5 A. According with the protocol all the measurements has been performed with the travelling standard in the Lo position with both its input and output earthed. To measure the output of the travelling thermal converter the provided adapter Cannon female to UHF twin female was used.

For the 10 mA reference a PTB/IPHT Planar Multijunction Thermal Converter calibrated by PTB at 10 mA was used. For the 5A, a combination of a 5 A shunt cage design and a PTB/IPHT PMJTC was used. The reference value was obtained by means of a build-up, starting from the PTB calibrated 10 mA standard. The chain was 10 mA-20 mA, 20 mA-50 mA, 50 mA-100 mA, 100 mA-200 mA, 200mA-500 mA, 500 mA- 1 A, 1 A-2 A and 2 A-5 A.

2. Definition of the measurand

The ac-dc current transfer differences of the travelling standards have been measured.

Ac-dc current transfer difference is defined as

$$d = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

where

I_{ac} is a rms ac current. The applied current was near sinusoidal

I_{dc} is a dc current which, when reversed, produces the same mean output response as the rms ac current. A positive sign signifies that more ac than dc current was required for the same output response.

The transfer difference was measured with both its input and output earthed.

The 10mA standard was a Planar Multi-Junction Thermal Converter, Type PTB/IPHT Serial Number PTC 19, manufactured by IPHT Jena.

The 5 ampere travelling standard comprises a 147 mΩ coaxial shunt (Serial No B3A) connected in parallel to the PMJTC (Serial No PTC 19). The shunt has been manufactured at BEV.

3. Measurement procedure

The reference standard and the travelling standard have been compared using the CEM procedure CEM-PT-0076- "Comparison of current thermal converter by the two channels method". There were two deviations from this procedure. All the measurement has been performed with the travelling standard in the "LO" position. In the normal procedure the shunt position are interchanged and the mean value of the two positions is considered. A correction has been evaluated and included in the uncertainty budget. For PMJTC a 1μF filter is connected in parallel with the output of the thermal converter. This filter was not used for the PMJTC travelling standard because it internally has a 2μF capacitor connected in parallel with its output.

The two converters to be compared are series connected to a current source. The output response of each thermal converter to a sequence of ac, dc+, ac, dc^{-}, ac is separately measured by using two DMM Agilent 3458.

For the 10 mA measurement, two Fluke-5700 calibrators are used for DC and AC sources. Vacuum relays are used to switch from ac and dc. For 5A a Clark-Hess transconductance amplifier is used. The transconductance amplifier is driven by two F-5700 for ac and dc using the vacuum relays switch.

To measure the output of the travelling thermal converter the provided adapter Cannon female to UHF twin female was used. The "LO" output was connected to the "LO" input using the cable connection provided with the thermal connector. The "LO" input was connected to earth. The screen of the output cable was also connected to the "LO" in the thermal converter side and to the guard of the DMM in other side. No connection was made to the screen of the adapter.

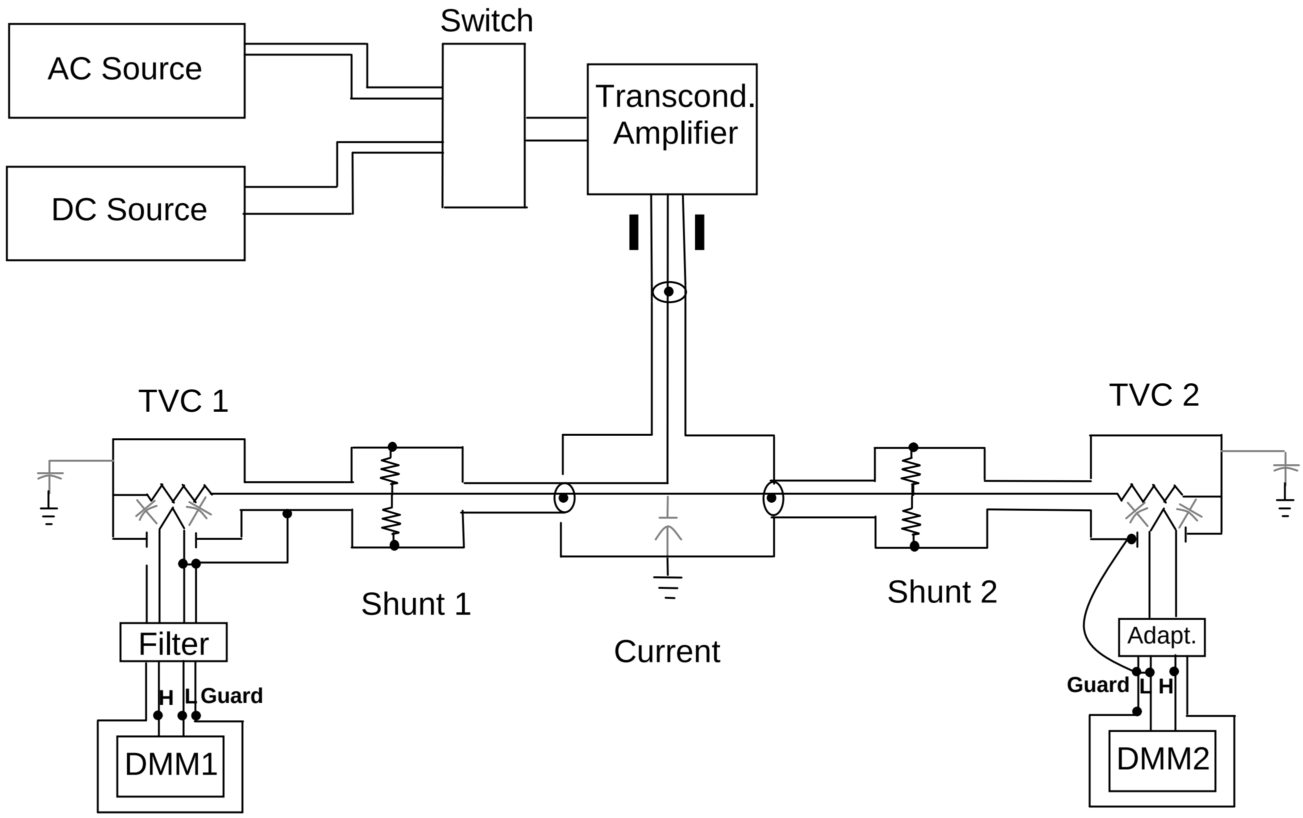
The input "LO" of the reference thermal converter was connected to the "HI" of the current source. The LO of the output was also connected to this point. The screen of the output cable at the thermal converter side was also connected to this point and to the guard of the DMM at the other side.

A computer was used to control the switch, the Fluke sources, and the DMMs. A IOTECH bus isolator was used for the connections.

At least 30 minutes after applying the current source to the thermal converters was waited before starting the measurement sequence. The first step in the measurements for each standard was the measurement of the sensibility of the travelling PMJTC. This was measured by alternatively applying dc current sources with known values above and below the nominal current and measured the output variation.

Once the sensibility was obtained sequences of ac, dc+, ac, dc-, ac are applied. The delay time between successive applications of ac and dc source was about 80 s. At the end of this time the computer takes the two DMM readings simultaneously.

From the outputs of the thermal converters corresponding to the ac and dc sources the difference in the ac-dc difference between the reference and the travelling standard is computed. From that, the ac-dc difference of the travelling standard is obtained.



4. *Traceability*

The 10 mA reference standard is traceable to PTB.

The 5 A reference standard was in-house obtained by means of a build-up starting from the PTB calibrated 10 mA standard. The chain was 10 mA-20 mA, 20 mA-50 mA, 50 mA-100 mA, 100 mA-200 mA, 200 mA-500 mA, 500 mA- 1 A, 1 A-2 A and 2 A-5 A.

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5. Ambient conditions

During the measurements the ambient conditions were the following:

Temperature: 23 ºC ± 1 ºC
Humidity: 50 % HR ± 5 HR%

6. Results

- 10 mA standard, PTC 19:

Frequency (kHz)	ac-dc transfer difference (µA/A)	Expanded Uncertainty (95 %) (± µA/A)
0.01	**7.6**	4.2
0.055	**0.1**	3.5
1	**-0.1**	3.5
10	**-0.2**	3.5
20	**-0.2**	3.7
50	**0.9**	3.8
100	**2.0**	4.4

- 5 A standard, PTC 19 + Shunt 5 A (No B3A):

Frequency (kHz)	ac-dc transfer difference (µA/A)	Expanded Uncertainty (95 %) (± µA/A)
0.01	**1.9**	17
0.055	**-2.0**	9.9
1	**-0.5**	9.9
10	**-9.4**	11
20	**-17.5**	13
50	**-37.1**	18
100	**-50.0**	24

Frequency measurements:

Frequency (kHz)	Measured (kHz)	Expanded Uncertainty (95 %)
0.01	**0.010 00**	± 0.05 %
0.055	**0.054 999**	± 0.01 %
1	**1.000 0**	± 0.01 %
10	**10.000**	± 0.01 %
20	**20.000**	± 0.01 %
50	**49.999**	± 0.01 %
100	**99.998**	± 0.01 %

7. Uncertainty budget

For each comparison the ac-dc difference is obtained form the reference according to the following equation:

$$d_t = d_s + dif + C_{drift} + C_{LF} + C_{LEV} + C_{DM1} + C_{DM2} + C_n + C_M + C_f + C_{dis} + C_{Tt} + C_{Ts} + + C_{HRs} + C_{HRt} + C_{Con} + C_{asym} + C_{guard}$$

d_t .	ac-dc difference of the thermal converter under test.
d_s	ac-dc difference of the standard thermal converter.
dif	Measured difference between Standard and test.
C_{drift}	Drift Correction of the standard.
C_{LF}	Low frequency correction of the Thermal converter level dependence.
C_{LEV}	Level dependence correction of the shunt
C_{DM1}	Linearity correction of DM1
C_{DM2}	Linearity correction of DM2
C_n	Correction of the sensitivity of the thermal converters
C_M	Reproducibility correction
C_f	Correction for frequency variation
C_{dis}	Correction for ac signal distortion

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C_{Tt}	Correction for temperature influence over test
C_{Ts}	Correction for temperature influence over standard
C_{HRs}	Correction for Humidity influence over standard
C_{HRt}	Correction for Humidity influence over test
C_{Con}	Correction due to the connectors
C_{asym}	Correction due to uncompensated "T" asymmetry
C_{guard}	Correction due to not perfect guarding

$$u_{d_t}^2 = u_{d_s}^2 + u_{dif}^2 + u_{C_{drift}}^2 + u_{C_{LF}}^2 + u_{CM}^2 + u_{C_{LEV}}^2 + u_{C_{DM1}}^2 + u_{C_{DM2}}^2 + u_{Cn}^2 + u_{C_M}^2 + u_{C_f}^2 + u_{C_{dis}}^2 + u_{C_{Tt}}^2 + u_{C_{Ts}}^2 +$$
$$+ u_{C_{HRs}}^2 + u_{C_{HRt}}^2 + u_{C_{Con}}^2 + u_{C_{asym}}^2 + u_{C_{guard}}^2$$

The uncertainties due to the humidity and temperature influence and frequency variation over the CEM standard were considered negligible. The possible influence of the temperature and humidity and frequency variation over the travelling standards were not included in the uncertainty estimation.

Uncertainty for 10 mA PTB/IPHT Serial Number PTC 19,

Current (A)	Uncertainties	Frequencies (kHz)							Type	Degrees of freedom
		0.01	0.055	1	10	20	50	100		
0.01	$u_{\delta s}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5	B	∞
	u_{Cdrift}	1.0	1.0	1.0	1.0	1.0	1.0	1.0	rectangular	∞
	u_{CDM1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	rectangular	∞
	u_{CDM2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	rectangular	∞
	u_{cn}	0.2	0.0	0.0	0.0	0.0	0.0	0.0	rectangular	∞
	u_{Cdis}	2.0	0.2	0.2	0.2	0.2	0.2	0.2	rectangular	∞
	u_{Casym}	0.5	0.5	0.5	0.5	1.0	1.0	1.0	rectangular	∞
	u_{Cguard}	0.1	0.1	0.1	0.5	0.5	1.0	1.1	rectangular	∞
	u_{Ccon}	0.1	0.1	0.1	0.1	0.2	0.3	0.6	rectangular	∞
	u_A	0.1	0.1	0.1	0.1	0.1	0.1	0.1	A	17
	u_M	1.0	1.0	1.0	1.0	1.0	1.0	2.0	rectangular	∞
	u_{test}	2.1	1.7	1.7	1.8	1.8	1.9	2.2		
	U_{test} (k=2)	**4.2**	**3.5**	**3.5**	**3.5**	**3.7**	**3.8**	**4.4**		

Build up process:

Calibration of the 20 mA standard against the 10 mA standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
0.01	u_{10mA}	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.51	0.07	0.00	0.09	0.30	0.52	0.84
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	0.2	0.2	0.2	0.5	0.5	1	1
	u_{Ccon}	0.2	0.2	0.2	0.1	0.2	0.2	0.5
	u_{CIEV}	0.5	0.5	0.5	0.5	1	1	1.5
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.49	0.31	0.29	0.32	0.38	0.64	0.39
	u_M	1.00	1.00	1.00	1.00	1.00	1.00	2.00
	u_{20mA}	3.36	1.82	1.80	1.92	2.28	3.07	4.17

Calibration of the 50 mA standard against the 20 mA standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
0.02	u_{20mA}	3.4	1.8	1.8	1.9	2.3	3.1	4.2
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.38	0.01	0.06	0.06	0.04	0.32	0.89
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	0.2	0.2	0.2	0.5	0.5	1	1
	u_{Ccon}	0.2	0.2	0.2	0.1	0.2	0.2	0.5
	u_{CIEV}	1	1	1	1	1.5	1.5	2
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.39	0.54	0.47	0.49	0.47	0.51	0.67
	u_M	1.00	1.00	1.00	1.00	1.00	1.00	2.00
	u_{50mA}	4.06	2.18	2.14	2.32	2.70	3.58	4.78

Calibration of the 100 mA standard against the 50 mA standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
0.05	u_{50mA}	4.1	2.2	2.1	2.3	2.7	3.6	4.8
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.16	0.02	0.01	0.17	0.30	0.68	1.16
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	0.2	0.2	0.2	0.5	0.5	1	1
	u_{Ccon}	0.2	0.2	0.2	0.1	0.2	0.2	0.5
	u_{ClEV}	1.5	1.5	1.5	1.5	2	2	3
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.30	0.34	0.35	0.21	0.17	0.21	0.33
	u_M	1.00	1.00	1.00	1.00	1.00	1.00	2.00
	u_{100mA}	4.70	2.53	2.50	2.70	3.14	4.09	5.47

Calibration of the 200 mA standard against the 100 mA standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
0.1	u_{100mA}	4.7	2.5	2.5	2.7	3.1	4.1	5.5
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.29	0.02	0.02	0.01	0.18	0.63	1.88
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	0.2	0.2	0.2	0.5	0.5	1	1
	u_{Ccon}	0.2	0.2	0.2	0.1	0.2	0.2	0.5
	u_{ClEV}	2	2	2	2	2.5	2.5	4
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.51	0.27	0.28	0.22	0.32	0.31	0.55
	u_M	1.00	1.00	1.00	1.00	1.00	1.00	2.00
	u_{200mA}	5.33	2.94	2.91	3.13	3.63	4.63	6.34

Calibration of the 500 mA standard against the 200 mA standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
0.2	u_{200mA}	5.3	2.9	2.9	3.1	3.6	4.6	6.3
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.33	0.02	0.11	0.29	0.20	0.12	0.99
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	0.2	0.2	0.2	0.5	0.5	1	1
	u_{Ccon}	0.2	0.2	0.2	0.1	0.2	0.2	0.5
	u_{ClEV}	2.5	2.5	2.5	2.5	3	3	5
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.61	0.33	0.36	0.37	0.40	0.44	0.60
	u_M	1	1	1	1	1	1	2
	u_{500mA}	5.97	3.41	3.39	3.63	4.18	5.20	7.25

Calibration of the 1 A standard against the 500 mA standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
0.5	u_{500mA}	6.0	3.4	3.4	3.6	4.2	5.2	7.3
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.26	0.01	0.03	0.02	0.04	0.14	0.27
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	2	0.5	0.5	1	1	2	2
	u_{Ccon}	0.2	0.2	0.2	0.5	0.5	1	1
	u_{ClEV}	3	3	3	3	3.5	3.5	6
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.28	0.10	0.26	0.33	0.42	0.24	0.41
	u_M	1	1	1	1	1	1	2
	u_{1A}	6.69	3.94	3.93	4.21	4.81	5.90	8.34

Calibration of the 2 A standard against the 1 A standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
1	u_{1A}	6.7	3.9	3.9	4.2	4.8	5.9	8.3
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.21	0.13	0.04	0.03	0.08	0.29	0.54
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	2	0.5	0.5	1	1	2	2
	u_{Ccon}	2	0.5	0.5	1	1	2	2
	u_{ClEV}	2.5	2.5	2.5	2.5	3	3	7
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.5	0.3	0.3	0.2	0.2	0.3	0.3
	u_M	1	1	1	1	1	1	2
	u_{2A}	7.38	4.32	4.31	4.64	5.28	6.53	9.58

Calibration of the 5 A standard against the 2 A standard:

Current (A)	Uncertainties	Frequencies (kHz)						
		0.01	0.055	1	10	20	50	100
2	u_{2A}	7.4	4.3	4.3	4.6	5.3	6.5	9.6
	u_{Cdrift}	1	1	1	1	1	1	1
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	u_{cn}	0.28	0.05	0.03	0.06	0.05	0.81	2.25
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1
	u_{Casym}	2	0.5	0.5	1	1	2	2
	u_{Cguard}	2	0.5	0.5	1	1	2	2
	u_{Ccon}	2	0.5	0.5	1	1	2	2
	u_{ClEV}	3	3	3	3	3.5	4	8
	u_{CLF}	2	0	0	0	0	0	0
	u_A	0.64	0.67	0.84	0.55	0.90	1.32	0.60
	u_M	1	1	1	1	1	3	3
	u_{5A}	8.08	4.80	4.82	5.15	5.88	7.57	11.07

Uncertainty for 5 A travelling standard, shunt 5 A (No B3A) + PTC 19:

Current (A)	Uncertainties	Frequencies (kHz)							Type	Degrees of freedom
		0.01	0.055	1	10	20	50	100		
5	u_{5A}	8.08	4.80	4.82	5.15	5.88	7.57	11.07	B	∞
	u_{cdrift}	1	1	1	1	1	1	1	B	∞
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	rectangular	∞
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	rectangular	∞
	u_{cn}	0.22	0.11	0.00	1.28	2.87	5.47	6.15	rectangular	∞
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1	rectangular	∞
	u_{Casym}	3	1	1	1	2	3	4	rectangular	∞
	u_{Cguard}	2	0.5	0.5	1	1	2	2	rectangular	∞
	u_{Ccon}	2	0.5	0.5	1	1	2	2	rectangular	∞
	u_A	0.24	0.33	0.47	0.34	0.33	0.56	0.41	A	17
	u_M	1	1	1	1	1	3	3	rectangular	∞
	u_{test}	8.55	4.93	4.96	5.37	6.33	8.76	12.11		
	U_{test} (k=2)	**17.1**	**9.9**	**9.9**	**10.7**	**12.7**	**17.5**	**24.2**		

Appendix 3: Summary of Results

EURAMET Key International Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Institute: CEM
Date of measurements: March 2013
Remarks:

Measurement Results:

Current	Measured ac-dc current difference (μA/A) At frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	7.6	0.1	-0.1	-0.2	-0.2	0.9	2
5 A	1.9	-2	-0.5	-9.4	-17.5	-37.1	-50.0

Expanded Uncertainty:

Current	Expanded Uncertainty (μA/A) At frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	4.2	3.5	3.5	3.5	3.7	3.8	4.4
5 A	17	9.9	9.9	11	13	18	24

Measurement Frequency:

	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Measured frequency	10.00 Hz	54.999 Hz	1.000 0 kHz	10.000 kHz	20.000 kHz	49.999 kHz	99.998 kHz
Expanded uncertainty	0.05 %	0.01 %	0.01 %	0.01 %	0.01 %	0.01 %	0.01 %

Environmental parameters:

	Min	Max	Remarks
Ambient temperature (ºC)	22.8	23.7	
Relative humidity (%)	48.7	54.0	

Appendix 4: Summary of Uncertainty Budget

Institute: CEM

Date: March 2013

Measurement Current: 10 mA

Current (A)	Contribution	Frequencies (kHz)							Type	Distribution
		0.01	0.055	1	10	20	50	100		
0.01	$u_{\delta s}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5	B	Normal
	u_{Cdrift}	1.0	1.0	1.0	1.0	1.0	1.0	1.0	B	rectangular
	u_{CDM1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	B	rectangular
	u_{CDM2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	B	rectangular
	u_{cn}	0.2	0.0	0.0	0.0	0.0	0.0	0.0	B	rectangular
	u_{Cdis}	2.0	0.2	0.2	0.2	0.2	0.2	0.2	B	rectangular
	u_{Casym}	0.5	0.5	0.5	0.5	1.0	1.0	1.0	B	rectangular
	u_{Cguard}	0.1	0.1	0.1	0.5	0.5	1.0	1.1	B	rectangular
	u_{Ccon}	0.1	0.1	0.1	0.1	0.2	0.3	0.6	B	rectangular
	u_A	0.1	0.1	0.1	0.1	0.1	0.1	0.1	A	Normal
	u_M	1.0	1.0	1.0	1.0	1.0	1.0	2.0	B	rectangular
	u_{test}	2.1	1.7	1.7	1.8	1.8	1.9	2.2		
	U_{test} $(k=2)$	**4.2**	**3.5**	**3.5**	**3.5**	**3.7**	**3.8**	**4.4**		

Measurement Current: 5 A

Current (A)	Uncertainties	Frequencies (kHz)							Type	Distribution
		0.01	0.055	1	10	20	50	100		
5	u_{5A}	8.08	4.80	4.82	5.15	5.88	7.57	11.07	B	Normal
	u_{cdrift}	1	1	1	1	1	1	1	B	rectangular
	u_{cdm1}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	B	rectangular
	u_{cdm2}	0.2	0.2	0.2	0.2	0.2	0.2	0.2	B	rectangular
	u_{cn}	0.22	0.11	0.00	1.28	2.87	5.47	6.15	B	rectangular
	u_{Cdis}	2	0.1	0.1	0.1	0.1	0.1	0.1	B	rectangular
	u_{Casym}	3	1	1	1	2	3	4	B	rectangular
	u_{Cguard}	2	0.5	0.5	1	1	2	2	B	rectangular
	u_{Ccon}	2	0.5	0.5	1	1	2	2	B	rectangular
	u_A	0.24	0.33	0.47	0.34	0.33	0.56	0.41	A	Normal
	u_M	1	1	1	1	1	3	3	B	rectangular
	u_{test}	8.55	4.93	4.96	5.37	6.33	8.76	12.11		
	U_{test} $(k=2)$	**17.1**	**9.9**	**9.9**	**10.7**	**12.7**	**17.5**	**24.2**		

BULGARIAN INSTITUTE OF METROLOGY (BIM)
NATIONAL CENTRE OF METROLOGY (NCM)
LABORATORY ELECTROMAGNETIC MEASUREMENTS

Measurement Report

EURAMET Key International Comparison of AC-DC Current Transfer Standards EURAMET.EM-K12

1. Definition of the ac-dc current transfer difference

The ac-dc current transfer difference δ of a transfer standard is defined as:

$\delta_I = (I_{ac} - I_{dc}) / I_{dc}$

where:

I_{ac} is the rms value of the ac input current

I_{dc} is the dc input current, which when reversed produces the same mean output voltage of the thermal converter as the ac current.

2. Description of the measurement set-up

The measurement set-up, which is used for measurement of AC-DC difference, is complex of the following instruments: multifunction calibrators Fluke 5720, used as AC and DC source, two nanovoltmeters Keithley 2182A, Amplifier Clarke Hess 8100 and MKP-2 swithching system.
The reference standard used for 10 mA is PMJTC (90 Ω) and for 5 A – another PMJTC (90 Ω) with shunt Fluke A40.
The standard and UUT are connected in series with coaxial Tee connector and adaptor for the link to 2-terminal thermal converter and Fluke shunt. The output voltages of both thermal converters are measured with the nanovoltmeters. Parallel at the output of the reference standard is put capacitor approximately 2 μF.

3. Description of the measurement procedure

The potential driven gards method is used. The measuring sequence is DC+, AC, DC-, AC; …. The time between switching is 90 s and 60 s. Between 150 and 245 measurements (in series of 12 and 40 observations) of AC-DC difference are used for calculation of the mean value and standard deviation of the mean.

4. Traceability

The reference standard is traceable to BEV. The standard for 5 A is traceable to reference standard by step-up procedure.

5. Ambient conditions

The temperature was from 22,62 °C to 23,62 °C.

The humidity was from 41,2 %rh to 55,5 %rh.

6. Measurement results

The detailed uncertainty budgets for 10 mA, 1 kHz and 5 A, 100 kHz are given in Appendix 1.
Summary of the measuring results and expanded uncertainty are given in Appendix 2 (Appendix 3 from the Technical protocol).
The uncertainty contributions are summarised in the uncertainty budgets in Appendix 3 (Appendix 4 from the Technical protocol).

07.10.2013 Responsible person:
/Radoslava Hadzhistoykova/

Appendix 1: Detailed of uncertainty budgets

EURAMET Key International Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Institute: BIM

Date of mesurements: 02.07. - 31.07.2013

Uncertainty Budget 10 mA, 1 kHz

i	**Quantity**	**Uncertainty Distribution**	x_i	**Standard Uncertainty** $u(x_i)$	v_i	**Sensitivity coefficient** c_i	**Uncertainty Contribution** $u_i(y)$
1	AC-DC difference of reference standard, δ_s µA/A	Normal	0	2	50,00	1	2
2	Drift of reference standard	Rectangular	0	0,0	infinity	1	0,0
3	Repeated measurement, δ_A µA/A	Normal	0,03	0,2	243,0	1	0,2
4	Measurement set-up, δset-up	Rectangular	0,0	1,4	infinity	1	1,4
	- reproducability	Rectangular	0,0	0,4	infinity	1	0,4
	- resolution, linearity of the NVM and scale factors	Rectangular	0,0	0,3	infinity	1	0,3
	- different set-up	Rectangular	0,0	0,6	infinity	1	0,6
	- EMI	Rectangular	0,0	1,0	infinity	1	1,0
	- connectors and adapters	Rectangular	0,0	0,5	infinity	1	0,5
y	AC-DC Difference of PTC 19, δ_x µA/A	Normal	0,03	2,4	109		

Confidence Level =	95,45%	*k* =	2,0000
Result =	0,0	*U* =	4,9

Uncertainty Budget 5 A, 100 kHz

i	**Quantity**	**Uncertainty Distribution**	x_i	**Standard Uncertainty** $u(x_i)$	ν_i	**Sensitivity coefficient** c_i	**Uncertainty Contribution** $u_i(y)$
1	AC-DC difference of standard (from step-up procedure)	Normal	3	18	50,00	1	18
2	Drift of the standard	Rectangular	0	0,0	infinity	1	0,0
3	Repeated measurement, µA/A	Normal	-68,41	0,3	149,0	1	0,3
4	Measuring set-up, µA/A	Rectangular	0,0	8,1	infinity	1	8,1
	- reproducibility	Rectangular	0,0	2,0	infinity	1	2,0
	- resolution, linearity of the NVM and scale factors	Rectangular	0,0	0,9	infinity	1	0,9
	- different set-up	Rectangular	0,0	7,6	infinity	1	7,6
	- EMI	Rectangular	0,0	1,0	infinity	1	1,0
	- connectors and adapters	Rectangular	0,0	1,0	infinity	1	1,0
5	Frequency dependence	Rectangular	0,0	2,2	infinity	1	2,2
6	Temperature dependence	Rectangular	0,0	0,4	infinity	1	0,4
y	AC-DC Difference of PTC 19+shunt B3A, δ_x µA/A	Normal	-65,27	19,8	74		
		Confidence Level =	95,45%	*k* =	2,0344		
		Result =	-65	*U* =	40		

Appendix 2: Summary of results

EURAMET Key International Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Institute: BIM

Date of mesurements: 02.07. - 31.07.2013

Remarks:

Measurement Results:

Current	Measured ac-dc current difference (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	7	-0,1	0	0,6	-0,7	-2,4	-3
5A	1	-2	6	-2	-11	-31	-65

Expanded Uncertainty:

Current	Expanded Uncertainty (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	14	5,1	4,9	5,0	4,9	7,2	13
5A	36	26	26	24	24	28	40

Measurement Frequency:

Current	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. Frequency	9,99998	54,99992	0,9999987	9,999987	19,99997	49,99994	99,99987
Expanded Uncertainty	1,5E-05	4,1E-05	5,8E-04	5,8E-06	1,2E-05	2,9E-05	5,8E-05

Environmental parameters:

	Min	Max	Remarks
Ambient temperature (^{0}C)	22,37	23,62	
Relative humidity (%)	41,2	55,5	

Appendix 3: Summary of uncertainty budgets

EURAMET Key International Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Institute: BIM

Date of mesurements: 02.7.2013 - 31.07.2013

Remarks:

Measurement Current: 10 mA

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
AC-DC difference of reference standard, µA/A	6	2	2	2	2	3	6	B	Normal
Drift of the standard	0	0	0	0,6	0,6			B	Rectangular
Repeated measurement, µA/A	0,3	0,2	0,2	0,2	0,2	0,2	0,2	A	Normal
Measuring set-up, µA/A	2,8	1,6	1,4	1,4	1,3	1,9	1,8	B	Rectangular
- reproducibility	0,5	0,3	0,4	0,2	0,2	0,3	0,7	B	Rectangular
- resolution, linearity of the NVM and scale factors	0,3	0,3	0,3	0,3	0,3	0,3	0,3	B	Rectangular
- different set-up	1,6	0,5	0,6	0,7	0,5	1,5	0,7	B	Rectangular
- EMI	1	1	1	1	1	1	1	B	Rectangular
- connectors and adapters	2,0	1,0	0,5	0,5	0,5	0,5	1,0	B	Rectangular

Standard unc.	6,6	2,5	2,4	2,5	2,4	3,6	6,3
Expanded unc.	14	5,1	5,0	4,9	4,9	7,2	13
Coverage factor *k*	2,03	2,00	2,00	2,00	2,00	2,00	2,04

Measurement Current: 5 A

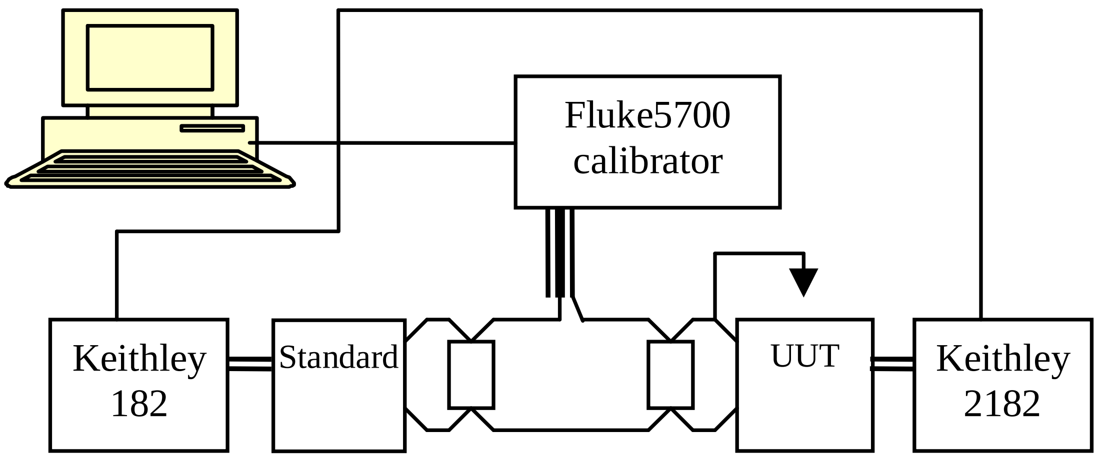
Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
AC-DC difference of standard (from step-up procedure)	17	13	12	11	12	13	18	B	Normal
Drift of the standard	0	0	1,2	0,0	0,6			B	Rectangular
Repeated measurement, µA/A	0,3	0,4	0,2	0,2	0,3	0,3	0,3	A	Normal
Measuring set-up, µA/A	3,2	2,5	2,8	1,6	2,2	3,6	8,1	B	Rectangular
- reproducibility	1,8	1,7	1,5	0,8	1,3	1,6	2,0	B	Rectangular
- resolution, linearity of the NVM and scale factors	0,9	0,9	0,9	0,9	0,9	0,9	0,9	B	Rectangular
- different set-up	1,0	0,8	1,9	0,2	0,9	2,9	7,6	B	Rectangular
- EMI	1	1	1	1	1	1	1	B	Rectangular
- connectors and adapters	2,0	1,0	0,5	0,5	0,5	0,5	1,0	B	Rectangular
Frequency dependence	0,0	0,0	0,0	0,0	0,0	2,0	2,2	B	Rectangular
Temperature dependence	0,4	0,4	0,4	0,4	0,4	0,4	0,4	B	Rectangular
Standard unc.	17,4	12,9	12,5	11,8	11,8	13,9	19,8		
Expanded unc.	36	26	26	24	24	28	40		
Coverage factor *k*	2,05	2,05	2,05	2,05	2,05	2,04	2,03		

EURAMET Key International Comparison of AC-DC Current Transfer Standards

EURAMET.EM-K12 , report of Hungary, MKEH

Detailed description of the measurement setup and the reference standard;

The reference standard of MKEH is a series of Fluke A40 type shunts with a Fluke A55 type thermal converter.
A Fluke5700A calibrator was used as the source of the excitation current for AC and for Dc too. At 5A level a Fluke 5725 amplifier was used to produce the excitation current.
The output voltage of the reference standard was measured by a Keithley 182 nanovoltmeter.
The output voltage of the travelling standard was measured by a Keithley 2182A nanovoltmeter. The Adapter UHF twin to Cannon 10SL-4S was used. The metallic house of the travelling standard (PMJTC) was connected to ground. The metallic house of the reference standard (Fluke A55) was connected to the high output binding post of the source (Fluke5700A or Fluke 5725A) . The inner point of the thermal converters (or the appropriate point of shunts at 5A) was connected together. This connection was as short as possible.



Our A40 type shunts were calibrated at the frequencies 40,100,1000,3000,10000 and 20000Hz.
The value of the AC-DC difference at 55 Hz was interpolated.
The Fluke calibrator can provide AC current up to 10kHz, so we could perform the measurement only at the frequencies of 55Hz, 1000Hz and 10kHz in the current mode of the calibrator.
The Fluke5700A can produce maximum 50mA as a voltage source and it can work up to 1MHz. This capability was used to perform measurements at 10mA by setting the calibrator as voltage source but a series resistor 1200Ω was connected to the high side binding post.
At first in current mode at 1kHz without the serial resistor the nominal 10mA excitation was applied and we measured the output voltage of the thermal converters. Later the excitation voltage was set to reach the same output with the series resistor in the voltage mode of the calibrator. We did the comparisons in this setup at the frequencies of 55, 1000, 10000 and 20000Hz.
A HART1620 instrument was used to measure the ambient parameters.

Definition of the measurand;

AC-DC current transfer difference is defined as

$$\delta = (I_{AC} - I_{DC}) / I_{DC},$$

where
I_{AC} is an rms AC current, and
I_{DC} is a DC current which, when reversed, produces the same mean output response as the rms AC current.
Positive sign signifies that more AC than DC current was required for the same output response.

Detailed description of the measurement procedure;

We are assuming that the output voltage of the thermal converter, in a small range, is calculable by the next formula:

$$U_{out} = A(t) * B(f) * I_{in}^{m}$$

Where

- *A(t)* does not depend on the frequency and on the input level but it represents all other dependence. We handle it as a function of the time however we know that really it comes principally from the changing of the temperature.
- *B(f)* is the frequency dependant part of the model. The measurand AC-DC transfer difference is its behavior.
- I_{in} the input current of the thermal converter
- *m* is the exponent. It is used for interpolation.

PMJTC shows near parabolic characteristic, it's *m* is nearly 2.
Our standard is a single junction converter. It has *m* smaller than 2.
Applying two excitations causing the same output we can write that:

$$U_{out} = A(t1) * B(DC) * I_{DC}^{m} = A(t2) * B(f) * I_{AC}^{m}$$

$$\sqrt[m]{\frac{A(t1) * B(DC)}{A(t2) * B(f)}} * I_{DC} = I_{AC}$$

$$\delta = \sqrt[m]{\frac{A(t1) * B(DC)}{A(t2) * B(f)}} - 1$$

The above formula gives to us the practical value of δ. Unfortunately we are not able to apply the different excitation at the same time. The mean time of the excitation with DC is *t1* and the mean time of the excitation with AC at the frequency *f* is *t2*. The *A(t)* functions are not the parts of the definition. They show that the converter can change between the two measurements with the two excitations. If *A(t1)* and *A(t2)* are significantly different this will cause error in the result.

Our conception is to perform a series of measurement with alternating the two different excitations. After finishing the data collection we will have a series of output voltage values for each excitation. We have the optimistic assuming that however *A(t)* functions can change significantly during the data collection but this functions are flat and we can interpolate their values between the given times. Of course we can not separate the three factors (*A*,*B*,*U*) of the product. We can interpolate the value of the output voltage of the converters only.

Example:
DC excitation was applied in times: t1,t3,t5,t7,t9 , the measured voltages are: UD1,UD3…UD9
AC excitation was applied in times: t2,t4…t8, the measured voltages are:UA2,UA4…UA8
t1,t2,t3…t8,t9 is a monotonic series.

A second order polynomial function will be fitted for the measured values with DC at t1,t3…t9 .
This function will be calculated for the times t2,t4…t8. The interpolated values are Ud2,Ud4...Ud8.

A second order polynomial function will be fitted for the measured values with AC at t2,t4,t6,t8.
This function will be calculated for the times t3,t5,t7. The interpolated values are Ua3,Ua5,Ua7.

Ud2 means the output voltage of the converter would had been measured in time t2 with DC excitation.
Ua5 means the output voltage of the converter would had been measured in time t5 with AC excitation.

Now we have 7 pair of values for the times t2,t3,t4,t5,t6,t7,t8. Each pairs consist of one measured and one interpolated value for the same time. Our computer program calculates the natural logarithm of the ratio of the two output voltage values for the 7 times.

At t2:

$$l_2 = \ln\left(Ud2/UA2\right) = \ln\left(a(t2)/A(t2)\right) + \ln\left(B(DC)/B(f)\right) + m*\ln\left(IDC/I(f)\right)$$

At t5:

$$l_5 = \ln\left(UD5/Ua5\right) = \ln\left(A(t5)/a(t5)\right) + \ln\left(B(DC)/B(f)\right) + m*\ln\left(IDC/I(f)\right)$$

a(t) means the interpolated value of *A(t)*.
We have seen above that:

$$\delta = \sqrt[m]{\frac{A(t1)*B(DC)}{A(t2)*B(f)}} - 1$$

$$\ln(1+\delta) = \ln\left(\frac{B(DC)}{B(f)}\right)/m$$

$$\delta \approx \ln\left(\frac{B(DC)}{B(f)}\right)/m$$

The last step is an approximation established on the knowledge that *d* is very small.

The second element of the calculated 7 values of l_2, l_3.. l_8 give us the flash of hope to calculate the value of the AC-DC difference but the formulas have a beginning and an ending part to disturb our hoping.
The first element is nearly zero. It is the ratio of the experienced value and the interpolated value of A(t) function for the same time. We know that interpolation is not perfect but the residuals will the contribution of the uncertainty so this beginning part will be neglected.
The third element comes from the ratio of the source current at DC and at AC. To handle this part we use our standard thermal converter with the same excitation as the (UUT) unit under test.

The above mentioned quantities will be measured and calculated for the standard converter too. Dividing the values *l* with the exponent of the characteristic gives us the values:

$$U_k = \ln\left(B_u(DC)/B_u(f)\right)/m_u + \ln\left(IDC/I(f)\right)$$
$$E = \ln\left(B_E(DC)/B_E(f)\right)/m_E + \ln\left(IDC/I(f)\right)$$

- k is the index of the point
- E and U show that the object is the standard (Etalon) or the unit under test (UUT).
- m_E and m_U is the exponent of the two converters

The difference of the above two quantities :

$$E_k - U_k = \ln\left(B_u(DC)/B_u(f)\right)/m_u - \ln\left(B_E(DC)/B_E(f)\right)/m_E$$

As it was shown above the first part is the AC-DC transfer difference of the standard converter and the second part is the AC-DC transfer difference of the UUT.
We can calculate the result as

$$\delta_k^{UUT} = \delta^E - E_k + U_k$$

- δ^E is the AC-DC transfer difference of the standard according it's calibration certificate
- $\delta^{UUT}{}_k$ is the AC-DC transfer difference of the UUT
- *k* is the index

The result is the average of the $\delta^{UUT}{}_k$ values.This method was developed to eliminate the possible error source coming from that the converter can change between applying the AC and DC excitation because of the changing of the temperature or other contributors. Up to this point we assumed that the excitation is constant through the measurement. This would be an unfounded optimistic so we should have been indexed *IDC* and *I(f)* quantities.
The set of U_k and the set of E_k quantities are influenced by the variation of IDC and I(f) . Fortunately the appropriate pair of this values contains the same IDC_k and $I(f)_k$ so their difference, the result of the measurement is nearly free from this effect.
The computer program calculates the average and the standard deviation of the U_k, E_k and $d^{UUT}{}_k$ values.
Usually the standard deviation of U and E is significantly larger than the standard deviation of d^{UUT}. This shows to us that U_k and E_k pairs strongly correlated values and this method can eliminate significant disturbances as the finite reproducibility of the source.

The measurements were executed under computer control. The program was developed in TESTPOINT.

The steps of the program:

The user gives the reference standard, the measuring levels, the measured object identifiers and their safety limitations. The program calculates common limits for the both converters and it checks the list of measuring levels. User can modify some parameters to influence the measuring strategy. After this setting the measuring procedure is ready to start. Before starting there is a possibility to check the setup. The program pops up a window and the read values of both nanovoltmeters are drawn on automatic scaling graphs. Only the recent 50 (or other) values are shown. The user can handle the calibrator by hand. We can monitor the setting up of the thermal voltages. Little knocking of objects can produce significant changing in the thermal voltage in the case of bad connections. After finding the setup appropriate we can start the automatic measurement.

At first the program sends 5000 ppm higher value to the calibrator than the desired measuring level. In this state the converters are warm up but the main goal is to fix the range of the nanovoltmeters.

Next step is the measuring of the near characteristic of the converters. Two significantly different levels are applied. They are typically nominal+4000ppm and nominal-4000ppm.
The exponent of the characteristic is calculated.

$$\left(\frac{UOut_+}{UOut_-}\right) = \left(\frac{I_{In+}}{I_{In-}}\right)^m = \left(\frac{1+\varepsilon}{1-\varepsilon}\right)^m \approx 1+2*m*\varepsilon$$

$$\left(\frac{UOut_+ - UOut_- + UOut_-}{UOut_-}\right) \approx 1+2*m*\varepsilon$$

$$m \approx \left(\frac{UOut_+ - UOut_-}{UOut_-}\right)/(2*\varepsilon)$$

Where U_{Out+} and U_{Out-} are the output voltage of the thermal converter for the excitation of I_{In+} and I_{In-} which are the nominal current + and – the relative step of ε .

After the determination of the exponents for both converters the next step is the AC-DC difference measurement at the desired frequencies.
In the following we will show the program steps by means of the log files generated by the program. For error tracing and to help the validation procedure the program writes a long and detail log. It's structure is very simple. It records in special lines the starting of the program and the starting of the main cycle with cross-links to the working log.

The other lines have the next columns:

1. The mean time in seconds from the start
2. The nominal value of the excitation signal, intended to produce by the calibrator as output.
3. The frequency in kHz
4. The average of the output voltage of the Standard converter in mV
5. The standard deviation of the output voltage of the Standard converter in mV
6. The average of the output voltage of the UUT in mV
7. The standard deviation of the output voltage of the UUT in mV
8. The time was spent to collect the above data in sec
9. The ambient temperature in °C
10. The relative humidity in %

The sample below shows that the warming up happened 75..174 s
The exponent measurement was performed 234…600 s
The first measurement of AC-DC difference at a frequency of 55Hz, was performed 653…1401 s
The second measurement of AC-DC difference at a frequency of 55Hz, was performed 1364…2131 s
The first measurement of AC-DC difference at a frequency of 1000Hz, was started 2093 s

```
Started, 2013.08.08 17:06:54,C:\Em-k12\AcCwrk0.csv,1987,AC/DCcurrent shunt Compare V0.4.5
    75,    5.025,    1.000,  7.422478, 1.3E-05, 50.626481, 1.2E-04,  73.2,
   100,    5.025,    1.000,  7.422456, 1.7E-05, 50.627153, 8.1E-05,  25.4,23.07, °C ,39, %
   116,    5.025,    1.000,  7.422439, 1.2E-05, 50.627394, 9.0E-05,  16.2,23.07, °C ,38.8, %
   141,    5.025,    1.000,  7.422458, 1.5E-05, 50.627825, 8.3E-05,  25.7,23.06, °C ,38.6, %
   158,    5.025,    1.000,  7.422498, 1.4E-05, 50.628107, 4.4E-05,  16.1,23.06, °C ,38.5, %
   174,    5.025,    1.000,  7.422538, 1.9E-05, 50.628181, 5.3E-05,  16.1,23.05, °C ,38.4, %
COMPARE AC/DC TRANSFER,LogFile:,C:\Em-k12\AcCwrk0.csv,  1991,DateTime: ,2013.08.08 17:10:12,UUT
   234,     4.98,    1.000,  7.313732, 1.2E-05, 49.731456, 7.9E-05,  39.5,23.05, °C ,38.4, %
   273,     5.02,    1.000,  7.410723, 1.1E-05, 50.528881, 5.3E-05,  36.2,23.03, °C ,38.2, %
   305,     4.98,    1.000,  7.313946, 1.6E-05,   49.7321, 6.1E-05,  28.6,23.02, °C ,38.1, %
   337,     5.02,    1.000,  7.410896, 1.7E-05, 50.529356, 1.1E-04,  29.1,23, °C ,37.9, %
   363,     4.98,    1.000,  7.314072, 1.3E-05, 49.732412, 9.9E-05,  22.8,23, °C ,37.9, %
   392,     5.02,    1.000,  7.410973, 7.9E-06, 50.529356, 7.0E-05,  25.9,23, °C ,37.9, %
   425,     4.98,    1.000,  7.314138, 1.6E-05, 49.732406, 5.6E-05,  30.1,23.02, °C ,38.1, %
   450,     5.02,    1.000,  7.410981, 1.3E-05,   50.5293, 8.7E-05,  22.3,23.06, °C ,38.8, %
   486,     4.98,    1.000,  7.314063, 2.4E-05,  49.73202, 5.4E-05,  32.8,23.07, °C ,39.2, %
   522,     5.02,    1.000,  7.410893, 1.1E-05, 50.528913, 7.0E-05,  33.2,23.1, °C ,40.1, %
```

```
  565,     4.98,    1.000,  7.313929, 1.3E-05,  49.73186, 6.1E-05,  39.5,23.11, °C ,40.8, %
  600,     5.02,    1.000,  7.410669, 1.3E-05, 50.528493, 8.5E-05,  32.2,23.12, °C ,42, %
  653,        5,    0.000,  7.361488, 1.5E-05, 50.120794, 9.7E-05,  47.8,23.12, °C ,42.8, %
  686,       -5,    0.000,  7.360579, 1.2E-05, 50.120906, 1.1E-04,  30.7,23.13, °C ,43.7, %
  739,        5,    0.055,  7.363733, 2.4E-05, 50.143375, 8.3E-05,  46.4,23.14, °C ,44.3, %
  777,       -5,    0.000,  7.360481, 1.3E-05, 50.120053, 5.0E-05,  32.9,23.12, °C ,44.3, %
  822,        5,    0.000,  7.361236, 1.7E-05, 50.119537, 7.0E-05,  42.2,23.1, °C ,44.1, %
  873,        5,    0.055,  7.363629, 2.3E-05, 50.142356, 9.3E-05,  45.2,23.06, °C ,43.7, %
  926,        5,    0.000,  7.361241, 1.8E-05, 50.119531, 9.2E-05,  48.0,23.03, °C ,43.3, %
  956,       -5,    0.000,  7.360372, 1.3E-05, 50.119587, 1.1E-04,  27.1,22.98, °C ,42.6, %
 1035,        5,    0.055,  7.363613, 2.2E-05, 50.142669, 8.5E-05,  73.4,22.97, °C ,42.5, %
 1093,       -5,    0.000,  7.360425, 1.5E-05, 50.119638, 7.8E-05,  52.3,22.93, °C ,41.8, %
 1125,        5,    0.000,  7.361255, 8.1E-06, 50.119393, 5.7E-05,  29.1,22.92, °C ,41.5, %
 1181,        5,    0.055,  7.363706, 1.7E-05,  50.14252, 8.3E-05,  50.1,22.93, °C ,41.2, %
 1239,        5,    0.000,  7.361393, 1.4E-05, 50.119375, 9.0E-05,  53.0,22.95, °C ,40.8, %
 1271,       -5,    0.000,  7.360547, 1.3E-05, 50.119506, 8.3E-05,  28.6,22.97, °C ,40.3, %
 1316,        5,    0.055,  7.363823, 1.7E-05,  50.14195, 1.3E-04,  39.7,22.98, °C ,40.1, %
 1364,       -5,    0.000,  7.360637, 1.7E-05, 50.119344, 7.9E-05,  42.7,22.99, °C ,39.8, %
 1401,        5,    0.000,  7.361458, 1.4E-05,  50.11868, 6.5E-05,  33.7,22.99, °C ,39.7, %
 1448, 4.998836,    0.055,  7.361015, 3.1E-05, 50.117575, 5.6E-05,  41.4,23, °C ,39.5, %
 1488,        5,    0.000,  7.361547, 1.4E-05, 50.117981, 6.3E-05,  34.7,22.99, °C ,39.2, %
 1518,       -5,    0.000,  7.360695, 1.7E-05, 50.118475, 7.5E-05,  26.6,22.99, °C ,39.1, %
 1577, 4.998836,    0.055,  7.360916, 2.3E-05, 50.116713, 7.0E-05,  53.5,23, °C ,39.1, %
 1652,       -5,    0.000,  7.360415, 1.5E-05, 50.117327, 5.7E-05,  69.9,23.04, °C ,40.2, %
 1685,        5,    0.000,  7.361095, 1.2E-05, 50.116413, 9.9E-05,  30.3,23.07, °C ,41.7, %
 1742, 4.998836,    0.055,  7.360355, 3.4E-05, 50.115037, 6.0E-05,  50.6,23.09, °C ,42.6, %
 1815,        5,    0.000,  7.360496, 1.8E-05, 50.114931, 1.0E-04,  67.9,23.12, °C ,43.6, %
 1844,       -5,    0.000,  7.359539, 1.7E-05, 50.114469, 8.5E-05,  25.6,23.18, °C ,44.9, %
 1899, 4.998836,    0.055,  7.359698, 2.3E-05, 50.113038, 6.0E-05,  49.2,23.19, °C ,45.1, %
 1947,       -5,    0.000,  7.359236, 2.4E-05, 50.113331, 9.2E-05,  43.5,23.2, °C ,45.8, %
 1989,        5,    0.000,  7.359952, 9.1E-06, 50.112619, 7.3E-05,  38.6,23.18, °C ,45.6, %
 2049, 4.998836,    0.055,  7.359306, 2.5E-05, 50.111556, 7.9E-05,  54.3,23.15, °C ,45.2, %
 2093,        5,    0.000,  7.359785, 1.4E-05, 50.111825, 9.0E-05,  38.0,23.12, °C ,44.6, %
 2131,       -5,    0.000,  7.358879, 1.7E-05, 50.111753, 5.0E-05,  34.9,23.1, °C ,44.1, %
 2197,        5,    1.000,  7.360202, 1.3E-05, 50.119312, 4.8E-05,  60.5,23.07, °C ,43.7, %
```

The sample above shows that the different measurements are overlapped. The subsequent measurements uses the same +DC and -DC points. The first to finish the second to start the data collection..

We have to make known the voltage measuring strategy of the program.
The program uses FIFO (First Input First Output) style memory areas to store the values coming from the nanovoltmeters. The length of the FIFO was usually 30. That means the last 30 value arrived form the nanovoltmeters was stored in the memory. After each new read the present set of values was analyzed by different methods to decide whether it is stabilized or it is necessary to wait for more new data. The waiting time was limited but usually the limitation was not activated.
The above log-example shows that the elapsed time was different in the different lines and this time was significantly longer if a significant change happened in the excitation.
Here we call the attention that the second measurement of AC-DC difference at 55Hz was executed with a little correction in the AC excitation. The details of this correction method will be described later.

A sample of the working log is shown below.

```
Started, 2013.08.08 17:06:54,C:\Em-k12\AcClong0.csv,10462,AC/DCcurrent shunt Compare V0.4.5
=====================================
COMPARE AC/DC TRANSFER
DateTime: ,2013.08.08 17:10:12,C:\Em-k12\AcClong0.csv, 10470
ETALON:  ,25
Manufacturer: ,FLUKE
Type: ,A40 5A
Ident: ,4321

DeviceUnderTest: ,24
Manufacturer: ,IPHT+Bev
Type: ,No:34 Pmjtc+Em-k12 shunt
Ident: ,B3A
MaxInputCurrent: ,5.1
Owner: ,BEV
OrderNumber: ,EM-K12

EnvironmentConditions:
Tempr. Humy:  ,23.05, °C ,38.4, %
LineVoltage: ,227.5V


ProgramSettings:
AvgFifoLength: ,30
FifoAvgFrom% : ,50
PntRepeat : ,5
MainRepeat : ,4
ExpDelt : ,4000

MeasureingCurrent : ,5A


MainLoop    0 , 17:10:12 ,    195,  23.05, °C ,38.4, %,Comment for log
Exponents : Etalon | UUT,  1.63387, 0.00019,  1.97160, 0.00020,UDC E/V,   7.411,  50.528
    0.055,+-+,      1.1,    2.17, #E,    381.3,    1.15, #U,    458.1,    3.47, #D,  232.9, 232.9,
    0.055,-+-,      1.0,    0.40, #E,    -12.6,    3.54, #U,    -17.4,    3.12, #D,   -8.3, 224.6,
    1.000,+-+,     -0.1,    1.66, #E,    129.3,    3.01, #U,    154.9,    1.79, #D,   78.9,  78.9,
    1.000,-+-,      1.8,    4.74, #E,     -1.3,    9.78, #U,     -5.2,    3.82, #D,   -1.7,  77.1,
   10.000,+-+,     -8.6,    3.74, #E,   -907.2,    4.00, #U,  -1077.9,    8.97, #D, -551.0,-551.0,
   10.000,-+-,    -10.0,    4.62, #E,     22.4,    6.86, #U,     46.8,    9.33, #D,   18.7,-532.3,
MainLoop    1 , 18:33:38 ,   5201,  23.12, °C ,48.3, %,Comment for log
Exponents : Etalon | UUT,  1.63360, 0.00019,  1.97178, 0.00022,UDC E/V,   7.403,  50.494
    0.055,+-+,      2.8,    3.67, #E,     27.5,    5.70, #U,     30.3,    3.82, #D,   16.1, 240.7,
    0.055,-+-,      0.1,    5.60, #E,     -4.1,    6.72, #U,     -5.2,    4.53, #D,   -2.6, 238.1,
    1.000,+-+,      3.4,    3.78, #E,     11.6,    5.35, #U,      7.3,    3.69, #D,    5.4,  82.5,
    1.000,-+-,      2.0,    4.63, #E,     11.4,    7.11, #U,      9.8,    1.44, #D,    6.0,  88.5,
   10.000,+-+,    -10.3,    4.74, #E,      5.1,    5.61, #U,     26.5,    6.61, #D,    8.3,-524.0,
   10.000,-+-,    -11.4,    3.58, #E,    -25.5,    4.83, #U,     -8.2,    4.63, #D,   -9.9,-533.9,!
MainLoop    2 , 19:53:46 ,  10009,  23.14, °C ,51.1, %,Comment for log
Exponents : Etalon / UUT,  1.63345, 0.00024,  1.97152, 0.00034,UDC E/V,   7.401,  50.455
    0.055,+-+,      1.0,    2.62, #E,     -1.0,    2.42, #U,     -3.1,    6.29, #D,   -1.1, 237.0,
    0.055,-+-,      0.9,    2.47, #E,     -1.9,    4.64, #U,     -4.0,    7.23, #D,   -1.6, 235.4,
    1.000,+-+,      1.4,    5.88, #E,     10.4,    6.25, #U,      9.9,    5.35, #D,    5.7,  94.2,
    1.000,-+-,      2.7,    2.41, #E,    -20.6,    3.76, #U,    -30.1,    1.92, #D,  -14.0,  80.3,
   10.000,+-+,     -9.5,    3.22, #E,     -8.8,    5.88, #U,      8.1,    5.85, #D,   -0.6,-534.5,
   10.000,-+-,     -9.7,    3.38, #E,    -11.9,    5.80, #U,      4.8,    5.12, #D,   -2.4,-536.9,
MainLoop    3 , 21:17:29 ,  15032,  23.05, °C ,47.2, %,Comment for log
Exponents : Etalon | UUT,  1.63357, 0.00018,  1.97171, 0.00030,UDC E/V,   7.400,  50.444
    0.055,+-+,      1.0,    3.01, #E,     -1.6,    6.09, #U,     -1.6,    4.55, #D,   -0.9, 234.5,
    0.055,-+-,      0.4,    4.38, #E,     -1.2,    6.53, #U,     -2.2,    3.07, #D,   -0.9, 233.6,
    1.000,+-+,      1.5,    4.48, #E,     12.8,    6.02, #U,     12.5,    3.15, #D,    7.1,  87.4,
    1.000,-+-,      4.0,    5.12, #E,     13.9,    8.55, #U,      8.9,    4.46, #D,    6.5,  93.9,
   10.000,+-+,     -9.9,    3.98, #E,      2.7,    7.08, #U,     22.7,    5.56, #D,    6.6,-530.3,
   10.000,-+-,    -10.1,    1.22, #E,      2.7,    7.83, #U,     22.3,    5.09, #D,    6.5,-523.9,
MainLoop    4 , 22:42:13 ,  20116,  23.04, °C ,47.7, %,Comment for log
Exponents : Etalon | UUT,  1.63342, 0.00021,  1.97145, 0.00037,UDC E/V,   7.400,  50.439
    0.055,+-+,      0.6,    3.36, #E,     -1.8,    6.20, #U,     -0.8,    4.24, #D,   -0.8, 232.8,
    0.055,-+-,      0.4,    5.00, #E,     -1.1,    6.17, #U,     -2.1,    2.75, #D,   -0.9, 232.0,
    1.000,+-+,      3.0,    3.33, #E,    -20.5,    3.56, #U,    -30.7,    2.35, #D,  -14.1,  79.8,
    1.000,-+-,      0.1,    3.41, #E,     11.4,    4.65, #U,     13.7,    3.03, #D,    7.0,  86.8,
   10.000,+-+,    -10.8,    7.55, #E,    -27.3,   13.75, #U,    -11.6,    8.42, #D,  -11.3,-535.2,
   10.000,-+-,    -10.8,    2.00, #E,      7.5,    4.28, #U,     28.8,    4.95, #D,    9.6,-525.6,
=====================================
COMPARE AC/DC TRANSFER
DateTime: ,2013.08.09 00:10:50,C:\Em-k12\AcClong0.csv, 10997
```

The beginning part of this sample contains the synchronization lines, the description of the standard and the UUT, the IEEE488 address of the nanovoltmeters connected to them, and some parameters to determine the data collecting strategy.

PntRepeat : so many of times will be repeated the applying of one excitation, It is the number of data points for the interpolation with the fitted polynomial function. It is 5 in the shown sample.
MainRepeat: so many of times will be repeated the full measurement procedure at one given level of excitation. It is 4 in the shown sample.

The results coming from the cycle signed as MainLoop 0 are not used. The main goal of this cycle is the first level correction of the source, the Fluke5700A calibrator.
The cycle starts with the Exponent measurement. This measurement is performed with the repeating of the different excitation a PntRepeat number of times. The same interpolation method is used as it was described above. The average value and the standard deviation of *m* is in the lines for the Standard and for the UUT. The final part of this line contains the DC output voltage of the converters however this values are not necessary later.
The following lines contain partially processed values to get the result. All values are in µA/A except the frequency which is given in kHz.

- The frequency
- The sign of the applied DC sequence
- The difference between the Standard and UUT AC-DC transfer
- The standard deviation of the above value
- #E means standard (Etalon)
- The average of *Ek* values
- The standard deviation of *Ek* values
- #U means UUT
- The average of *Uk* values
- The standard deviation of *Uk* values
- #D means difference
- The modification of level correction applied in this cycle
- The full level correction for this frequency

The level correction:
In the MainLoop 0, at 0.055 kHz we can find the next two lines.

```
0.055,+-+,      1.1,    2.17, #E,    381.3,    1.15, #U,    458.1,    3.47, #D,  232.9, 232.9,
0.055,-+-,      1.0,    0.40, #E,    -12.6,    3.54, #U,    -17.4,    3.12, #D,   -8.3, 224.6,
```

The first line we find E=381.3 and U=458.1
The measured exponents were, m_E=1.63387 and m_{UUT}=1.97160,
So we can calculate the result as U/m_{UUT}- E/m_E=233.37-232.35=1.02
We can see that the result is the little difference of two large numbers. A relative small changing in the value of the large numbers can cause large changing in the result. This means that the sensitivity for the exponent can be large.
The value of (U/m_{UUT}+ E/m_E) /2 which is (233.37+232.35)/2=232.9 gives us the correction which will make E and U move to near zero. It was applied in the second line and we can see that the correction was successful.
At starting the level corrections have the value of 0. The first correction at 0.055 kHz is 232.9 and the full correction is 232.9 too. The next line shows that the second modification of the correction was -8.3 and the full correction become 224.6 ppm.
The little difference between the shown calculation and the values in the log sample comes from that while the program is running it calculates the values from the joined pairs of *Ek* and *Uk* values to eliminate the mentioned effects, so it calculates first the differences or the sum of *Ek* and *Uk* values and then calculate the average, to get the result and the level correction. Now we did it in reverse order because the individual values of *Ek* and *Uk* are not known yet.

The explained measurement procedure was repeated a number of times.
Different arrangements were tried to examine whether there is significant effect coming from the mutual inductance between the current wires and voltage measurement loops. A perpendicular N type male/female connector angle was inserted to perform this experiment. We could not detect any significant effect of the arrangement for the result so finally all the measurement results were handled uniformly. The very little differences became the part of the A type uncertainty.

At 10mA some measurements were performed by the voltage working mode of the source (Fluke5700) to reach the 20 kHz frequency. A series resistor was connected to simulate current source. At the frequencies below 20 kHz each type (current mode and voltage mode with resistor) were performed too. We could not detect any significant different between the two type of measurements. Finally all the results were handled uniformly.

A statement of traceability, if the national standard is not considered to be a primary standard; otherwise a description how the own value was determined;

We do not have primary standard.

Our reference standard was calibrated in NPL.

Unfortunately the certificate of our standard does not contain data at 55Hz frequency. The AC-DC difference and the uncertainty were interpolated for this point.

The certificate is shown on the following pages.

NATIONAL PHYSICAL LABORATORY

Teddington Middlesex UK TW11 0LW   Switchboard 0181-977 3222

DIVISION OF ELECTRICAL SCIENCE

Certificate of Calibration

11 CURRENT SHUNTS
AND THERMAL ELEMENT

For:	Mr András Jakab, Országos Mérésügyi Hivatal, National Office of Measures, H-1535, Budapest Pf.919. Hungary.
Order Number:	PF 40579 dated 29th July 1995
Manufacturer:	J Fluke Mfg Co.
Ranges:	10, 20, 30, 50, 100, 200, 300 and 500 mA 1, 2 and 5 A
Calibration Dates:	19th June 1995 to 28th June 1995

The thermal transfer element and each shunt in turn were tested on direct and alternating current. The black terminal of each shunt was connected to earth throughout the measurements.

Measurements were obtained at an air temperature of 23 ± 1°C.

The uncertainties in the reported values have been estimated by combining, where appropriate, the individual uncertainties in quadrature, at a confidence level of at least 95%. These values are given in Table 1.

They relate only to the measured value and carry no implication regarding the stability of the instrument.

Table 2 gives the differences between the alternating and direct currents required to give the same output when successively applied to the input connector. The direct current was taken as the mean of values obtained with forward and reverse polarities. A positive sign indicates a higher value of alternating current was required to produce the same output.

Reference: DESA/07/95/020 **Page 1 of 2**

Date of issue: 29th September 1995 Signed: R G Jones **for Director**

Checked by: AJW, RGJ **Name: Dr R G Jones**

NPL-C01-94/1

Uncertainty to at least 95% Confidence Level, ppm

Applied Current (A)	Frequency / kHz					
	0.04	0.1	1	3	10	20
5	20	30	20	20	20	30
2	20	25	20	20	20	35
1	10	20	15	15	15	35
0.5	15	25	15	20	20	35
0.3	20	25	20	20	20	35
0.2	15	15	15	15	10	35
0.1	10	10	15	10	10	35
0.05	10	10	10	10	10	10
0.03	10	20	15	10	10	10
0.02	20	15	15	15	20	15
0.01	20	15	15	15	20	15

AC/DC Difference, ppm

Shunt Range (A)	Serial Number	Frequency / kHz					
		0.04	0.1	1	3	10	20
5	4321	0	-11	-11	-11	-10	+30
2	3835	+6	-9	-6	-6	+6	+38
1	4046	+3	-11	-9	-22	+44	-46
0.5	4166	+2	-9	-5	-11	-19	-11
0.3	3762	+2	-10	-2	-5	-3	+16
0.2	3734	+3	-5	-2	-1	+4	+21
0.1	4352	-1	-4	-2	-1	+9	+24
0.05	4384	-4	0	-1	+1	+14	+28
0.03	4156	-1	-7	-3	-12	-18	-20
0.02	3647	-9	-4	-5	-12	-6	-6
0.01	4074	-7	-5	-6	-9	-4	+2

Reference: DESA/07/95/020 **Page 2 of 2**

Checked by: AJW, RGJ

The measurement results;

Measurement Results

Current	Measured ac-dc current difference (μA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	-	-4.7	-4.9	-4.5	-0.1	-	-
5A	-	-5.5	-9.1	-20.5	-	-	-

Expanded Uncertainty:

Current	Expanded Uncertainty (μA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	-	21	18	23	19	-	-
5A	-	28	23	24	-	-	-

The ambient conditions of the measurement: the temperature and the humidity with limits of variation;

Environmental parameters:

	Min	Max	Remarks
Ambient temperature (ºC)	22.62	24.18	
Relative humidity (%)	34.5	58.8	

Measurement Frequency:

Current	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. Frequency	-	55.0006	1.000011	10.00011	20.00022	-	-
Expanded Uncertainty		5e-6	5e-6	5e-6	5e-6		

The complete uncertainty budget

Values are given in µA/A

Calibration of the travelling standard at 10mA

	55Hz	1kHz	10kHz	20kHz	type	Distribution	Degree of freedom
Comparison uncertainties	0.4	0.3	0.4	0.4	A	Gaussian	61,61,61,43
Assembly ,cables, connectors	0.58	0.58	0.58	1.15	B	Rectangular	∞
Calibration uncertainty of standard	9	7.5	10	7.5	B	Gaussian	∞
Interpolation of standard value	0.58	-	-	-	B	Rectangular	∞
Stability of standard (0.5µA/A/year)	5.20	5.20	5.20	5.20	B	Rectangular	∞
Bead capacitor	0	0.06	0.58	1.15	B	Rectangular	∞
Combined standard uncertainty	10.4	9.1	11.3	9.3		Gaussian	∞
Expanded uncertainty (k=2)	20.9	18.3	22.6	18.6		Gaussian	
Effective degree of freedom	>100	>100	>100	>100			

Calibration of the travelling standard at 5A

	55Hz	1kHz	10kHz	20kHz	type	Distribution	Degree of freedom
Comparison uncertainties	0.1	0.1	0.2	-	A	Gaussian	85,85,85,-
Assembly ,cables, connectors	0.58	0.58	1.73	-	B	Rectangular	∞
Calibration uncertainty of standard	13	10	10	-	B	Gaussian	∞
Interpolation of standard value	0.58	-	-	-	B	Rectangular	∞
Stability of standard (0.5µA/A/year)	5.20	5.20	5.20	-	B	Rectangular	∞
Stray mutual inductances	-	0.29	2.89	-	B	Rectangular	∞
Combined standard uncertainty	14.0	11.3	11.8			Gaussian	
Expanded uncertainty (k=2)	28.0	22.6	23.5			Gaussian	
Effective degree of freedom	>100	>100	>100				

Budapest 18 October 2013

Németh Tibor
metrologist

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Metrology Authority
Section of Thermophysical, Electrical and Optical Measurements

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fax: +36 1 4585 -823

Title of Report: Results of NSAI National Metrology Laboratory's participation in EURAMET Key Comparison of AC-DC Current Transfer Standards (EURAMET.KM-K12)

Date of Report: 19 Jan 2014

Report by: ____________________ Oliver Power

Approved by: ____________________ Paul Hetherington, Manager NSAI NML

1. Introduction

This report presents the results of the NSAI National Metrology Laboratory's (NSAI NML) participation in the EURAMET International Key Comparison of AC-DC Current Transfer Standards (EURAMET.EM-K12). The results reported are based on measurements made by NSAI-NML over the period 07 to 28 November 2013. NSAI NML's purpose in participating in the comparison is to provide evidence to support its CMC entries for AC current measurement (NSAI NML does not have CMC entries for AC-DC current transfer measurements).

Due to AC current sourcing limitations, the 5 A measurements are limited to an upper frequency of 20 kHz.

This report presents a brief description of NSAI NML's measurement set-up and measurement procedure, a statement of traceability, the measurement results, and a statement of the uncertainties.

2. Measurement Set-up

Figure 1 shows a schematic of the measurement set-up used for the 10 mA measurements.

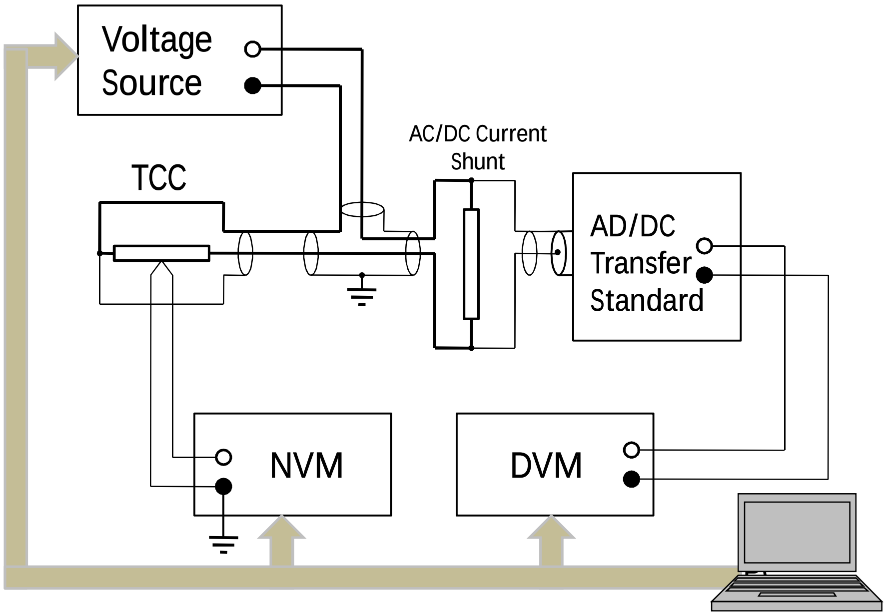


Figure 1 Schematic of measurement set-up for 10 mA measurements

A voltage calibrator (Wavetek 4808) is used to provide DC and AC currents. The current is passed through two thermal current converters (TCCs), connected in series. The TCC on the high side of the comparator comprises a 30 mA current shunt (JV design) connected across an AC-DC transfer standard (Fluke 792A), whose output is measured by a digital multimeter (Wavetek 1281). This TCC acts as a transfer standard.

A substitution measurement technique is used whereby a reference TCC (Holt HCS-1 Current Shunt and 84506 Thermal Converter) and the TCC under test are connected in turn to the low side of the comparator and compared with the transfer standard TCC. The output of the reference TCC or the TCC under test is measured using a nanovoltmeter (Agilent 34420A). Both the input and the output of the TCC connected to the low side of the comparator are grounded, as shown in the figure. The TCC connected to the low side of the comparator is compared to the transfer standard TCC by simultaneously measuring their outputs.

Control of the voltage calibrator and acquisition of the DVM and NVM readings are handled by a PC.

The measurement set-up for the 5 A measurements, shown schematically in figure 2, is similar to that used for the 10 mA measurements.

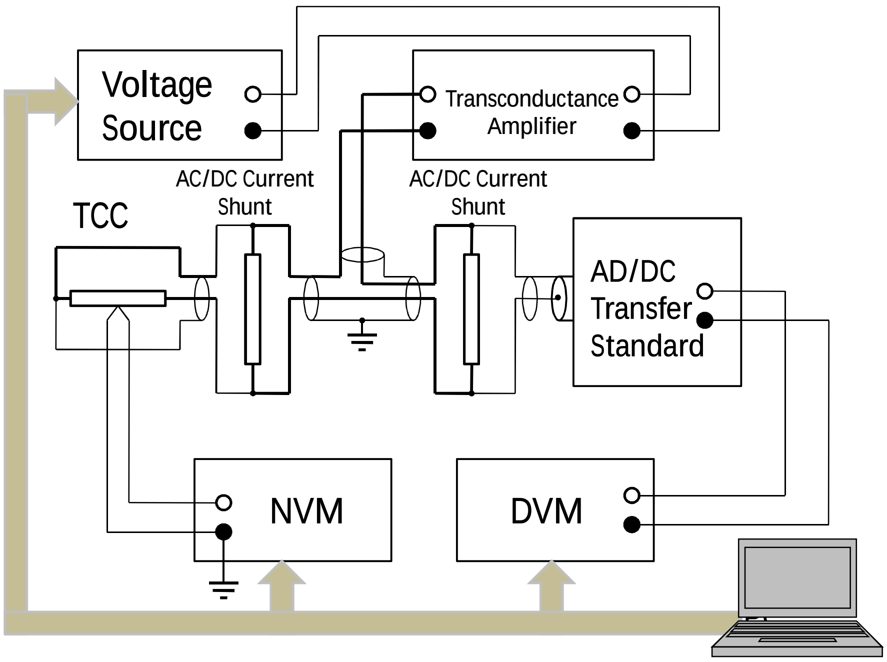


Figure 2 Schematic of measurement setting for 5 A measurements

A voltage calibrator and transconductance amplifier (Wavetek 4808 and 4600) are used to provide DC and AC currents. The current is passed through two thermal current converters (TCCs), connected in series. The TCC on the high side of the comparator comprises a 10 A current shunt (JV design) connected across an AC-DC transfer standard (Fluke 792A), whose output is measured by a digital multimeter (Wavetek 1281). This TCC acts as the reference TCC transfer standard.

The TCC under test, comprising a thermal converter and shunt, is connected to the low side of the comparator. The output of the this TCC is measured using a nanovoltmeter (Agilent 34420A). Both the input and the output of the reference TCC are grounded as shown in the figure. A direct comparison is made between the reference TCC and the TCC under test by simultaneously measuring the outputs of the TCCs.

Control of the voltage calibrator and acquisition of the DVM and NVM readings are handled by a PC.

3. Measurement Procedure

The method used to compare a pair of TCCs is the same for both the 10 mA and the 5 A measurements.

The test current (DC) is applied to the TCCs for at least 30 minutes prior to beginning the measurements. The test currents are then applied in the sequence +DC, -DC, AC, +DC and -DC. The magnitudes of the currents are adjusted so that the output of a TCC does not vary by more than 1 part in 10^4 for the +DC, -DC and AC inputs. A settling time of 60 s is allowed after switching the current. After the outputs of the TCCs have settled, they are recorded, together with corresponding timestamps, for a period of about 100 seconds.
Second order polynomials are fitted to the +DC values, the –DC values, and the AC values. The fit parameters are used to predict the value of the +DC, -DC and AC outputs of the TCCs at the mid-point (in time) of the transfer. The difference in the AC-DC current transfer differences of the TCCs is then calculated using:

$$d_X - d_Y = \frac{\hat{E}_Y^{AC} - \hat{E}_Y^{DC}}{n_Y \cdot \hat{E}_Y^{DC}} - \frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{n_X \cdot \hat{E}_X^{DC}}$$

where d is the AC-DC current transfer difference of the TCC, n is the sensitivity of the TCC, $\hat{E}^{AC}$ is the predicted TCC output at the mid-point of the transfer when AC current is applied and $\hat{E}^{DC}$ is the mean of the predicted TCC outputs at the mid-point of the transfer when +DC and –DC currents are applied. The subscripts *X* and *Y* refer to the TCCs connected to the lower and the upper arms of the comparator, respectively.
The TCC sensitivities had been measured previously by measuring the change in the output of the TCC for a known (1 part in 10^4) change in input.

A measurement set, for each test frequency, comprised three AC-DC transfers. Six measurement sets were obtained for the 10 mA and the 5 A devices over the course of the measurement period.

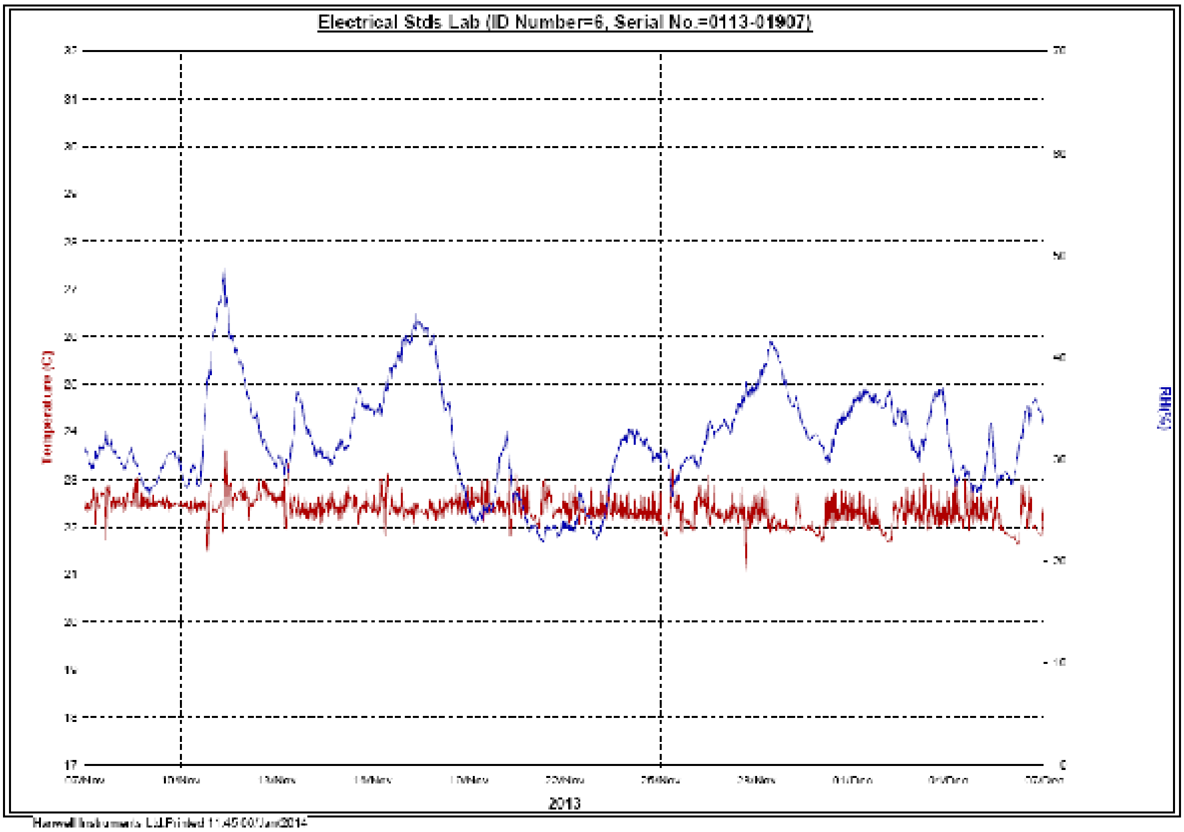
4. Traceability

Measurement traceability for the reported results is obtained as follows:

Quantity	Device	NMI	Certificate Number
Current AC-DC Difference	Holt HCS-1 Current Shunt and 84508 Thermal Converter	Justervesenet	13/6485-7
Current AC-DC Difference	JV-NT-160-160-10A Current Shunt	Justervesenet	13/6485-3
Voltage AC-DC Difference	Fluke 792A	METAS	212-04803

5. Ambient Conditions

A continuous record of the ambient temperature and relative humidity in the laboratory space during the measurement period was maintained. The complete record is shown below.



The summary data are as follows:

Parameter	Minimum Value	Maximum Value	Mean Value
Ambient Temperature	21.1 °C*	23.6 °C	22.4 °C
Ambient Relative Humidity	21%RH	49%RH	32%RH

*Note that this minimum temperature did not occur while measurements were underway. The minimum temperature when measurements were being carried out was 21.7 °C.

6. Measurement Results

6.1 10 mA Measurement Results

Date	Current AC-DC Difference (mA/A)						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
7 Nov 2013	+10	+2	+3	+3	0	-6	-19
8 Nov 2013	+7	+4	+4	+2	-2	-6	-17
8 Nov 2013	+6	+4	+4	+3	+2	-3	-18
11 Nov 2013	+9	+5	+5	+3	-1	-5	-6
13 Nov 2013	+9	+3	+3	+3	+3	+4	-18
15 Nov 2013	+10	+3	+3	+1	-1	-6	-17
Mean Values							
10 Nov 2013	+8	+4	+4	+2	0	-4	-16

	Expanded Measurement Uncertainty (95% Coverage Factor) (mA/A)						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
	50	30	30	47	103	200	410

6.2 5 A Measurement Results

Date	Current AC-DC Difference (mA/A)						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz**	100 kHz**
25 Nov 2013	+3	+4	+1	-5	-13	-	-
25 Nov 2013	+4	+3	+1	-6	-13	-	-
26 Nov 2013	+1	+3	+1	-4	-12	-	-
27 Nov 2013	0	+5	+4	-10	-19	-	-
27 Nov 2013	-1	+4	+6	-7	-19	-	-
28 Nov 2013	-1	+6	+2	-9	-20	-	-
Mean Values							
26 Nov 2013	+1	+4	+3	-7	-16	-	-

	Expanded Measurement Uncertainty (95% Coverage Factor) (mA/A)						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz**	100 kHz**
	185	73	73	120	230	-	-

** No measurements were made at 5A/50 kHz and 5A/100 kHz

6.3 Frequency

Nominal Value	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Deviation from Nominal	0.0 mHz	-0.2 mHz	-4 mHz	-0.04 Hz	-0.08 Hz	-0.19 Hz	-0.4 Hz
Meas. Uncertainty	0.1 mHz	0.1 mHz	1 mHz	0.01 Hz	0.02 Hz	0.05 Hz	0.1 Hz

7. Analysis of Measurement Uncertainty

7.1 10 mA Measurements

7.1.1 Measurement Equation

For the comparison of the unknown TCC with the transfer standard TCC, we have:

$$d_X - d_T = \frac{1}{n_T} \cdot \left(\frac{\hat{E}_T^{AC} - \hat{E}_T^{DC}}{E_T^{DC}} \right) - \frac{1}{n_X} \left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{\hat{E}_X^{DC}} \right) + e_L \quad .....(1.1)$$

where d is the AC-DC current transfer difference of the TCC, n is the sensitivity of the TCC, $\hat{E}^{AC}$ is the predicted TCC output at the mid-point of the transfer when AC current is applied and $\hat{E}^{DC}$ is the mean of the predicted TCC outputs at the mid-point of the transfer when +DC and –DC currents are applied, e_L is an error correction term to account for leakage effects. The subscripts *T* and X refer to the transfer standard and the unknown TCCs respectively.

Similarly, for the comparison of the reference TCC with the transfer standard TCC, we have:

$$d_R - d_T = \frac{1}{n_T} \cdot \left(\frac{\hat{E}_T'^{AC} - \hat{E}_T'^{DC}}{E_T'^{DC}} \right) - \frac{1}{n_R} \left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{\hat{E}_R^{DC}} \right) + e_L' \quad ....(1.2)$$

where the subscript *R* refers to the reference TCC and the primed quantities indicate that the measurement conditions for the transfer standard TCC and for the leakage effect are not exactly the same as for the comparison with the unknown TCC.
Taking the difference of (1.1) and (1.2) we have:

$$d_X = d_R + \frac{1}{n_R} \cdot \left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{E_R^{DC}} \right) - \frac{1}{n_X} \left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{\hat{E}_X^{DC}} \right) + \frac{1}{n_T} \cdot \Delta_T + \Delta_L + e_M \quad ....(1.3)$$

where Δ_T represents the difference in the transfer standard's output term , Δ_L is the difference in the leakage correction term and e_M is an artificially introduced correction term, with a nominal value of zero, which takes account of the non-reproducibility of the measurement.

7.1.2 Input Quantities and Associated Standard Uncertainties

<u>AC-DC current transfer difference of reference TCC</u> (d_R): The best estimate of this quantity is its most recently certified value. The associated standard uncertainty is a combination of the uncertainty of the certified value and uncertainty components due to drift and measurement conditions. The resultant standard uncertainty, which is frequency dependent, is given in the following table:

(Standard Uncertainty of d_R) x 10^6						
10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
17	8	8	10	8	10	50

<u>Sensitivity of reference TCC</u> (n_R): This quantity was measured during the measurement period. The associated relative standard uncertainty is 2%.

<u>Reference TCC output</u> $\left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{E_R^{DC}}\right)$: This quantity is obtained from the predicted outputs of the reference TCC at the mid-point of the transfer which, in turn, are obtained from the NVM readings. The quantities $\hat{E}_R^{AC}$ and $\hat{E}_R^{DC}$ are negatively correlated, so that any uncertainties due to the zero offset and range error of the NVM can be ignored. The standard uncertainty of the quantity is obtained from the data scatter and the differential linearity of the NVM. The standard uncertainty is assigned a value of 20 x 10^{-6} at 10 Hz and 10 x 10^{-6} at all other test frequencies.

<u>Sensitivity of unknown TCC</u> (n_X): This quantity was measured during the measurement period. The associated relative standard uncertainty is 2%.

<u>Unknown TCC output</u> $\left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{E_X^{DC}}\right)$: This quantity is obtained from the predicted outputs of the unknown TCC at the mid-point of the transfer which, in turn, are obtained from the NVM readings. The quantities $\hat{E}_X^{AC}$ and $\hat{E}_X^{DC}$ are negatively correlated, so that any uncertainties due to the zero offset and range error of the NVM can be ignored. The standard uncertainty of the quantity is obtained from the data scatter and the differential linearity of the NVM. The standard uncertainty is not dependent on frequency and is assigned a value of 10 x 10^{-6} for all frequencies.

<u>Sensitivity of transfer standard TCC</u> (n_T): This quantity was measured during the measurement period. The associated relative standard uncertainty is 2%.

Difference in transfer standard TCC outputs (Δ_T): The best estimate of this term is the value obtained from the DMM readings. Due to negative correlations, uncertainties due to zero offset and range error of the DMM are negligible. Also, since the terms $\left(\frac{\hat{E}_T^{AC} - \hat{E}_T^{DC}}{E_T^{DC}}\right)$ and $\left(\frac{\hat{E}_T'^{AC} - \hat{E}_T'^{DC}}{E_T'^{DC}}\right)$ are almost identical, the effect of the differential linearity of the DMM is also negligible. The main source of uncertainty is therefore due to data scatter and the standard uncertainty is estimated to be 2 x 10^{-6}.

Difference in leakage correction (Δ_L):This quantity was assigned a value of zero. The associated standard uncertainty is frequency dependent and is estimated to range from 10 x 10^{-6} at low frequencies to 200 x 10^{-6} at 100kHz.

Non-reproducibility of measurement result (e_M). This quantity is taken to have a value of zero, by definition. Its standard uncertainty is estimated from the results of repeated measurements. It is found to be less than 5 x 10^{-6} for all frequencies.

7.1.3 Sample Uncertainty Budget

The following sample uncertainty budget refers to a test frequency of 1 kHz.

Input Quantity	Standard Uncertainty	Sensitivity Coefficient	Uncertainty Contribution	Type A or B	Degrees of Freedom
d_R	8 μV/V	1 $(\mu\Omega/\Omega)^{-1}$	8 μA/A	B	> 10^4
n_R	0.036 μΩ/Ω	-10 μA/A $(\mu\Omega/\Omega)^{-1}$	0 μA/A	B	> 10^4
$\left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{E_R^{DC}}\right)$	10 μV/V	0.55 $(\mu\Omega/\Omega)^{-1}$	6 μA/A	B	> 10^4
n_X	0.04 μΩ/Ω	7 μA/A $(\mu\Omega/\Omega)^{-1}$	0 μA/A	B	> 10^4
$\left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{E_X^{DC}}\right)$	10 μV/V	-0.5 $(\mu\Omega/\Omega)^{-1}$	-5 μA/A	B	> 10^4
n_T	0.02 μΩ/Ω	-1 μA/A $(\mu\Omega/\Omega)^{-1}$	0 μA/A	B	> 10^4
Δ_T	2 μV/V	1	2 μA/A	B	> 10^4
e_L Δ_L	10 μA/A	1	10 μA/A	B	> 10^4
e_X	2 μA/A	1	2 μA/A	A	5
Combined Standard Uncertainty			15 μA/A		> 10^4
Expanded Uncertainty (95% Coverage Probability)			30 μA/A		

7.2 5 A Measurements

7.2.1 Measurement Equation

For the comparison of the unknown TCC with the reference TCC, we have:

$$d_X - d_R = \frac{1}{n_R}\cdot\left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{E_R^{DC}}\right) - \frac{1}{n_X}\left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{\hat{E}_X^{DC}}\right) + e_L + e_M \qquad .....(2.1)$$

where d is the AC-DC current transfer difference of the TCC, n is the sensitivity of the TCC, $\hat{E}^{AC}$ is the predicted TCC output at the mid-point of the transfer when AC current is applied and $\hat{E}^{DC}$ is the mean of the predicted TCC outputs at the mid-point of the transfer when +DC and –DC currents are applied, and e_L is an error correction term to account for leakage effects. *R* and X refer to the reference and the unknown TCCs respectively.

The reference TCC comprises the JV 10 A reference shunt and the Fluke 792A AC-DC transfer standard. Since the resistance of the shunt is much lower than the input resistance of the AC-DC transfer standard, the AC-DC transfer difference of the shunt-TVC combination can be taken to be:

$$d_R = d_V + d_S \qquad ....(2.2)$$

where d_V is the AC-DC voltage transfer difference of the AC-DC transfer standard, and d_S is the AC-DC transfer difference of the shunt.

The measurement equation is therefore:

$$d_X = d_V + d_S + \frac{1}{n_R}\cdot\left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{E_R^{DC}}\right) - \frac{1}{n_X}\left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{\hat{E}_X^{DC}}\right) + e_L + e_M \qquad ...(2.3)$$

where, as before, e_M is an artificially introduced correction term, with a nominal value of zero, which takes account of the non-reproducibility of the measurement.

7.2.2 Input Quantities and Associated Standard Uncertainties

AC-DC voltage transfer difference of reference TVC (d_V): Since the Fluke 792A was not operating at a point for which certified AC-DC voltage transfer difference values were available, it was necessary to characterise the instrument at the measuring point. The standard uncertainties of the AC-DC voltage transfer differences are given in the following table:

(Standard Uncertainty of d_V) x 10^6				
10 Hz	55 Hz	1 kHz	10 kHz	20 kHz
90	30	30	30	50

AC-DC transfer difference of reference current shunt (d_S): The best estimate of this quantity is its most recently certified value. The associated standard uncertainty is a combination of the uncertainty of the certified value and uncertainty components due to drift and measurement conditions. The resultant standard uncertainties are given in the following table:

(Standard Uncertainty of d_V) x 10^6				
10 Hz	55 Hz	1 kHz	10 kHz	20 kHz
14	14	14	14	19

Sensitivity of reference TCC (n_R): This quantity was measured during the measurement period. The associated relative standard uncertainty is 2%.

Reference TCC output $\left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{E_R^{DC}} \right)$: This quantity is obtained from the predicted outputs of the reference TCC at the mid-point of the transfer which, in turn, are obtained from the DVM readings. The quantities $\hat{E}_R^{AC}$ and $\hat{E}_R^{DC}$ are negatively correlated, so that any uncertainties due to the zero offset and range error of the DVM can be ignored. The standard uncertainty of the quantity is obtained from the data scatter and the differential linearity of the DVM. The standard uncertainty is not dependent on frequency and is assigned a value of 10 x 10^{-6} for all frequencies.

Sensitivity of unknown TCC (n_X): This quantity was measured during the measurement period. The associated relative standard uncertainty is 2%.

Unknown TCC output $\left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{E_X^{DC}}\right)$: This quantity is obtained from the predicted outputs of the unknown TCC at the mid-point of the transfer which, in turn, are obtained from the NVM readings. The quantities $\hat{E}_X^{AC}$ and $\hat{E}_X^{DC}$ are negatively correlated, so that any uncertainties due to the zero offset and range error of the NVM can be ignored. The standard uncertainty of the quantity is obtained from the data scatter and the differential linearity of the NVM. The standard uncertainty is not dependent on frequency and is assigned a value of 10 x 10^{-6} for all frequencies.

Leakage correction (e_L): This quantity was assigned a value of zero. The associated standard uncertainty is frequency dependent and is estimated to range from 20 x 10^{-6} at low frequencies to 100 x 10^{-6} at 20kHz.

Non-reproducibility of measurement result (e_M). This quantity is taken to have a value of zero, by definition. Its standard uncertainty is estimated from the results of repeated measurements. It is found to be less than 3 x 10^{-6} for all frequencies.

7.2.3 Sample Uncertainty Budget

The following sample uncertainty budget refers to a test frequency of 1 kHz.

Input Quantity	Standard Uncertainty	Sensitivity Coefficient	Uncertainty Contribution	Type A or B	Degrees of Freedom
d_V	30 µV/V	1 (µΩ/Ω)$^{-1}$	30 µA/A	B	> 10^4
d_S	14 µA/A	1	14 µA/A	B	> 10^4
n_R	0.02 µΩ/Ω	-4 µA/A (µΩ/Ω)$^{-1}$	0 µA/A	B	> 10^4
$\left(\frac{\hat{E}_R^{AC} - \hat{E}_R^{DC}}{E_R^{DC}}\right)$	10 µV/V	1 (µΩ/Ω)$^{-1}$	10 µA/A	B	> 10^4
n_X	0.04 µΩ/Ω	10 µA/A (µΩ/Ω)$^{-1}$	0 µA/A	B	> 10^4
$\left(\frac{\hat{E}_X^{AC} - \hat{E}_X^{DC}}{E_X^{DC}}\right)$	10 µV/V	-0.5 (µΩ/Ω)$^{-1}$	-5 µA/A	B	> 10^4
e_L	10 µA/A	1	10 µA/A	B	> 10^4
e_X	1 µA/A	1	1 µA/A	A	5
Combined Standard Uncertainty			36 µA/A		> 10^4
Expanded Uncertainty (95% Coverage Probability)			72 µA/A		

EURAMET.EM-K12 Key comparison

AC-DC CURRENT TRANSFER STANDARDS

VSL Results

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Summary

This report presents the results of the regional EURAMET.EM-K12 Key International Comparison carried out at VSL, the Netherlands in December 2013.
The project concerns AC-DC current transfer devices used for current measurements in the range of 10 mA and 5 A at frequencies from 10 Hz to 100 kHz.
The pilot laboratory of this Key comparison is Austria (BEV), supported by the Technical Research Institute of Sweden (SP), Laboratoire National de Métrologie et d'Essais, France (LNE) and the Norwegian Metrology Service Justervesenet (JV).

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1 Introduction

In 2009 the EURAMET Technical Committee for Electricity and Magnetism decided to organise a regional key comparison of current transfer standards, this in order to link the National Metrology Institutes to the key comparison CCEM-K12.

Today alternating current measurements to frequencies as high as 100 kHz are carried out by nearly all national measurements institutes of the European community to meet the demand of industry.
CPIM and the Regional Metrology Organisations, RMO stimulates mutual recognition of reference standards used by these measurements and for this reason the EURAMET-K12 is organised.

The travelling standards were provided by the pilot laboratory, Austria and consisted of one current converter and a combination of current shunt with thermal converter.
The travelling standard is thoroughly characterized by the pilot laboratory before it was sent to the different participants. They investigated the effects of several parameters on the ac-dc error.
Also drift of the travelling standard during the comparison loop will be registered. All these preparations will contribute to realize a good agreement between the results of measurements at national levels.

The results mentioned in this report represent the activities executed by the Department of Calibration & Reference Materials as part of VSL, Dutch Metrology Institute (the national measurement standards laboratory of the Netherlands), and will be accomplished in accordance with the EURAMET Guidelines on Conducting Comparisons.

2 Intercomparison at VSL

2.1 The travelling standards

The travelling standards for this EURAMET key comparison are a Planar Multi-Junction Thermal Converter with a current range of 10 mA and a coaxial current shunt with readout converter for the range of 5 A. Both converters (10 mA and readout) are the same item.
The measurements at both ranges have to be carried out at the frequencies 10 Hz, 55 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz.

<u>Details of the 10 mA travelling standard :</u>

Manufacturer	:	IPHT, Jena
Type	:	PTP/IPHT
Serial number	:	PTC 19
Current range	:	10 mA
Heater resistance	:	90 Ω
Thermocouple resistance	:	7.6 kΩ
Nominal output voltage	:	100 mV
Input connector	:	type N female
Output connector	:	type Cannon 10SL-4S male

Note1: In the supplied Technical Protocol (ver. 14. May 2012) the serial number was mentioned as number 17 instead of 19.
Note2: An internal capacitance of 2.2 µF is soldered in parallel to the output.

<u>Details of the 5 A travelling standard :</u>

Manufacturer	:	BEV, Austria
Type	:	coaxial
Serial number	:	B3A
Current range	:	5 A
Nominal resistance	:	147 mΩ
Input connector	:	type N female
Output connector	:	type N male

We checked the heater and thermocouple resistance and the isolation resistance between the input and output of the PTC19. They were as expected.

2.2 The VSL standards for current measurements

Our primary standards for current measurements are the JV-NT set, manufactured at Justervesenet (JV) and calibrated by Physikalisch-Technische Bundesanstalt (PTB). This set consists of seven shunts with ranges of 30 mA, 100mA, 300mA, 1 A, 3 A, 5 A en 10A. For this current comparison we used our JV-NT 30 mA and JV-NT 5 A types.

Details of the reference JV-NT shunts :

Manufacturer	:	Justervesenet, Norwegian			
Type	:	JV-NT			
Serial number	:	009	Serial number	:	002
Current range	:	30 mA	Current range	:	5A
Nominal resistance	:	42 Ω	Nominal resistance	:	0.2 Ω
Input connector	:	type N female			
Output connector	:	type N male			

For readout of the voltages across the shunts we made use of two of our Planar Multi Junction Thermal Converters (PMJTC's). Both converters are manufactured at the Physikalisch-Technische Bundesanstalt and their corrections are included in the PTB-certificate of the JV-NT set.

Details of the reference standards for readout :

Manufacturer	:	PTB			
Type	:	PMJTC			
Voltage range	:	1 V			
Serial number	:	1	Serial number	:	2
Heater resistance	:	94 Ω	Heater resistance	:	88 Ω
Thermocouple resistance	:	14.3 kΩ	Thermocouple resistance	:	14.9 kΩ
Nominal output voltage	:	100 mV			
Input connector	:	type N male			
Output connector	:	type Cannon 10SL-4S male			

2.3 Measurement method

The measurements have been performed at our operating system, called OS4 which was made available for AC-DC measurement to 100 kHz. The system has build-in facilities to obtain settings for compensation of several parameters, see also chapter 3.

The10 mA travelling standard (PTC19) is measured against the VSL reference AC-DC standard JV-NT 10 mA in combination with the readout converter (PM1) on operating system 4. For this low current measurement it was possible to directly apply the source to the standards.

The 5 A travelling standard (B3A+PTC19) is measured against the VSL reference AC-DC standard JV-NT 5A in combination with the readout converter (PM2) also on operating system OS4. For this high current measurement it was necessary to apply an extra amplifier between the source and the input of the standards. Because of the limited bandwidth of this amplifier these measurements could only be realized to frequencies at the maximum of 20 kHz.

The measurements determine the AC-DC error of the DUT by measuring the difference between the REF and the DUT and correcting for the error of the reference, all realised by the use of a step-down procedure.

The AC-DC transfer difference is defined as :

$$\delta = \frac{I_{ac} - I_{dcavg}}{I_{dcavg}} \qquad (1)$$

Where:

δ	AC-DC transfer difference (µA/A)
I_{ac}	RMS value of the supplied alternating current (A)
I_{dcavg}	average of a positive and a negative supplied direct current to produce the same output voltage as the current I_{ac} (A)

A positive sign for the AC-DC transfer difference indicates that more ac current than dc current is needed for the same output voltage.

Calibration of the devices under test with the VSL references.

We started with the calibration of the 10 mA converter PTB19 (DUT) against the JV-NT30mA/PMJTC-1 (REF). The reference value including readout converter was determined by PTB. The uncertainties mentioned in related certificate were the starting point of the calculation of the overall uncertainties at the 10 ma level. The input connections were made free in the air and not with a connection box to avoid current leakage to earth. To check if there were systematic errors in the measurements we also made some measurements with one of our three-dimensional Multi Junction Thermal Converters (MJTC's) in its current mode.
The case of the PTC19 (= low input) converter was grounded at the input low and connected to the low of the source. The lows of the output voltages of both converters, PTC19 and PMJTC-1 were also connected to the central earth and the low inputs of the measuring system.

Figure 1 shows the set-up of this measurement.

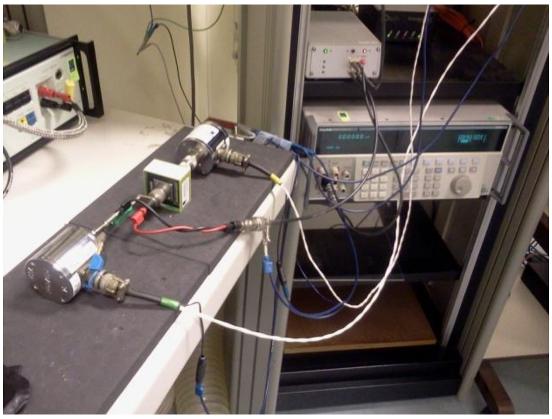
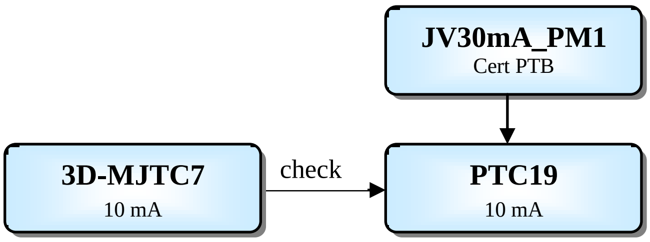


Figure 1. JV30mA_PM1 against PTC19 10 mA.

The measuring current of 10 mA was directly supplied by both of our Fluke 5720A's sources, one for DC and one for AC. In total 15 runs were made over several days with a frequency range of 10 Hz, 55 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz. Temperature and relative humidity were constantly monitored during the measurements.

Traceability 10 mA measurements

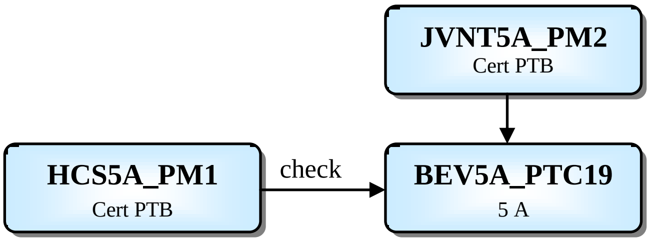


After the 10 mA measurements we started with the 5 A measurements with our reference shunt JVNT5A_PM2 against the travelling standard BEV5A_PTC19. The PTC19 first used as 10 mA converter now functioned as readout converter over the shunt.

The reference value of our reference shunt including readout converter was determined by PTB. The uncertainties mentioned in related certificate were the starting point of the calculation of the overall uncertainties at the 5 A level. For this current range we used our Fluke 5220A amplifier. The measurements have been performed at frequencies 10 Hz, 55 Hz, 1 kHz, 10 kHz and 20 kHz. Higher frequencies at this range were not possible because of the limited bandwidth of this amplifier. To check if there were systematic errors at this current level we made extra measurements with a shunt of our Holt HCS set. The input cables were twisted to avoid the magnetic fields as good as possible.
Temperature and relative humidity were constantly monitored during the measurements.
Figure 2 shows the set-up of this measurement.

Figure 2. JVNT5A_PM2 against BEV5A_PTC19.

Traceability 5 A measurements



3 Measurement set-up

The measurements were carried out on the VSL operating system OS4. Figure 3 gives a good overview of this system. The measurement set-up consists of an AC source (Fluke 5720A) and a DC source (a second Fluke 5720A). Both sources are floating and internally guarded to give the system the possibility of grounding at one point. The alternating or direct signal is in turn connected to the shunts by an AC-DC switch. Depending on the current range a transconductance amplifier (Fluke 5220A) is inserted between the switch and the shunts. Its operation is controlled via IEEE interfacing of the computer.

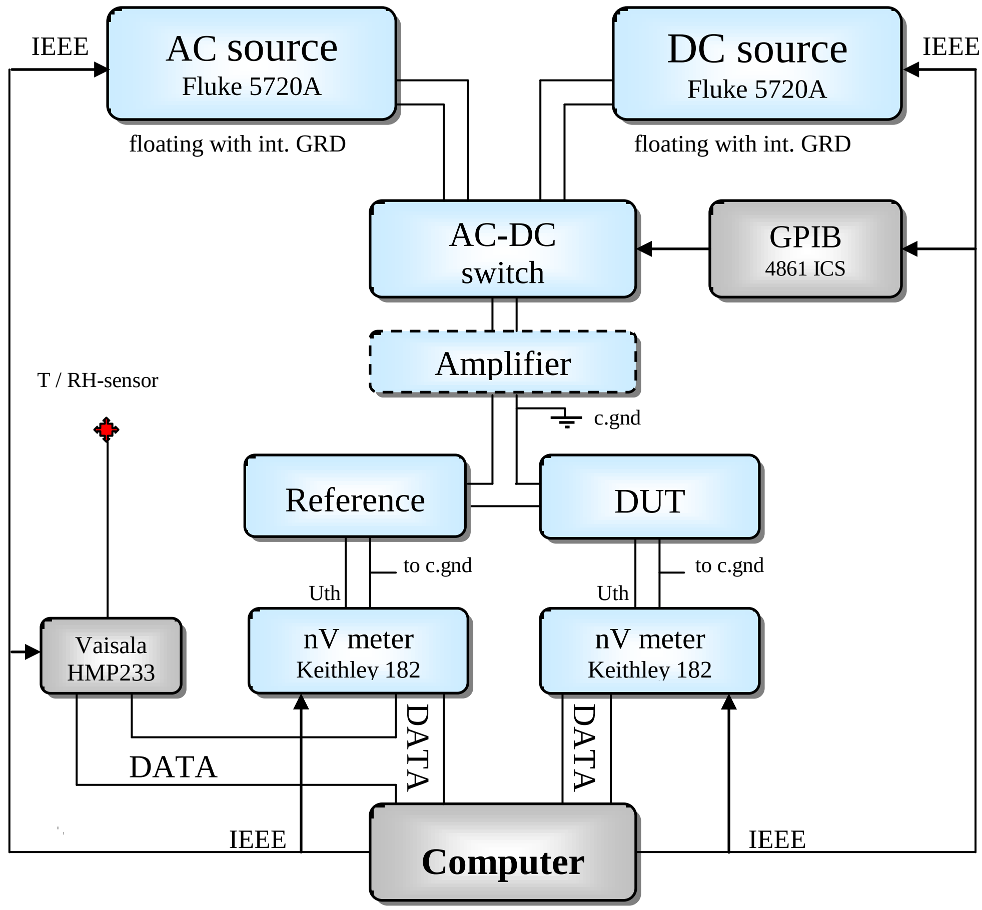


Figure 3. Current measurement set-up realised on VSL operating system OS 4.

The outputs of the thermal element of both transfer standards (Uth) are simultaneously read with two nV-meters. Because of the importance of the temperature and relative humidity these parameters are continuously monitored during the measurement. The data of all the meters is collected by the computer and transferred to AC-DC differences.

The central point of grounding is chosen on the place where the low terminal of the DUT is connected to the low of the current source. The low's of outputs voltages (Uth) are floating, so these points are connected to the central ground. Also all the guards of the connecting cables are on one side tied with the central grounding point.

Before the actual measurement starts, determination of the sensitivity of both standards will take place. Together with this parameter and a DC-characterization, which delivers a DC-average point, the AC adjustment at a certain frequency is started. After this action a sequence of DC+, AC(freq1), DC-, AC(freq1), DC+,…. is supplied to the input of the standards. The length of the sequence depends on the chosen number of cycles. The AC-DC differences will be calculated from the differences in Uth of the standards between the average of supplied DC+ / DC- and AC(freq1). Next step is the AC-adjustment of the next frequency (freq2) and supplying a new sequence with this frequency.

4 Measurement results

4.1 Environmental conditions

The measurements were performed under the following conditions:

Ambient temperature : (23.7 ± 1.0) °C

Relative humidity : (41 ± 10) %

The temperature and relative humidity were monitored during the measurements with a sensor, which was placed near the standards. The results are corrected for both the measured parameter variations. The measurements have been carried out in December 2013 and January 2014.

4.2 Measuring frequency

The aim for the accuracy of the supplied input signal was the frequency to be within 1 % of nominal. A Keithley 2000 in frequency measurement mode was used to check this. The results and the expanded uncertainties of these measurements are reported in the summary of results (appendix 1) of this report.

4.3 References & Transfer measurement results

The results of the transfer measurements of the used reference standards and the travelling standard are shown in the next tables. Table 1 represents the values and uncertainties of the reference standards. The values and their uncertainties come directly from the PTB certificate and include the differences of the readout converters of the shunts.

Table 1. AC-DC values and their uncertainties of the used references

	JV30mA_PM1	Unc.(*k*=2)	JVNT5A_PM2	Unc.(*k*=2)
Range:	30 mA		5 A	
Sn:	009 / 1		002 / 2	
Cert:	3189/3185PTB08		3192/3186PTB08	
Freq. (kHz)	(µA/A)	(µA/A)	(µA/A)	(µA/A)
0.01	**0**	3	**0**	15
0.055	**0**	3	**0**	15
1	**-1**	3	**1**	15
10	**1**	3	**-1**	15
20	**3**	3	**-2**	15
50	**8**	3		
100	**16**	3		

The results of the measurements on the 10 mA-level between JV30mA_PM1 and PTC19 are summarized in table 2. The second and third column shows the differences between both standards and their standard deviations, composed by 15 measurements on different days.
The last two columns represent the result of the device under test (PTC19), corrected for the differences of the reference including associated uncertainties.

Table 2. AC-DC differences of **PTC19 10 mA** with reference JV30mA_PM1

Dut:	PTC19	*std.dev.*	**PTC19**	Unc.(*k*=2)
Ref:	JV30mA_PM1			
Input:	10 mA			
Freq. (kHz)	(µA/A)	(µA/A)	(µA/A)	(µA/A)
0.01	6.0	*1.6*	**6.0**	18.3
0.055	0.3	*1.0*	**0.3**	18.2
1	0.4	*0.8*	**-0.6**	18.1
10	5.7	*1.7*	**6.7**	19.5
20	6.8	*0.8*	**9.8**	30.8
50	7.3	*0.6*	**15.3**	48.2
100	18.3	*0.9*	**34.3**	98.4

Next table shows the results of the measurements on the 5 A-level between JVNT5A_PM2 and BEV5A_PTC19. The second and third column shows here the differences between these 5 A standards and their standard deviations, composed by several cycles with in total 70 measurements.
The last two columns represent the result of the device under test (BEV5A_PTC19), corrected for the differences of the reference include associated uncertainties.

Table 3. AC-DC differences of **BEV5A_PTC19** with reference JVNT5A_PM2

Dut:	BEV5A_PTC19	*std.dev.*	BEV5A_PTC19	Unc.(*k*=2)
Ref:	JVNT5A_PM2			
Input:	5 A			
Freq. (kHz)	(µA/A)	(µA/A)	(µA/A)	(µA/A)
0.01	**-0.7**	0.9	**-0.7**	23.7
0.055	**0.6**	1.0	**0.6**	23.7
1	**0.0**	0.8	**1.0**	23.7
10	**-9.3**	1.0	**-10.3**	28.2
20	**-21.2**	19.1	**-23.2**	50.5

In the next chapter we show how all the uncertainties contributions are included in the calculations of the expanded uncertainty.

5 Uncertainty calculations

The uncertainty budgets mentioned in this report are based on the reference publication EA-4/ 02 Expression of the Uncertainty of Measurement in Calibration which is in agreement with the recommendations of the Guide to the Expression of Uncertainty in Measurement.
The different contributions to the uncertainty budget are schematic summarized in figure 4.

Schematic summary of the uncertainty budget according to EA-4/02

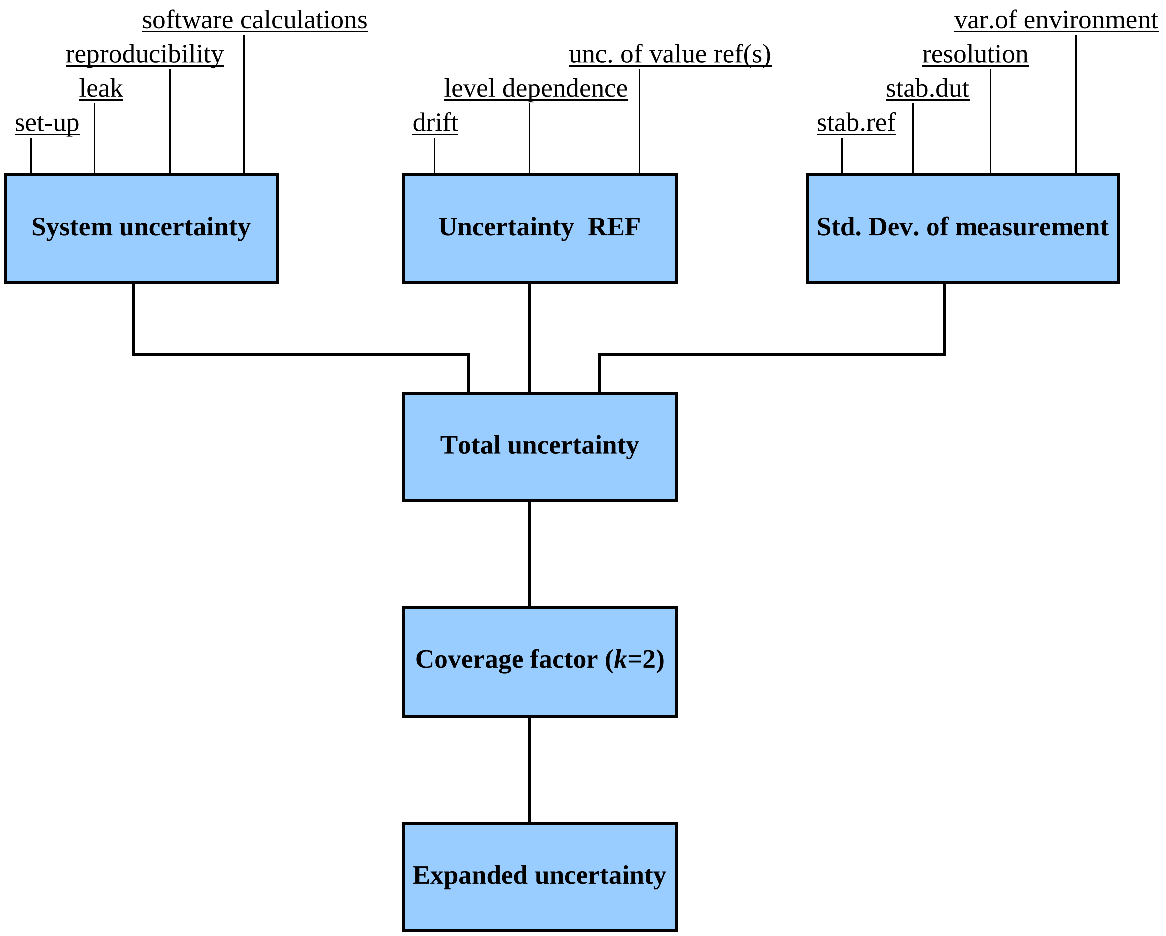


fig. 4. Expression of the contributions to the expanded uncertainty budget of AC/DC measurements.

For determination of the AC-DC difference of the device under test counts now the following equation:

$$\delta_{DUT} = \delta_{REF} + d_{level} + d_{drift} + (\delta_{m,REF} - \delta_{m,DUT}) \cdot d_S + d_{set\text{-}up} + d_{repr} + d_{leak}$$

δ_{REF}	AC-DC difference of the reference
d_{level}	current level dependence of the AC-DC difference
d_{drift}	long term drift of the reference
d_S	determination of the sensitivity (relative)
$d_{set\text{-}up}$	set-up of the measurement
d_{repr}	reproducibility of the measurement
d_{leak}	influence of leakage currents

"d" stands for contributions which are not measured during the measurement itself. They have a value of 0 (if absolute) and 1 (if relative) and only a standard uncertainty contribution is added here. Because these contributions are rectangular , they are transferred to normal distributions by:

$$u_{norm} = \frac{u_{rect}}{\sqrt{3}}$$

Description of the different contributions:

- The uncertainty in current level of the AC-DC difference for the reference consists of the difference between input current of calibration and the current used during the measurement.
- The long-term drift was estimated to zero for both standards because of the very short time between calibration and using the value in the measurement.
- The uncertainty in the determination of the sensitivity is supposed to be always less than 1%. This contribution is mainly determined by the magnitude of the AC-DC difference.
- Set-up contribution is the summarized influence of the remaining uncertainty caused by used cables, connectors, grounding, environmental conditions, offsets, response differences and linearity.
  It is estimated by acquired experience with this kind of measurements.
- The reproducibility of the measurement was determined by a second measurement on a later point of time.
- Leakage currents caused by parasitic capacitances, most contributions at small current measurements.

The following table, based on the EA-4/ 02 publication, shows for example the determination of the AC-DC difference and the corresponding uncertainty at 10 kHz in the 10 mA range.
All other frequencies and ranges are mentioned in table 5 and 6 of this report.

Table 4. AC-DC difference with uncertainty of PTC19 on 10 mA-level at 10 kHz.

Quantity	Estimate	Uncertainty	Probability distribution	Sensitivity coefficient	Uncertainty contribution
δ_{REF}	1.0	1.5	normal	1	1.5
d_{level}	0	3.0	rectangular	1	1.7
d_{drift}	0	0.0	rectangular	1	0.0
δm,REF - δm,DUT	5.7	1.7	normal	1	1.7
d_S	1	0.057	rectangular	5.7	0.033
d_{set-up}	0	15.0	rectangular	1	8.7
d_{repr}	0	6.0	rectangular	1	3.5
d_{leak}	0	1.0	rectangular	1	0.6
δ_{DUT}	**6.7**			U_{TOTAL}	9.8
				$U_{EXP(k=2)}$	**19.5**

Table 5. K12 Uncertainty calculation for PTC19 at 10 mA with the standard JV-NT_30mA shunt (incl. PMJTC1).

Freq (kHz)	U_{REF}	$U(\delta m)$	U_{level}	U_{drift}	$\delta m(R\text{-}D)$	U_s	$U_{set\text{-}up}$	U_{repr}	U_{leak}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	JVNT30mA		10 to 30 mA				10 mA			PTC19	PTC19
	(uA/A)	(uA/A)	(uA/A)	(uA/A)	(uA/A)	(%)	(uA/A)	(uA/A)	(uA/A)	(uA/A)	(uA/A)
0.010	1.5	1.6	3	0	6.0	1	15	2	0	9.2	**18.3**
0.055	1.5	1.0	3	0	0.3	1	15	2	0	9.1	**18.2**
1	1.5	0.8	3	0	0.4	1	15	2	0	9.1	**18.1**
10	1.5	1.7	3	0	5.7	1	15	6	1	9.8	**19.5**
20	1.5	0.8	3	0	6.8	1	25	8	2	15.4	**30.8**
50	1.5	0.6	3	0	7.3	1	40	10	5	24.1	**48.2**
100	1.5	0.9	3	0	18.3	1	80	25	15	49.2	**98.4**

Table 6. K12 Uncertainty calculation for BEV5A_PTC19 at 5 A with the standard JV-NT_5 A shunt (incl. PMJTC2).

Freq (kHz)	U_{REF1}	$U(\delta m)$	U_{level}	U_{drift}	$\delta m(R\text{-}D)$	U_s	$U_{set\text{-}up}$	U_{repr}	U_{leak}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	JV-NT 5A		5 A to 5 A				5 A			B5A_PTC19	B5A_PTC19
freq.(kHz)	(uA/A)	(uA/A)	(uA/A)	(uA/A)	(uA/A)	(%)	(uA/A)	(uA/A)	(uA/A)	(uA/A)	(uA/A)
0.010	7.5	0.9	0	0	0.7	1	15	5	0	11.8	**23.7**
0.055	7.5	1.0	0	0	0.6	1	15	5	0	11.9	**23.7**
1	7.5	0.8	0	0	0.0	1	15	5	0	11.8	**23.7**
10	7.5	1.0	0	0	9.3	1	20	5	0	14.1	**28.2**
20	7.5	19.1	0	0	21.2	1	25	5	0	25.2	**50.5**

U_{REF} : Uncertainty of the current reference; k=1

$U(\delta m)$: Experimental standard deviation of the measurement

U_{level} : Uncertainty caused by change in current-level; calibration current of reference to calibration current of dut; estimated

U_{drift} : The long-term drift of the used standard; estimated as zero unless known values, no uncertainty added

$\delta m(R\text{-}D)$: The measured difference between the reference and the device under test

U_s : The accuracy of linearisation of the operating point; considered that 1% of the difference between REF and DUT will always be enough as uncertainty contribution.

$U_{set\text{-}up}$: set-up of the measurement system; estimated uncertainties caused by used cables, connectors, grounding, environmental conditions, offsets, response differences and linearity. If one of the included contributions forms a substantial part it will be mentioned separately.

U_{repr} : reproducibility of the measurement

U_{leak} : influence of leaking currents caused by parasitic capacitances

U_{TOTAL} : The total uncertainty, calculated as root of the sum of the squares

$U_{EXP(k=2)}$: The expanded uncertainty, calculated as twice the total uncertainty

6 Conclusions

The measurements for the Euramet.EM-K12 key comparison performed at VSL were satisfying but not without some obstacles. Some of our normally used current sources got unstable after a power failure and also our normally used operating system for current calibrations was not completely reliable. Therefore we had to modify our other measuring system which normally is used for voltage. After this delay we were able to realize a lot of useful measurements. The agreement between measurements results at different times, setups and with different standards was good in relation to their related uncertainties.

This comparison will give us the opportunity to show our equivalence to other National Measurement Institutes in Europe in the field of measuring AC-DC current transfer differences. The results and further research will provide us to upgrade the values and uncertainties of our standards for current in the future.

7 References

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451	PTB –E-29	PTB-Bericht Entwicklung von vielfachthermokonvertern..., March 1987 nr E-29 (M. Klonz).
406	94/SEL182/CM	AC-DC Voltage transfer at the lowest level of uncertainty, CCE 92-3, (C.J. van Mullem, J.T. Dessens, J.P.M. de Vreede), Sept '94
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457	IEEE-95-1	M. Klonz, R. Bergeest, A. Caizergues, D. Fraisse, C.A.D. Winther, U. Pogliano, F. Cabiati, G. C. Bosco, G. Zago, J.T. Dessens, J.P.M. de Vreede, K.-E. Rydler, and H. Nilsson, BCR Intercomparison of AC-DC Current Transfer Standards, IEEE IM-44, pg. 403-406, 1995.
465	THP-8	BCR Intercomparison of AC-DC Current Transfer Standards, M. Klonz, R. Bergeest, A. Caizergues, D. Fraisse, C.A.D. Winther, U. Pogliano, F. Cabiati, G. C. Bosco, G. Zago, J.T. Dessens, J.P.M. de Vreede, K.-E. Rydler, and H. Nilsson, THP-8, pg. 421-422, 1995.

8 Appendices

Appendix 1. Summary of results

EURAMET Key International Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Please send this information by e-mail also to martin.garcocz@bev.gv.at.

Institute: VSL, Dutch Metrology Institute

Date of measurements: December 23, 2013 until January 08, 2014

Remarks: 5 A measurements only to 20 kHz

Measurement results:

Current	Measured ac-dc current difference (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	6.0	0.3	-0.6	6.7	9.8	15.3	34.3
5 A	-0.7	0.6	1.0	-10.3	-23.2		

Expanded uncertainty:

Current	Expanded uncertainty (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	18.3	18.2	18.1	19.5	30.8	48.2	98.4
5 A	23.7	23.7	23.7	28.2	50.5		

Measurement frequency:

	Nominal frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. frequency	10.000	55.00	1.0000	10.000	19.999	50.00	100.00
Expanded uncertainty (%)	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Environmental parameters:

	Min	Max	Remarks
Ambient temperature (°C)	23.6	23.7	Measured 1 meter from dut
Relative humidity (%)	41.0	41.2	Measured 1 meter from dut

Appendix 2. Summary of uncertainty budget

EURAMET Key International Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Please also send this information by e-mail also to martin.garcocz@bev.gv.at.

Institute: VSL, Dutch Metrology Institute

Date: February 21, 2014

Remarks: 5 A uncertainties only to 20 kHz

Measuring current: 10 mA

Contribution of:	Standard uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference	1.5	1.5	1.5	1.5	1.5	1.5	1.5	B	N
Standard deviation	1.6	1.0	0.8	1.7	0.8	0.6	0.9	A	N
Level dependence	1.7	1.7	1.7	1.7	1.7	1.7	1.7	B	R
Drift	0.0	0.0	0.0	0.0	0.0	0.0	0.0	B	R
Sensitivity	0.0	0.0	0.0	0.0	0.0	0.0	0.1	B	R
Setup	8.7	8.7	8.7	8.7	14.4	23.1	46.2	B	R
Reproducibility	1.2	1.2	1.2	3.5	4.6	5.8	14.4	B	R
Leakage	0.0	0.0	0.0	0.6	1.2	2.9	8.7	B	R

Standard unc:	9.2	9.1	9.1	9.8	15.4	24.1	49.2
Expanded unc:	18.3	18.2	18.1	19.5	30.8	48.2	98.4
Coverage factor *k*:	2	2	2	2	2	2	2

Measuring current: 5 A

Contribution of:	Standard uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz				
Reference	7.5	7.5	7.5	7.5	7.5			B	N
Standard deviation	0.9	1.0	0.8	1.0	19.1			A	N
Level dependence	0.0	0.0	0.0	0.0	0.0			B	R
Drift	0.0	0.0	0.0	0.0	0.0			B	R
Sensitivity	0.0	0.0	0.0	0.1	0.1			B	R
Setup	8.7	8.7	8.7	11.5	14.4			B	R
Reproducibility	2.9	2.9	2.9	2.9	2.9			B	R
Leakage	0.0	0.0	0.0	0.0	0.0			B	R

Standard unc:	11.8	11.9	11.8	14.1	25.2		
Expanded unc:	23.7	23.7	23.7	28.2	50.5		
Coverage factor *k*:	2	2	2	2	2		

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Test Report

CURRENT SHUNTS
10 mA Serial No. PTC 19
5 A Serial No. B3A

COMPARISON TITLE	EURAMET Key International Comparison of AC-DC Current Transfer Standards
COMPARISON NUMBER	Euramet.EM-K12
PILOT LABORATORY	Federal Office of Metrology and Surveying BEV Arltgasse 35 A-1160 Vienna Austria
DATE OF MEASUREMENT	17 January 2014 to 29 January 2014

The objective of this comparison is to demonstrate the capabilities of the NMI's in Europe in the area of AC-DC Current Transfer measurements.

Quantity to be measured:

The quantity to be measured and reported on is the AC-DC current transfer difference of both current shunts at applied current levels of 10 mA and 5 A at frequencies up to 100 kHz.

AC-DC current transfer difference is defined as

$$\delta = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

where

I_{ac} is an rms ac current, and
I_{dc} is a dc current which, when reversed, produces the same mean output response as the rms ac current.

Differences are expressed in microamperes per ampere (μA/A) and a positive value signifies that more ac than dc current was required for the same output response.

Date of Issue: 23 April 2014 **Signed:** AJWheaton **(Authorised Signatory)**

Checked by: AJW SM. **Name:** **A J Wheaton** **on behalf of NPLML**

CURRENT SHUNTS
10 mA Serial No. PTC 19
5 A Serial No. B3A

Travelling Standards

10 mA Current Shunt	Serial No. PTC 19
Rated Input Current:	10 mA
Heater Resistance:	90 Ω
Thermocouple Resistance:	7.6 kΩ
Output Voltage at Rated Current:	approx. 100 mV

5 A Current Shunt	Serial No. B3A
Nominal Resistance:	147 mΩ
Input Connector:	type N (female)
Output Connector:	type N (male)

Measurement Method

The primary standard is a Multi-Junction Thermal Converter (MJTC) with a known AC/DC Transfer error. This MJTC is rated at 50 mA and is used to calibrate NPL current shunt standards up to 20 A using a build-up technique. The MJTC was then used to calibrate a 10 mA single-junction thermal converter (SJTC).

Measurements were made in a temperature controlled environment. At NPL, all of the standards are measured in an RF shielded laboratory. The heat load in this laboratory is kept to a minimum allowing the measurements to be made in a stable environment. The ambient temperature and relative humidity during the measurement period were measured to be 23 ± 1°C and 40 ± 10 % respectively.

The outputs from a DC and AC calibrator are fed into a 4 terminal switch box, the output of which was connected to the input of a transconductance amplifier. The output of this amplifier was connected, using a series box, linking the inputs of both the travelling standard and the NPL standard by means of a low loss co-axial cable.

The travelling standard was connected to the “low” side of the series box and both the input and output of the travelling standard were connected to the measurement earth of the system.

The measurements were made using the "digital bridge" as described in References 1 and 2. Thermal transfer device outputs are prone to drifting. Measurement of the AC/DC transfer difference at NPL are made under computer control, to allow switching between AC and DC to take place at regular, precise intervals. Sufficient readings can be made to allow curve fitting routines to be applied to allow for high order drifts. The following measurement sequence is used:

$$ac - dc_f - ac - dc_r - ac - dc_f - ac - dc_r - ac - dc_f - ac - dc_r - ac$$

The results are fitted to an expression of the form:

$$y = A + B\,t + C\,t^2 + D\,t^3$$

where A can take the values A_A, A_F or A_R corresponding to inputs of ac, dc_f (forward) and dc_r (reversed), respectively, and t represents the time interval of the measurements. B, C and D are constants.

Since it is the change in the output between ac and dc rather than the absolute value of the output which is important, most of the voltage from the thermocouple can be backed–off using a low noise milli-volt DC source. The residual signal is amplified using a commercial high resolution amplifier and the resulting signal measured using a high resolution DMM. In this way the mV output signal can be measured to the sub–nanovolt level required.

The measurements are then carried out using the digital bridge. The two DMM's are read by the computer via the IEEE488 bus. The readings are normalised so that changes in the outputs are related to changes in the inputs. After applying the curve–fitting routines, the relative AC/DC difference between the two devices is calculated by the computer. Such a procedure gives all the advantages of using a conventional analogue bridge to compare the outputs but obviates the need to perform the sort of manual bridge–balancing techniques normally needed to compare non–linear devices such as thermal converters.

The AC/DC transfer error is given by:

$$AC/DC\,Transfer\ Error = -\left(A_A - \frac{(A_F + A_R)}{2}\right)$$

It can be seen that this differs from the conventional expression for the AC/DC transfer error, in that, it is the difference between the AC and DC inputs required to give the same thermocouple output. Provided its transfer errors are small and the DC reversal errors are small then any difference between the above expression and the conventional definition is of the second order. That is, the error in the result will only amount to 1 ppm even if the transfer error, the reversal error or the difference between the supplies was 0.1%. A positive AC/DC transfer error means that the AC supply needs to be greater than the DC supply to give the same thermocouple output.

Measurement traceability

All measurement results quoted within this report were made using equipment where there is an unbroken traceability chain to UK national standards held and maintained by NPL.

CURRENT SHUNTS
10 mA Serial No. PTC 19
5 A Serial No. B3A

Measurement conditions

Figure 1. details the measurement set up used at NPL.

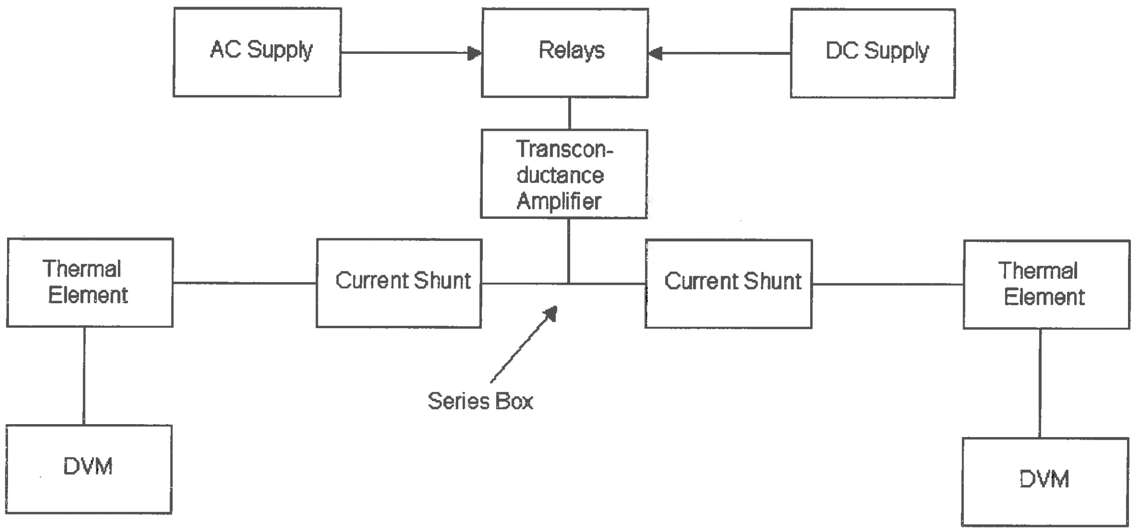

Figure 1. NPL Measurement Set-Up

As required in the protocol, the travelling standard was connected to the 'lo' side of the measurement circuit. Both the input and output of the shunt were connected to the measurement earth.

The ambient temperature was measured to be 23 ± 1°C.

The AC-DC current transfer difference of each travelling standard was measured at its nominal current and at the following frequencies:

10 Hz, 55 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz.

A check of both the input and output resistances of the shunts was performed to confirm figures as indicated on Page 2.

CURRENT SHUNTS
10 mA Serial No. PTC 19
5 A Serial No. B3A

The applied frequencies from the AC voltage calibrator were measured using a calibrated frequency counter and the results are detailed in Table 1.

Table 1 - Calibrator Frequency Calibration

Calibrator Frequency Hz	Measured Frequency Hz	Error ppm	Uncertainty ppm
10	9.999 998	-0.2	4.3
55	54.999 98	-0.4	
1 000	999.999 5	-0.5	
10 000	9 999.996	-0.4	
20 000	19 999.994	-0.3	
50 000	49 999.98	-0.5	
100 000	99 999.96	-0.4	

The reported expanded uncertainty given in Table 1 is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95%.

CURRENT SHUNTS
10 mA Serial No. PTC 19
5 A Serial No. B3A

The pictures below show the measurement setup at both current levels (Figues 2 & 3), the calibrator & switch box (Figure 4) and a close up of the series box used (Figure 5).

Figure 2. 10mA Measurement Setup

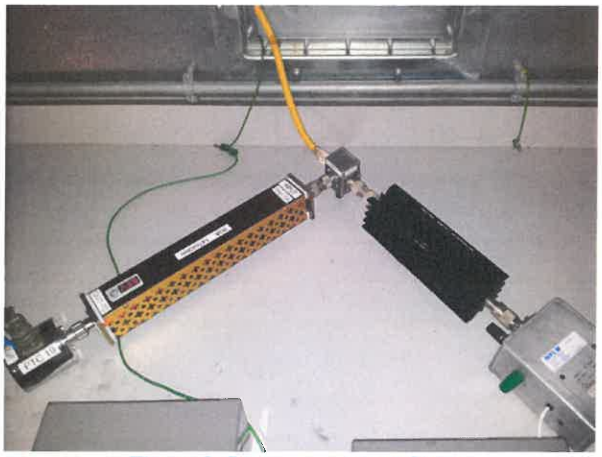
Figure 3. 5A Measurement Setup


Figure 4. Calibrator & Switch Box

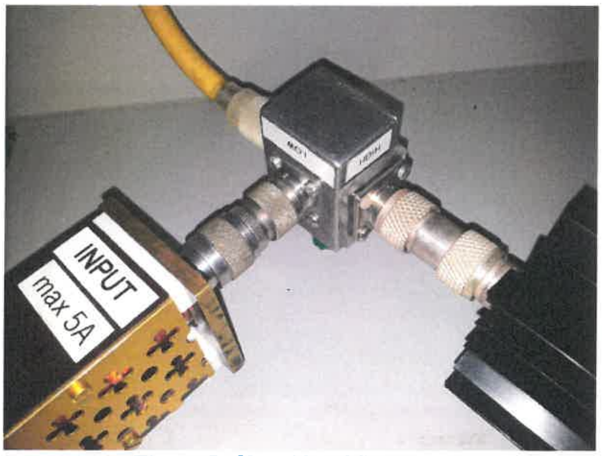

Figure 5. Close Up of Series Box

CURRENT SHUNTS
10 mA Serial No. PTC 19
5 A Serial No. B3A

Results

The reported expanded uncertainties given in Table 2 are based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95%.

Table 3 gives the differences between alternating and direct currents required to give the same output when successively applied to the input connector of the travelling standard. The direct current was taken as the mean of values obtained with forward and reverse polarities. A positive sign indicates a high value of alternating current was required to produce the same output.

Table 2 Uncertainty providing a coverage probability of approximately 95%, µA/A

Current Shunt Serial Number	Applied Current (A)	Frequency, Hz						
		10	55	1 000	10 000	20 000	50 000	100 000
PTC 19	0.01	± 11	± 11	± 11	± 12	± 14	± 15	± 22
B3A	5	± 55	± 22	± 21	± 19	± 28	± 42	± 94

Table 3 AC/DC Difference, µA/A

Current Shunt Serial Number	Applied Current (A)	Frequency, Hz						
		10	55	1 000	10 000	20 000	50 000	100 000
PTC 19	0.01	2	2	1	-1	-3	-8	-7
B3A	5	-26	1	-6	-15	-27	-58	-44

CURRENT SHUNTS
10 mA Serial No. PTC 19
5 A Serial No. B3A

Uncertainty Budgets

Table 4 - Break Down of Uncertainty Calculations for Current Level of 10 mA

	Divisor	*10 Hz*	*55 Hz*	*1 kHz*	*10 kHz*	*20 kHz*	*50 kHz*	*100 kHz*
Freq Dependant Bridge Errors	Normal	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Typical Scatter	Rectangular	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Freq Dependant Bridge Errors	Normal	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Typical Scatter	Rectangular	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Level Dependancy	Rectangular	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Network/Potential of Housing	Rectangular	3.0	3.0	3.0	4.0	5.0	6.0	10.0
Repeatability	Normal	1.4	1.0	1.2	1.2	1.4	1.5	1.2
rss x2		**10.8**	**10.6**	**10.6**	**11.9**	**13.4**	**15.0**	**21.9**
Degrees of Freedom		**>1000**	**>1000**	**>1000**	**>1000**	**>1000**	**>1000**	**>1000**

Table 5 - Break Down of Uncertainty Calculations for Current Level of 5 A

	Divisor	*10 Hz*	*55 Hz*	*1 kHz*	*10 kHz*	*20 kHz*	*50 kHz*	*100 kHz*
Build Up Uncertainty	Normal	11.0	7.7	9.4	7.8	8.1	10.3	13.3
Level Dependancy	Rectangular	24.0	6.0	0.0	0.0	0.0	0.0	0.0
Network/Potential of Housing	Rectangular	3.5	3.5	3.5	3.5	10.0	15.0	40.0
Freq Dependant Bridge Errors	Normal	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Typical Scatter	Rectangular	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Repeatability	Normal	5.5	1.6	1.2	3.0	4.5	10.3	19.9
rss x2		**54.6**	**21.5**	**20.7**	**18.6**	**27.6**	**42.0**	**93.4**
Degrees of Freedom		**>1000**	**>1000**	**>1000**	**>1000**	**>870**	**>175**	**>300**

Uncertainty Statement

The reported expanded uncertainties in Tables 4 and 5 are based upon a standard uncertainty multiplied by a coverage factor of $k = 2$, providing a coverage probability of approximately 95%. The quoted uncertainties given in Tables 1, 2, 4 and 5 apply only to the measured values and do not carry any implication as to the long-term stability of the devices under test.

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END OF MEASUREMENTS

EURAMET.EM-K12

Measurement Report on EURAMET Key International Comparison of AC-DC Current Transfer Standards

Prepared for:
Federal Office of Metrology and Surveying, Austria

Prepared by:
Andrei Pokatilov

METROSERT

2014

Contents

1. Measurement setup and reference standards

The measurement results reported below have been performed in a screened laboratory with environmental parameters regulated within the limits as given in Table 5.
Calibration of ac-dc current transfer standards at Metrosert has been performed by an automated measurement system consisting of a solid-state thermal voltage converter (TVC) as the reference ac-dc transfer standard, ac current shunts, a current source generating dc and ac currents, a multimeter measuring the output voltage of the TVC.
As the reference standard and device under test should be grounded during the measurements, the substitution method with the high-stability calibrator Fluke 5720A/5725A as a current source has been used. The current of 5 A at 10 Hz frequency has been generated with the transconductance amplifier Wavetek 4600.
The reference standards and equipment used in the measurement are given below.

Reference standards:
Ac-dc transfer standard Fluke 792 s/n 8600001
Ac current shunt Fluke 792A-7004 s/n 040510.01
Ac current shunt Fluke A40-10mA s/n 8586001
Ac current shunt Fluke A40A-5A s/n 8586013
Ac current shunt Fluke A40A-10A s/n 8586014

Measurement equipment and software:
Calibrator Fluke 5720A s/n 9781214
Transconductance amplifier Fluke 5725A s/n 1189016
Transconductance amplifier Wavetek 4600 s/n 44928
Multimeter Agilent 3458A s/n MY45047495
Software ac-dci 5720_3458 v2.0, Metrosert

Measured ac-dc current transfer standards (BEV):
Multi junction thermal converter, PTP/IPHT s/n PMJTC 19
Current shunt, BEV s/n B3A

2. Definition of measurand

Ac-dc current transfer difference δ is defined as:

$$\delta = \frac{I_{ac} - I_{dc}}{I_{dc}},$$

where
I_{ac} – is an rms ac current, and
I_{dc} – is a dc current which, when reversed, produces the same mean output response as the rms ac current.

Differences are expressed in microamperes per ampere (μA/A) and a positive ac-dc difference δ indicates that more alternating than direct current is required to produce the same TVC output.

3. Measurement procedure

The measurement procedure described below has been automated by software “ac-

dci_5720_3458_v2.0" developed at Metrosert.
The ac and average dc currents of the calibrator have been adjusted to produce the same output of the reference TVC with the uncertainty (k=2) from 8 µA/A to 26 µA/A depending on the measurement frequency and output value.
At least an hour has been allowed TVCs to warm-up with the nominal current applied.
Each ac-dc difference is averaged from 20 measurements according to the measurement sequence given in Figure 1, where the ac point AC_{fx} is located between DC+ and DC- measurement points. Delay time around 70 seconds has been used between successive applications of the DC and AC currents.

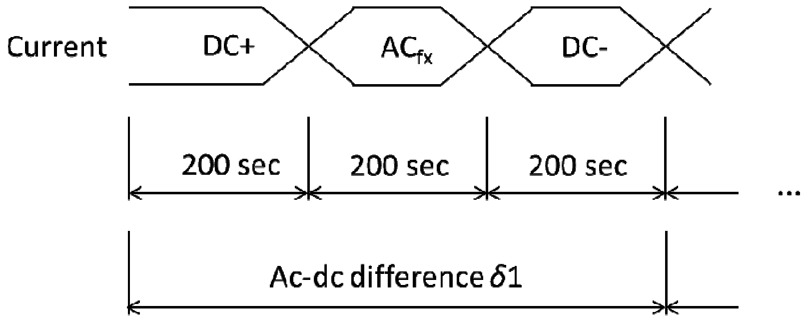

Figure 1. Timing diagram for the ac-dc difference measurement sequence.

The ac-dc differences are calculated for both reference and transfer TVCs and subtracted from each other cancelling the ac-dc difference of the calibrator. The resulting ac-dc difference δ_{trf} assigned to the transfer standard is obtained from the following equation:

$\delta_{trf} = \delta_A - \delta_B + \delta_{ref}$,

where

δ_A – the ac-dc difference measured by the reference TVC,
δ_B – the ac-dc difference measured by the transfer TVC,
δ_{ref} – the ac-dc difference of the reference TVC from the calibration certificate.

4. Traceability

Ac-dc current transfer measurements of AS Metrosert are traceable to measurement standards of SP Technical Research Institute of Sweden. The reference TVC Fluke 792 has a calibration certificate MTePX26444-K02--K07.

5. Measurement results

Table 1. Measurement results.

Current	Measured ac-dc current difference (µA/A) at frequency			
	10 Hz	55 Hz	1 kHz	10 kHz
10 mA	6	0	-1	-17
5 A	6	-9	-9	-12

Table 2. Expanded uncertainty.

Current	Expanded uncertainty (µA/A) at frequency			
	10 Hz	55 Hz	1 kHz	10 kHz
10 mA	28	13	12	33
5 A	36	19	19	55

Table 3. Measurement frequency at 10 mA current.

	Nominal frequency			
	10 Hz	55 Hz	1 kHz	10 kHz
Meas. frequency	10,000	55,001	1,000017	10,00017
Expanded uncertainty	0,005	0,001	0,000001	0,00001

Table 4. Measurement frequency at 5 A current.

	Nominal frequency			
	10 Hz	55 Hz	1 kHz	10 kHz
Meas. frequency	10,000	55,001	1,000017	10,00017
Expanded uncertainty	0,001	0,001	0,000001	0,00001

Table 5. Environmental parameters.

	Min	Max	Remarks
Ambient temperature (°C)	22,5	24,5	-
Relative humidity (%)	30	50	-

6. Uncertainty budget

The uncertainty budget is composed in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement, including degrees of freedom (D.o.F.) for every component and calculation of the coverage factor.

The main contributors to the uncertainty budget are listed below:

u_{ref_crt} – the ac-dc difference of the reference standard from the calibration certificate,
u_{ref_stb} – long-term stability of the reference standard,
u_{ref_ind} – the ac-dc difference indicated by the reference standard,
u_{trf_ind} – the ac-dc difference indicated by the transfer standard,
u_{rep} – reproducibility of the measurement,
u_{cur_stb} – short-term stability of the current source,
u_{dmm_10} – stability and linearity of the multimeter at the 10 V range,
u_{dmm_100} – stability and linearity of the multimeter at the 100 mV range.

Table 6. Uncertainty budget. Measurement current: 10 mA.

Contribution of:	Standard Uncertainty (μA/A) at frequency				Type A or B	Distri-bution	D.o.F.
	10 Hz	55 Hz	1 kHz	10 kHz			
Ac-dc difference 10 mA reference standard	6,5	3,5	3,5	3,5	B	Normal	Inf.
Long-term stability 10 mA reference standard	2,9	2,9	2,9	2,9	B	Rect.	Inf.
Indicated ac-dc difference 10 mA reference standard	0,4	0,1	0,1	0,4	A	Normal	19
Indicated ac-dc difference 10 mA transfer standard	0,8	0,4	0,3	0,4	A	Normal	19
Reproducibility	11,5	3,0	1,9	15,6	B	Rect.	Inf.
Short-term stability current source	2,9	2,9	2,9	2,9	B	Rect.	Inf.
Stability and linearity multimeter range 10 V	0,8	0,8	0,8	0,8	B	Rect.	Inf.
Stability and linearity multimeter range 100 mV	0,6	0,6	0,6	0,6	B	Rect.	Inf.

Standard unc:	13,9	6,3	5,8	16,5
Expanded unc:	27,8	12,6	11,6	33,0
Coverage factor *k*:	2	2	2	2

Table 7. Uncertainty budget. Measurement current: 5 A.

Contribution of:	Standard Uncertainty (μA/A) at frequency				Type A or B	Distri-bution	D.o.F.
	10 Hz	55 Hz	1 kHz	10 kHz			
Ac-dc difference 5 A reference standard	11,5	6	6	6	B	Normal	Inf.
Long-term stability 5 A reference standard	2,9	2,9	2,9	2,9	B	Rect.	Inf.
Indicated ac-dc difference 5 A reference standard	0,4	0,2	0,5	0,2	A	Normal	19
Indicated ac-dc difference 5 A transfer standard	1,7	0,2	0,8	0,2	A	Normal	19
Reproducibility	11,5	3,0	3,0	26,0	B	Rect.	Inf.
Short-term stability current source	5,8	5,8	5,8	5,8	B	Rect.	Inf.
Stability and linearity multimeter range 1 V	0,2	0,2	0,2	0,2	B	Rect.	Inf.
Stability and linearity multimeter range 100 mV	0,9	0,9	0,9	0,9	B	Rect.	Inf.

Standard unc:	17,6	9,4	9,4	27,5
Expanded unc:	35,2	18,8	18,8	55,0
Coverage factor *k*:	2	2	2	2

Andrei Pokatilov
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28.03.2014

Report on key comparison EURAMET.EM-K12

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Contents

Report on the EURAMET Key Comparison of AC-DC Current Transfer Standards, EURAMET.EM-K12

1 Introduction

The ac-dc difference of the travelling standard has been determined by comparison with the ac-dc transfer standards of SP Technical Research Institute of Sweden, during the period 27 March -8 April 2014. The 10 mA travelling standard was a Planar Multijunction Thermal Converter (PMJTC), Serial Number PTC 19, and the 5 A travelling standard was a 0.15 □ coaxial shunt, Serial NoB3A manufactured by BEV used together with the PMJTC.

2 Ac-dc current transfer standards of SP

The SP realisation of ac-dc current transfer difference at the primary level 10 mA is based on three different methods depending on the frequency band. At medium frequencies around 1 kHz the realisation is based on the fast reversed dc method (FRDC). Around 1 kHz the ac-dc current transfer difference of a 3-dimensional Multijunction Thermal Converter (MJTC) of PTB type is assumed to depend only on the dc-effects due to Peltier and Thomson [1]. At low frequencies the ac-ac(1 kHz) transfer difference of the MJTC is determined by a special comparison to a resistor with large thermal time constant [2]. At high frequencies the ac-ac(1 kHz) transfer difference of a single junction converter (SJTC) is modelled by its reactive and loss components [3].

For higher currents and frequencies of 1 kHz and higher the ac-dc transfer difference of the number of shunt/PMJTC combinations are determined by a step-up procedure, comparing adjacent ranges. The low frequency behaviour is determined by the ac-ac(1 kHz) transfer difference of the two PMJTCs by the method mentioned above [2] together with the assumption that the shunts do not contribute at frequencies <1 kHz. Earlier some steps have been checked by a measuring system that allows comparison of thermal current converters with a ratio of 2:1 without introducing any error due to level dependence with good agreement at frequencies up to 1 kHz [4].

The level dependence of the ac-ac(1 kHz) transfer difference at low frequencies is proportional to the power in the PMJTC. The level dependence of the ac-ac(1 kHz) transfer difference of the PMJTCs at high frequencies is determined by comparison to SJTCs in both voltage and current mode.

3 Measuring system

The comparison of the travelling standard and the standards of SP was made by an automated measuring system, Fig. 1. In the measuring system the inputs of the two transfer standards are connected in series by a current T-connector, manufactured by SP. The transfer standard on high potential is guarded to maintain the same defined measuring conditions as the transfer standard on the grounded side [5]. The ac-dc difference of the travelling standard is measured on the grounded side and with the centre of the T-connector as the reference plane. As can be seen in the uncertainty budget the influence of the T-connector is negligable so the measured ac-dc difference will be the same if the reference plane is at the input connector of the PMJTC (10 mA) or shunt (5 A), respectively.

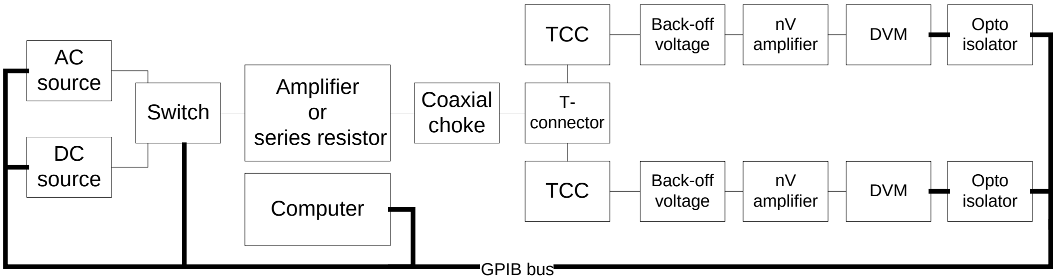

Fig. 1. Automated measuring system for comparison of ac-dc current transfer standards.

Low measuring currents are generated by voltage generators in series with a resistor. High currents are generated by a transconductance amplifier.The ac- and dc-voltages are applied using a switch with a switching time less than 1 ms.

To eliminate errors due to different potentials the system is made symmetric by using a guard so that input low and output low of each transfer standard is on equal potential, Fig 2. On the high potential side are the low terminal of the output voltage, the screen of the back off voltage source and the nanovoltmeter (i e nanovoltamplifier+DVM) case guarded to the same potential as the low input terminal of the transfer standard.

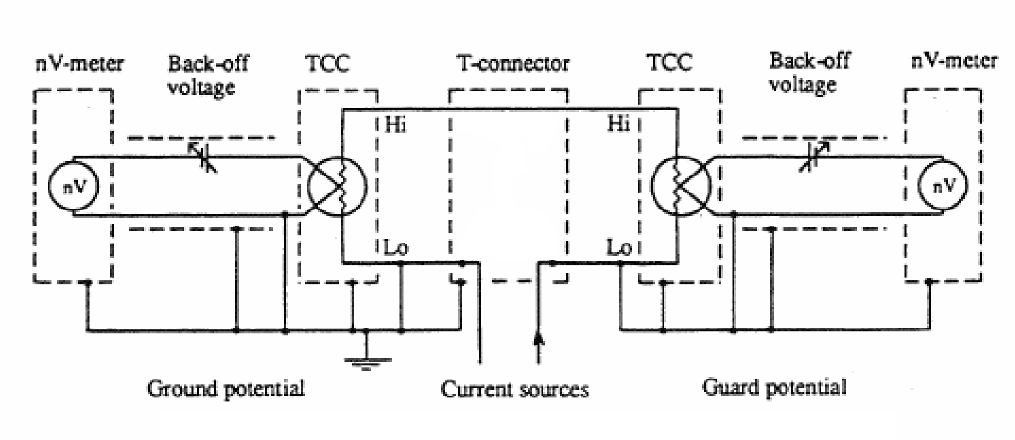

Fig 2. Circuit diagram of the guard arrangement.

After minimum 30 min warm up, the measurement starts by determining the scale factors of the transfer standards. At each frequency the rms-value of the ac-current is then adjusted to within $1 \cdot 10^{-4}$ of the dc-current. Ac- and dc-current is applied consecutively and the differences between the output voltages of the transfer standards and the back-off voltages are amplified with nV-amplifiers and measured by digital voltmeters. The ac-dc transfer difference is determined by computation.

Errors in the measured values due to drift in the output voltages and the back-off voltages are minimised by using a symmetric measuring sequence: DC^{+}, AC, DC^{-}. Errors in the measured values due to instability of the input currents are minimised by simultaneous triggering of the DVMs.

4 Measuring conditions

4.1 General

The ac-dc current difference of the travelling standards is measured at 10 mA and 5 A, respectively. The ac-current was of practically sine wave form and the frequencies were nominal within ±0,01%. The ambient temperature was 23±1ºC and the relative humidity 45±10 %. The input low and the output low of the travelling standards were connected to the grounded side of the T-connector, which was the common ground point. The output of the travelling standards have had a large capacitive load. Care has been taken to keep the ambient space free from disturbing electromagnetic fields and draught and to avoid fast air pressure changes in the laboratory.

4.2 Definition of the measurand

The ac-dc current transfer difference is defined as:

$$\delta = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

where

I_{ac} is an RMS ac current, and
I_{dc} is a dc current which, when reversed, produces the same mean output response as the RMS ac current.

Differences are expressed in microamperes per ampere (μA/A) and a positive sign signifies that more ac than dc current was required for the same output response.

5 Measurements on the travelling standard

Initial check of input, output and isolation resistances of the TC's were made in accordance with the Technical Protocol:

TC	Rin	R out	R in-out
s/n PTC19	97,6 ohm	7,7 kohm	>200 Mohm

The ac-dc current transfer difference of the travelling standards of the EURAMET.EM-K12 has been measured by comparison to the standards of SP. At 10 mA the standard used is a 3-dimensional multijunction thermal converter (MJTC) and at 5 A the standard is a current shunt in combination with a planar multijunction thermal converter (PMJTC). A summary of the results is given in table 1.

Table 1. Measured ac-dc current transfer difference and expanded uncertainty of the travelling standards in µA/A.

		Measured ac-dc transfer difference and expanded uncertainty in µA/A at the frequency						
Meas. current	Quantity	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	Measured ac-dc diff.	6,3	0,4	0,1	0,4	0,4	1,2	2,0
	Expanded uncertainty	3,2	2,2	1,5	2,0	2,0	2,4	3,4
5 A	Measured ac-dc diff.	1,3	0,0	0,3	-8,4	-18,3	-38	-51
	Expanded uncertainty	4,8	4,2	3,8	4,2	5,0	10	15

6 Uncertainty of the ac-dc current transfer standards of SP

The measurement uncertainty of the ac-dc transfer standards of SP at the current levels and frequencies required for the EURAMET.EM-K12 key comparison are given in table 4, a detailed analysis is given in appendix A.

Table 4. Expanded uncertainty of the ac-dc transfer difference at 10 mA and 5 A of the standards of SP

	Expanded uncertainty in µA/A at the frequency						
Current	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	2,4	1,6	1,0	1,6	1,6	1,8	2,4
5 A	4,2	3,8	3,6	4,0	4,8	8,4	14

7 Uncertainty of the travelling standard

The ac-dc current transfer difference of the travelling standard δ_T is determined as:

$$\delta_T = \delta_A + \delta_B + \delta_C + \delta_S + \delta_D \quad (1)$$

where

δ_A indicated ac-dc transfer difference between the travelling standard and the standard of SP

δ_B correction for the error in the indicated ac-dc transfer difference due to the measurement set-up, excluding T-connector

δ_C correction for the error in the indicated transfer difference due to the T-connector

δ_S ac-dc transfer difference of the standard

δ_D drift of the standard

The variance of the ac-dc transfer difference $u^2(\delta_T)$ is

$$u^2(\delta_T) = u^2(\delta_A) + u^2(\delta_B) + u^2(\delta_C) + u^2(\delta_S) + u^2(\delta_D) \quad (2)$$

Indicated ac-dc transfer difference (δ_A): The indicated value is the mean of a set of determinations of the ac-dc transfer difference between the standard and the test. The standard uncertainty $u(\delta_A)$ is the standard deviation of the mean. Normal distribution.

Measurement set-up (δ_B): The correction δ_B is estimated to zero. The following sources of uncertainty are considered to contribute to the uncertainty of the correction: non-linearity and resolution of nV-amplifiers and DVMs, non-linearity of the drift in output voltages and back-off voltage sources, the uncertainty in the scale factors and non-ideal guarding. Normal distribution.

T-connector (δ_C): The correction δ_C is estimated to zero. The uncertainty is estimated based on the modelling and measurement of the inductance, capacitance and conductance of the T-connector. Rectangular distribution.

Ac-dc transfer difference of the standard (δ_S): The ac-dc transfer differences of the standard of SP. The standard uncertainty is from the realisation and the step-up procedure. Normal distribution.

Drift of the standard (δ_D): The correction δ_d is estimated to zero. The uncertainty due to the drift of the ac-dc transfer difference is estimated. Rectangular distribution.

The uncertainties due to the following reasons are estimated to be negligible: difference in ac- and dc-current levels, dc-current level, ac-current frequency, reversal errors, non-pure spectra of ac- and dc-sources, common mode currents, switching time and time constants of the transfer standards, external fields, temperature and relative humidity in the laboratory.

The uncertainty budgets of the travelling standards at 10 mA and 5 A are given in table 5 and 6.

Table 5. Uncertainty budget of the travelling standard at 10 mA. The effective degrees of freedom is ≥80.

Quantity	u	Standard uncertainties in μA/A at frequency							Effective degrees of freedom						
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
1:1 comparison															
Ac-dc difference 10 mA	$u(\delta_S)$	1,2	0,8	0,5	0,8	0,8	0,9	1,2	200	200	200	200	200	200	200
Drift of standard	$u(\delta_D)$	0,3	0,2	0,2	0,2	0,3	0,4	0,5	20	20	20	20	20	20	20
Indicated ac-dc difference	$u(\delta_A)$	0,1	0,1	0,1	0,1	0,1	0,1	0,2	4	4	4	4	4	4	4
Measurement set-up	$u(\delta_B)$	1	0,7	0,5	0,5	0,5	0,7	1	20	20	20	20	20	20	20
T-connector	$u(\delta_C)$	0	0	0	0	0	0	0,1	100	100	100	100	100	100	100
Standard uncertainty 10 mA	$u(\delta_T)$	1,6	1,1	0,75	1,0	1,0	1,2	1,7	106	98	85	167	175	130	118
Expanded uncertainty	U = 2u	3,2	2,2	1,5	2,0	2,0	2,4	3,4							

Table 6. Uncertainty budget of the travelling standard at 5 A. The effective degrees of freedom is ≥200.

Quantity	u	Standard uncertainties in μA/A at frequency							Effective degrees of freedom						
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
1:1 comparison															
Ac-dc difference 5 A	$u(\delta_S)$	2,1	1,9	1,8	2,0	2,4	4,5	7,0	200	200	200	200	200	200	200
Drift of standard	$u(\delta_D)$	0,6	0,4	0,4	0,4	0,6	0,8	1,0	20	20	20	20	20	20	20
Indicated ac-dc difference	$u(\delta_A)$	0,1	0,1	0,1	0,2	0,2	0,2	0,3	4	4	4	4	4	4	4
Measurement set-up	$u(\delta_B)$	1	0,7	0,5	0,5	0,5	0,7	1	20	20	20	20	20	20	20
T-connector	$u(\delta_C)$	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Standard uncertainty 5 A	$u(\delta_T)$	2,4	2,1	1,9	2,1	2,5	4,6	7,1	217	232	235	234	234	220	216
Expanded uncertainty	U = 2u	4,8	4,2	3,8	4,2	5,0	10	15							

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A0 Appendix A. Uncertainty analysis of the standards of SP

A1 Introduction

The SP realisation of ac-dc current transfer difference at the primary level 10 mA is based on three different methods depending on the frequency band. At medium frequencies around 1 kHz the realisation is based on the fast reversed dc method (FRDC). Around 1 kHz the ac-dc current transfer difference of a MJTC is assumed to depend only on the dc-effects due to Peltier and Thomson [1]. At low frequencies the ac-ac(1 kHz) transfer difference of MJTC is determined by a special comparison to a resistor with large thermal time constant [2]. At high frequencies the ac-ac(1 kHz) transfer difference of a single junction converter (SJTC) is modelled by its reactive and loss components [3].

For higher currents and frequencies of 1 kHz and higher the ac-dc transfer difference of the number of shunt/PMJTC combinations are determined by a step-up procedure, comparing adjacent ranges. The low frequency behaviour is determined by the ac-ac(1 kHz) transfer difference of the two PMJTCs by the method mentioned above [2] together with the assumption that the shunts do not contribute at frequencies <1 kHz. Earlier some steps have been checked by a measuring system that allows comparison of thermal current converters with a ratio of 2:1 without introducing any error due to level dependence with good agreement at frequencies up to 1 kHz [4].
The level dependence of the ac-ac(1 kHz) transfer difference at low frequencies is proportional to the power in the PMJTC. The level dependence of the ac-ac(1 kHz) transfer difference of the PMJTCs at high frequencies is determined by comparison to SJTCs in both voltage and current mode.

A2 Model of the SJTC ac-ac(1 kHz) current transfer difference at ≥1 kHz

The ac-ac(1 kHz) current transfer difference of a SJTC, δ_{SJTC}, is modelled as:

$$\delta_{SJTC} = \delta_{CGL} + \delta_b + \delta_M \qquad (A1)$$

where

$$\delta_{CGL} = R_h G + \omega^2[0{,}5(R_h C)^2 - LC] \qquad (A2)$$

$$\delta_b = R_h G_b/8 + (\omega R_h C_b)^2/8 \qquad (A3)$$

and

δ_M is correction for the error in the ac-ac(1 kHz) transfer difference due to mismatch
ω angular frequency = 2π*frequency
other symbols according to Fig A1.

The model has been verified by comparison of six TC with different parameters and by PSpice simulation [6].

The variance of the measured ac-dc transfer difference $u^2(\delta_{SJTC})$ is:

$$u^2(\delta_{SJTC}) = u^2(\delta_{CGL}) + u^2(\delta_b) + u^2(\delta_M) \qquad (A4)$$

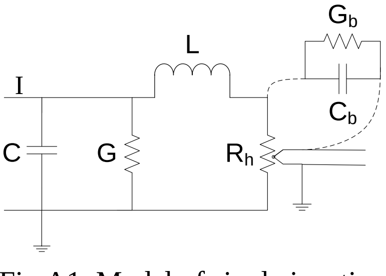


Fig A1. Model of single junction thermal converter for ac-ac(1 kHz) current transfer difference realisation.

A3 Model of the MJTC ac-dc current transfer difference

The measured ac-ac(1 kHz) current transfer difference of the MJTC at frequencies >1 kHz, $\delta_{MJTC>1k}$, is modelled as:

$$\delta_{MJTC>1k} = \delta_A + \delta_B + \delta_C + \delta_{SJTC} \qquad \text{(A5)}$$

where

δ_A indicated ac-ac(1kHz) transfer difference between the standard SJTC and the test MJTC

δ_B correction for the error in the indicated transfer difference due to the measurement set-up, except T-connector

δ_C correction for the error in the indicated transfer difference due to the T-connector

δ_{SJTC} ac-ac(1 kHz) transfer difference of the standard SJTC

and the ac-dc current transfer difference of the MJTC, δ_{MJTC}, is modelled as:

$$\delta_{MJTC} = \delta_{DC} + \delta_{LF} + \delta_{MJTC>1k} \qquad \text{(A6)}$$

where

δ_{DC} is the ac-dc transfer difference of the MJTC due to dc-effects, Peltier and Thomson

δ_{LF} ac-ac(1 kHz) transfer difference of the MJTC due to low frequency effects at frequencies < 1 kHz, which is level dependent

$\delta_{MJTC>1k}$ ac- ac(1 kHz) transfer difference of the MJTC at frequencies >1 kHz

The ac-dc transfer difference of the MJTC due to dc-effects has been measured by FRDC [1]. The ac-ac(1 kHz) transfer difference of the MJTC at frequencies <1 kHz is determined by a special comparison to a resistor with large thermal time constant [2].

The variance of the measured ac-ac(1 kHz) transfer difference $u^2(\delta_{MJTC>1k})$ is

$$u^2(\delta_{MJTC>1k}) = u^2(\delta_A) + u^2(\delta_B) + u^2(\delta_C) + u^2(\delta_{SJTC}) \qquad \text{(A7)}$$

and the variance of the ac-dc transfer difference $u^2(\delta_{MJTC})$ is

$$u^2(\delta_{MJTC}) = u^2(\delta_{DC}) + u^2(\delta_{LF}) + u^2(\delta_{MJTC>1k}) \qquad \text{(A8)}$$

A4 Model of the step-up procedure used for frequencies ≥1 kHz

Starting from the primary level the ac-dc transfer difference of the shunt/PMJTC combinations at frequencies ≥1 kHz are determined by a step-up procedure comparing adjacent ranges.

The ac-dc transfer difference at frequencies ≥1 kHz, $\delta_{T\geq 1kHz}$, of the test shunt/PMJTC at nominal current level is determined as:

$$\delta_{T\geq 1k} = \delta_A + \delta_B + \delta_S + \delta_{LD} \qquad \text{(A9)}$$

where

δ_A indicated ac-dc transfer difference between the standard, MJTC in the first step and then shunt/PMJTC, and the test shunt/PMJTC

δ_B correction for the error in the indicated ac-dc transfer difference due to the measurement set-up, including T-connector

δ_S ac-dc transfer difference of the standard

δ_{LD} correction for the error in the ac-dc transfer difference of the test due to possible level dependence when changing from the current level of the measurement to the nominal current level.

The variance of the ac-dc transfer difference $u^2(\delta_{T\geq 1k})$ is

$$u^2(\delta_{T\geq 1k}) = u^2(\delta_A) + u^2(\delta_B) + u^2(\delta_S) + u^2(\delta_{LD}) \qquad (A10)$$

A5 Model of the ac-dc transfer difference of shunt/PMJTC

The ac-dc transfer difference δ_T of the test shunt/PMJTC is determined as:

$$\delta_T = \delta_{T\geq 1k} + \delta_{LF} \qquad (A11)$$

where

$\delta_{T\geq 1k}$ ac-dc transfer difference the test shunt/PMJTC at nominal current level and frequencies ≥1 kHz

δ_{LF} ac-ac(1 kHz) transfer difference of the PMJTC due to low frequency effects at frequencies < 1 kHz, which depends on the shunt and the level [2]

The variance of the ac-dc transfer difference $u^2(\delta_T)$ is

$$u^2(\delta_T) = u^2(\delta_{T\geq 1k}) + u^2(\delta_{LF}) \qquad (A12)$$

A6 Uncertainty budget

Quantity	u	Standard uncertainties in µA/A at frequency							Effective degrees of freedom						
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Ac-dc current diff realisation, 10 mA															
SJTC at frequencies >1 kHz															
Reactive and loss components	$u(\delta_{CGL})$				0	0	0	0,05						200	200
Heater to couple loss	$u(\delta_{b})$				0	0	0,05	0,1						200	200
Mismatch	$u(\delta_{M})$				0	0	0	0						200	200
Ac-ac(1 kHz) difference SJTC	$u(\delta_{SJTC})$				0,00	0,00	0,05	0,11				200,0	200,0	200,0	294,1
MJTC at frequencies >1 kHz															
Ac-ac(1 kHz) difference SJTC	$u(\delta_{SJTC})$				0,00	0,00	0,05	0,11				200,0	200,0	200,0	294,1
Indicated ac-dc difference	$u(\delta_{A})$				0,2	0,2	0,2	0,3				4	4	4	4
Measurement set-up	$u(\delta_{B})$				0,5	0,5	0,7	1				200	200	200	200
T-connector	$u(\delta_{C})$				0	0	0	0,1				200	200	200	200
Ac-ac(1 kHz) difference MJTC	$u(\delta_{MJTC>1k})$				0,54	0,54	0,73	1,05				118,0	118,0	177,2	176,2
Ac-dc differnce of MJTC															
Ac-ac(1 kHz) difference MJTC	$u(\delta_{MJTC>1k})$				0,54	0,54	0,73	1,05				118,0	118,0	177,2	176,2
Dc-effects	$u(\delta_{DC})$	0,5	0,5	0,5	0,5	0,5	0,5	0,5	200	200	200	200	200	200	200
Low frequency effects	$u(\delta_{LF})$	1	0,5						200	200					
Ac-dc differnce of MJTC	$u(\delta_{MJTC})$	1,12	0,71	0,50	0,73	0,73	0,88	1,17	294,1	400,0	200,0	284,5	284,5	320,1	253,0
Standard uncertainty 10 mA	$\mathbf{u(\delta_{10mA})}$	**1,2**	**0,8**	**0,5**	**0,8**	**0,8**	**0,9**	**1,2**	**294**	**400**	**200**	**284**	**284**	**320**	**253**
From 10 mA to 20mA															
1:1 comparison															
Ac-dc difference MJTC 10 mA	$u(\delta_{S})$			0,5	0,8	0,8	0,9	1,2			200	284	284	320	253
Indicated ac-dc difference	$u(\delta_{A})$			0,2	0,2	0,3	0,5	0,5			2	2	2	2	2
Measurement set-up	$u(\delta_{B})$			0,5	0,5	0,5	0,7	1			100	100	100	100	100
Level dependence	$u(\delta_{LD})$			0	0	0	0	0			20	20	20	20	20
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	0,73	0,73	0,73	0,96	0,99	1,24	1,64	167,8	167,8	167,8	301,6	157,0	67,3	146,3
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 20 mA	$u(\delta_{T})$	1,24	0,89	0,73	0,96	0,99	1,24	1,64	352,0	304,4	167,8	301,6	157,0	67,3	146,3
Standard uncertainty 20 mA	$\mathbf{u(\delta_{20mA})}$	**1,3**	**0,9**	**0,8**	**1,0**	**1,0**	**1,3**	**1,7**	**352**	**304**	**167**	**301**	**157**	**67**	**146**

Quantity	u	Standard uncertainties in µA/A at frequency							Effective degrees of freedom						
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
From 20 mA to 50mA															
1:1 comparison															
Ac-dc difference 20 mA	$u(\delta_S)$			0,8	1,0	1,0	1,3	1,7			167,0	301,0	157,0	67,0	146,0
Indicated ac-dc difference	$u(\delta_A)$			0,2	0,2	0,3	0,5	0,5			2	2	2	2	2
Measurement set-up	$u(\delta_B)$			0,5	0,5	0,5	0,7	1			50	50	50	50	50
Level dependence	$u(\delta_{LD})$			0	0	0	0	0			20	20	20	20	20
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	0,96	0,96	0,96	1,14	1,16	1,56	2,03	192,1	192,1	192,1	309,8	153,9	75,0	158,0
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 50 mA	$u(\delta_T)$	1,39	1,09	0,96	1,14	1,16	1,56	2,03	392,0	289,2	192,1	309,8	153,9	75,0	158,0
Standard uncertainty 50 mA	$\mathbf{u(\delta_{50mA})}$	**1,4**	**1,1**	**1,0**	**1,2**	**1,2**	**1,6**	**2,1**	**392**	**289**	**192**	**309**	**153**	**75**	**158**
From 50 mA to 100mA															
1:1 comparison															
Ac-dc difference 50 mA	$u(\delta_S)$			1,0	1,2	1,2	1,6	2,1			192	309	153	75	158
Indicated ac-dc difference	$u(\delta_A)$			0,2	0,2	0,3	0,5	0,5			2	2	2	2	2
Measurement set-up	$u(\delta_B)$			0,5	0,5	0,5	0,7	1			20	20	20	20	20
Level dependence	$u(\delta_{LD})$			0	0	0	0	0			20	20	20	20	20
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	1,14	1,14	1,14	1,32	1,33	1,82	2,38	182,2	182,2	182,2	281,4	152,9	83,4	156,8
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 100 mA	$u(\delta_T)$	1,51	1,24	1,14	1,32	1,33	1,82	2,38	371,0	251,1	182,2	281,4	152,9	83,4	156,8
Standard uncertainty 100 mA	$\mathbf{u(\delta_{100mA})}$	**1,6**	**1,3**	**1,2**	**1,4**	**1,4**	**1,9**	**2,4**	**371**	**251**	**182**	**281**	**152**	**83**	**156**
From 100 mA to 200mA															
1:1 comparison															
Ac-dc difference 100 mA	$u(\delta_S)$			1,2	1,4	1,4	1,9	2,4			182	281	152	83	156
Indicated ac-dc difference	$u(\delta_A)$			0,2	0,2	0,3	0,7	1,0			2	2	2	2	2
Measurement set-up	$u(\delta_B)$			0,5	0,5	0,5	0,7	1			20	20	20	20	20
Level dependence	$u(\delta_{LD})$			0	0	0	0	0			20	20	20	20	20
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	1,32	1,32	1,32	1,50	1,52	2,14	2,79	195,4	195,4	195,4	287,7	163,0	72,9	79,0
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 200 mA	$u(\delta_T)$	1,65	1,41	1,32	1,50	1,52	2,14	2,79	366,8	250,8	195,4	287,7	163,0	72,9	79,0
Standard uncertainty 200 mA	$\mathbf{u(\delta_{200mA})}$	**1,7**	**1,5**	**1,4**	**1,5**	**1,6**	**2,2**	**2,8**	**366**	**250**	**195**	**287**	**163**	**72**	**79**

Quantity	u	Standard uncertainties in µA/A at frequency							Effective degrees of freedom						
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
From 200 mA to 500mA															
1:1 comparison															
Ac-dc difference 200 mA	$u(\delta_S)$			1,4	1,5	1,6	2,2	2,8			195,0	287,0	163,0	72,0	79,0
Indicated ac-dc difference	$u(\delta_A)$			0,2	0,2	0,3	0,7	1,0			2	2	2	2	2
Measurement set-up	$u(\delta_B)$			0,5	0,5	0,5	0,7	1			20	20	20	20	20
Level dependence	$u(\delta_{LD})$			0	0,05	0,1	0,25	0,5			200	200	200	200	200
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	1,50	1,50	1,50	1,59	1,71	2,43	3,18	214,3	214,3	214,3	299,8	178,7	75,6	76,6
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 500 mA	$u(\delta_T)$	1,80	1,58	1,50	1,59	1,71	2,43	3,18	369,0	261,1	214,3	299,8	178,7	75,6	76,6
Standard uncertainty 500 mA	$\mathbf{u(\delta_{500mA})}$	**1,8**	**1,6**	**1,5**	**1,6**	**1,8**	**2,5**	**3,2**	**369**	**261**	**214**	**299**	**178**	**75**	**76**
From 500 mA to 1 A															
1:1 comparison															
Ac-dc difference 500 mA	$u(\delta_S)$			1,5	1,6	1,8	2,5	3,2			214	299	178	75	76
Indicated ac-dc difference	$u(\delta_A)$			0,2	0,2	0,3	0,7	1,0			2	2	2	2	2
Measurement set-up	$u(\delta_B)$			0,5	0,5	0,5	0,7	1			20	20	20	20	20
Level dependence	$u(\delta_{LD})$			0	0,1	0,2	0,5	1			200	200	200	200	200
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	1,59	1,59	1,59	1,69	1,90	2,73	3,64	233,9	233,9	233,9	316,5	198,1	85,7	90,6
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 1 A	$u(\delta_T)$	1,88	1,67	1,59	1,69	1,90	2,73	3,64	384,6	279,1	233,9	316,5	198,1	85,7	90,6
Standard uncertainty 1 A	$\mathbf{u(\delta_{1A})}$	**1,9**	**1,7**	**1,6**	**1,7**	**1,9**	**2,8**	**3,7**	**384**	**279**	**233**	**316**	**198**	**85**	**90**
From 1 A to 2 A															
1:1 comparison															
Ac-dc difference 1 A	$u(\delta_S)$			1,6	1,7	1,9	2,8	3,7			233	316	198	85	90
Indicated ac-dc difference	$u(\delta_A)$			0,2	0,2	0,3	0,7	1,0			2	2	2	2	2
Measurement set-up	$u(\delta_B)$			0,5	0,5	0,5	0,7	1			20	20	20	20	20
Level dependence	$u(\delta_{LD})$			0	0,2	0,4	1	2			200	200	200	200	200
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	1,69	1,69	1,69	1,79	2,03	3,13	4,44	253,4	253,4	253,4	341,5	231,0	112,1	142,9
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 2 A	$u(\delta_T)$	1,96	1,76	1,69	1,79	2,03	3,13	4,44	400,0	296,9	253,4	341,5	231,0	112,1	142,9
Standard uncertainty 2 A	$\mathbf{u(\delta_{2A})}$	**2,0**	**1,8**	**1,7**	**1,8**	**2,1**	**3,2**	**4,5**	**400**	**296**	**253**	**341**	**231**	**112**	**142**

Quantity	u	Standard uncertainties in µA/A at frequency							Effective degrees of freedom						
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
From 2 A to 5 A															
1:1 comparison															
Ac-dc difference 2 A	$u(\delta_S)$			1,7	1,8	2,1	3,2	4,5			253,0	341,0	231,0	112,0	142,0
Indicated ac-dc difference	$u(\delta_A)$			0,2	0,2	0,3	0,7	1,0			2	2	2	2	2
Measurement set-up	$u(\delta_B)$			0,5	0,5	0,5	0,7	1			20	20	20	20	20
Level dependence	$u(\delta_{LD})$			0,05	0,5	1	2,5	5			200	200	200	200	200
Ac-dc difference frequency ≥1 kHz	$u(\delta_{T\geq 1k})$	1,78	1,78	1,78	1,94	2,40	4,18	6,87	274,2	274,2	274,2	408,0	343,1	241,5	340,2
Low frequency effects	$u(\delta_{LF})$	1	0,5	0	0	0	0	0	200	200					
Ac-dc diff shunt/PMJTC 5 A	$u(\delta_T)$	2,05	1,85	1,78	1,94	2,40	4,18	6,87	417,1	316,3	274,2	408,0	343,1	241,5	340,2
Standard uncertainty 5 A	$\mathbf{u(\delta_{5A})}$	**2,1**	**1,9**	**1,8**	**2,0**	**2,4**	**4,2**	**6,9**	**417**	**316**	**274**	**408**	**343**	**241**	**340**

A7 Summary of uncertainty budget

		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Expanded uncertainty 10 mA	U = 2u	2,4	1,6	1,0	1,6	1,6	1,8	2,4
Expanded uncertainty 5 A	U = 2u	4,2	3,8	3,6	4,0	4,8	9	14
Effective degrees of freedom 10 mA		>200	>200	>200	>200	>200	>200	>200
Effective degrees of freedom 5 A		>200	>200	>200	>200	>200	>200	>200

EURAMET.EM–K12

Comparison of AC – DC Current Transfer Standards

BEV – Report

Institute: BEV
Federal Office of Metrology and surveying
Vienna, AUSTRIA
Acting as pilot laboratory

By: M.Garcocz and G.Heine

Date: March 2015

Measurements performed in:
May, August and December 2012
April and August 2014 and January 2015

The measurements dated April 2014 have been taken as the official participation of BEV in this comparison.

1. Definition of the Measurand

Ac-dc current transfer difference is defined as

$$d = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

where

I_{ac} is an rms ac current, and

I_{dc} is a dc current which, when reversed, produces the same mean output response as the rms ac current.

Differences are expressed in microamperes per ampere (μA/A) and a positive sign signifies that more ac than dc current was required for the same output response.

2. Travelling Standards

The travelling standard for the current of 10 mA is a Planar Multi-Junction Thermal Converter (PMJTC), Type PTP/IPHT Serial Number PTC 19 (replacement of PTC 17), manufactured by IPHT Jena. It has the following nominal parameters:

Rated Input Current:	10 mA
Heater Resistance:	90 Ω
Thermocouple Resistance:	7.6 k Ω
Output Voltage at Rated Current:	approx. 100 mV

The Thermal Converter has a type N (female) input connector and a type Cannon 10SL-4S (male) output connector. An internal capacitance of 2.2 µF is soldered in parallel to the output.

The 5 ampere travelling standard comprises a 147 mΩ coaxial shunt (Serial No B3A) connected in parallel to the PMJTC (Serial No PTC 19 as described above). The main parameters are as follows:

Current Shunt, Serial No B3A:

Nominal Resistance	147 mΩ
Input Connector	type N (female)
Output Connector	type N (male)

3. Ambient Conditions

Room temperature: 23°C ± 1°C

Relative Humidity: 45% ± 10%

4. BEV- Standards

10 mA - Low Frequency:

In the frequency range from 10 Hz to 1 kHz a PMJTC (S.N."PTC10"; 93.1 Ohms; manufactured at IPHT Germany) was used as standard.

10 mA - High Frequency:
In the frequency range from <1 kHz to 100 kHz a Single Junction Thermal Converter ("SJb19", 27.8 Ohms, manufactured at Best U.S.A.) has been used to determine the High- Frequency response.

5A:
In the frequency range from 10 Hz to 100 kHz a combination of a PMJTC (S.N."PTC10"; 93.1 Ohms; manufactured at IPHT Germany) and a parallel Resistor (S.N.“B4A”; 109 mΩ; manufactured at BEV, Austria) has been used as standards.

5) Traceability

The primary value at the level 10 mA for AC/DC current at BEV is considered as an own independent value and has been evaluated in three steps:

1) Determination of the frequency independent thermo-electric effects:
   A FRDC- source has been rent from METAS, Switzerland, and both U-TE and I-TE effects of different thermal converters were measured [1].

2) Determination of the Low Frequency errors in the range 10 Hz to 1 kHz:
   The Low Frequency behaviour of two PMJTC’s with series- and parallel-resistors was determined using [2].

3) Determination of the High Frequency errors in the range >1 kHz to 1 MHz:
   A model has been developed which includes all known sources of error to calculate the High Frequency errors of two Single Junction Converters. Measurements have been performed to evaluate the model – parameters [3].

A Stepup with home- made shunts combined PMJTC’s was used then to determine the ac-dc transfer difference for currents up to 100 A.

6) Measurement setup

A Low Capacitive Tee connector has been fabricated to connect the travelling standards with the standards of BEV at both current levels (Picture 1).


Picture1: coaxial tee connector

Two different measurement- circuits were used for Low- respectively High frequencies:
The circuit for frequencies up to 1 kHz includes a filter at the output of the converters.

Both outputs of the converters are grounded.
The circuit for frequencies < 1 kHz is a potential driven circuit as shown in Figure 1.
The nanovoltmeters are connected to the PC via a fibre optic link.

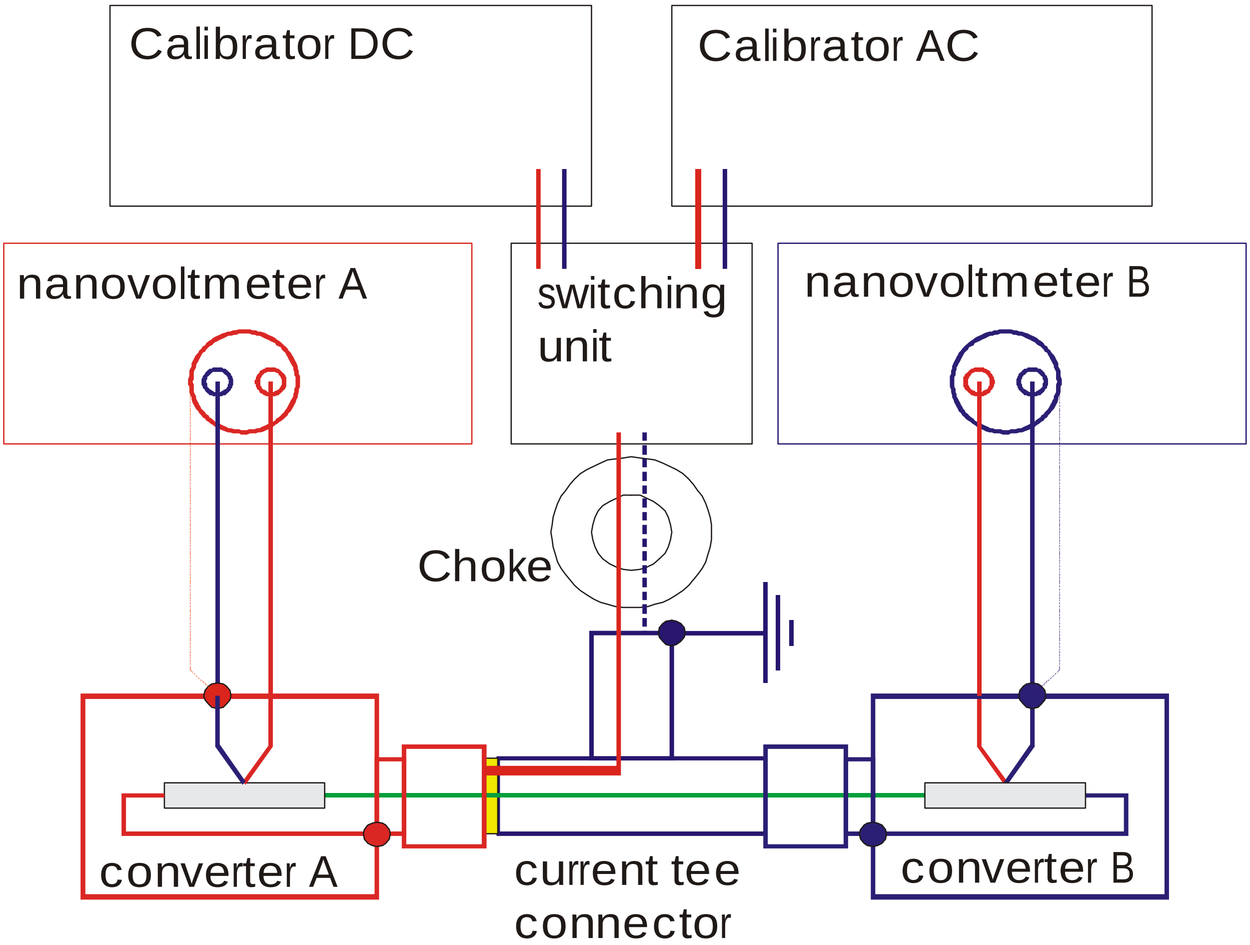


Figure 1: potential driven measurement circuit

<u>Instruments used:</u>

Calibrators:	Fluke 5700
	Datron 4808
Nanovoltmeters:	Keithley 182
Amplifier:	Clarce & Hess 8100
GPIB-isolators:	I/O-Tech 488F
Transferswitch:	BEV < 5ms, 1000 V, AC/DC and polarity
Filter:	BEV, 10 Hz to 40 Hz, 3-stage double Twin,180 dB
Software:	BEV, MS-Visual Basic

6) Measurement procedure

The measurements have been performed automatically, controlled by a PC with a home-made software.
Sensitivity coefficient: has been measured at the beginning of the comparison for both thermal converters in the whole used current- range. Both values were put into the software at the beginning of each measurement.
Warm-up time: more than 60 min with nominal current
The AC current was fitted to the mean of DC current of both polarities for equal output response of the TC within better than 20 µA/A.

The measurement sequence was AC1 - DC plus - DC minus - AC2. A minimum of 20 measurements per point were conducted.
At the current level 10 mA the calibrators acted in voltage mode. The proper voltage level to achieve 10 mA through the converters was computed; no amplifier was used.

After completing the measurements the software calculates mean and standard-deviation for each point. All single readings are stored in a text-file for later corrections, if necessary.

7) Measurement results

The AC/DC current transfer difference in µA/A is:

	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	6,4	0,1	0,3	0,5	0,7	1,3	2,1
5 A	1	0	0	-11	-21	-37	-49

8) Measurement uncertainty

The measurement uncertainty for a confidence level of 95 % in µA/A is:

	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	2,2	2,2	2,2	2,2	2,4	2,6	3,4
5 A	2	2	2	9	9	10	13

9) Uncertainty calculation

Uncertainty budgets for 10 mA and 5 A for the travelling standards:

Measurement Current : 10 mA

frequency [Hz]	BEV basic value 10 mA	Std. Dev.	T-Connect	Reprod ucability	NVM 1	NVM 2	sensi tivity	different NVM	DC effects	sum k=1	sum k=2
	normal	normal	rect.	rect.	rect.	rect.	rect.	rect.	rect.		
	∞	39	∞	∞	∞	∞	∞	∞	∞		
10	0.50	0.26	0.00	0.29	0.52	0.63	0.00	0.00	0.29	**1.1**	**2.2**
55	0.50	0.26	0.00	0.29	0.52	0.63	0.00	0.00	0.29	**1.1**	**2.2**
1000	0.50	0.26	0.00	0.29	0.52	0.63	0.00	0.00	0.29	**1.1**	**2.2**
10000	0.45	0.26	0.00	0.29	0.52	0.63	0.00	0.00	0.29	**1.1**	**2.2**
20000	0.45	0.26	0.06	0.29	0.52	0.63	0.00	0.46	0.29	**1.2**	**2.4**
50000	0.45	0.26	0.09	0.29	0.52	0.63	0.00	0.69	0.29	**1.3**	**2.6**
100000	0.45	0.26	0.14	0.29	0.52	0.63	0.00	1.27	0.29	**1.7**	**3.4**

Measurement Current : 5 A

frequency [Hz]	BEV basic value 5.0 A	Std. Dev.	T-Connect	Reprod ucability	NVM 1	NVM 2	sensi tivity	different NVM	DC effects	sum k=1	sum k=2
	normal	normal	rect.	rect.	rect.	rect.	rect.	rect.	rect.		
	∞	39	∞	∞	∞	∞	∞	∞	∞		
10	0.27	0.25	0.00	0.29	0.17	0.77	0.00	0.00	0.29	**1.0**	**2.0**
55	0.27	0.25	0.00	0.29	0.17	0.77	0.00	0.00	0.29	**1.0**	**2.0**
1000	0.27	0.25	0.00	0.29	0.17	0.77	0.00	0.00	0.29	**1.0**	**2.0**
10000	4.34	0.25	0.00	0.29	0.17	0.77	0.01	0.00	0.29	**4.5**	**9.0**
20000	4.34	0.25	0.00	0.29	0.17	0.77	0.02	0.46	0.29	**4.5**	**9.0**
50000	4.60	0.25	0.00	0.29	0.17	0.77	0.06	0.69	0.29	**4.8**	**9.6**
100000	6.05	0.25	0.00	0.29	0.17	0.77	0.10	1.27	0.29	**6.3**	**12.6**

10) Additional parameters:

Measurement Frequency:

	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. Frequency in Hz	10.0001	54.999	1000.004	10000.04	20000.08	50000.1	100000.4
Expanded Uncertainty in Hz	0.0001	0.0005	0.01	0.1	0.2	0.5	1

Environmental parameters:

	Min	Max	Remarks
Ambient temperature in ºC	22.4	23.6	
Relative humidity in %	42	52	

Uncertainty calculation for the Stepup scheme from 10 mA to 5 A:

frequency [Hz]	**basis**	**Std. Dev.**	**T-con.**	**Rep.-duc.**	**NVM 1**	**NVM 2**	**sensi-tivity**	**diff. NVM**	**DC eff.**	**sum k=1**	
	norm	**norm**	**rect.**	**rect.**	**rect.**	**rect.**	**rect.**	**rect.**	**rect.**	**norm**	
		19									**effective degrees of freedom**
Step 1: (PTC10)-(SJb19)											
10000	0.45	0.42	0.00	0.29	0.52	0.39	0.17	0.00	0.29	**1.19**	1175
20000	0.45	0.42	0.00	0.29	0.52	0.39	0.17	0.00	0.29	**1.19**	1175
50000	0.45	0.42	0.06	0.29	0.52	0.39	0.17	0.46	0.29	**1.28**	1561
100000	0.45	0.42	0.23	0.29	0.52	0.39	0.17	1.27	0.29	**1.76**	5560
Step 2: (PTC10)-(PTC11+B20mA)											
10000	1.19	0.40	0.00	0.29	0.39	0.36	0.15	0.00	0.29	**1.53**	3929
20000	1.19	0.40	0.00	0.29	0.39	0.36	0.15	0.00	0.29	**1.53**	3929
50000	1.28	0.40	0.06	0.29	0.39	0.36	0.15	0.46	0.29	**1.66**	5526
100000	1.76	0.40	0.14	0.29	0.39	0.36	0.15	1.27	0.29	**2.37**	22962
Step 3: (PTC11+B20mA)-(PTC10+B30mA)											
10000	1.53	0.36	0.00	0.29	0.18	0.64	0.15	0.00	0.29	**1.88**	14442
20000	1.53	0.36	0.00	0.29	0.18	0.64	0.15	0.00	0.29	**1.88**	14442
50000	1.66	0.36	0.00	0.29	0.18	0.64	0.15	0.46	0.29	**2.04**	20220
100000	2.37	0.36	0.06	0.29	0.18	0.64	0.15	1.27	0.29	**2.91**	82761
Step 4: (PTC10+B30mA)-(PTC11+B50mA)											
10000	1.88	0.36	0.00	0.29	0.56	0.20	0.15	0.00	0.29	**2.13**	23960
20000	1.88	0.36	0.00	0.29	0.56	0.20	0.15	0.00	0.29	**2.13**	23960
50000	2.04	0.36	0.00	0.29	0.56	0.20	0.15	0.46	0.29	**2.32**	33884
100000	2.91	0.36	0.00	0.29	0.56	0.20	0.15	1.27	0.29	**3.33**	142309
Step 5: (PTC11+B50mA)-(PTC10+B100mA)											
10000	2.13	0.34	0.00	0.29	0.28	0.56	0.15	0.00	0.29	**2.37**	47604
20000	2.13	0.34	0.00	0.29	0.28	0.56	0.15	0.00	0.29	**2.37**	47604
50000	2.32	0.34	0.00	0.29	0.28	0.56	0.15	0.46	0.29	**2.59**	67480
100000	3.33	0.34	0.00	0.29	0.28	0.56	0.15	1.27	0.29	**3.71**	284932
Step 6: (PTC10+B100mA)-(PTC11+B200mA)											
10000	2.37	0.42	0.00	0.29	0.45	0.25	0.15	0.00	0.29	**2.55**	24839
20000	2.37	0.42	0.00	0.29	0.45	0.25	0.15	0.00	0.29	**2.55**	24839
50000	2.59	0.42	0.00	0.29	0.45	0.25	0.15	0.46	0.29	**2.80**	35599
100000	3.71	0.42	0.00	0.29	0.45	0.25	0.15	1.27	0.29	**4.04**	154664

frequency [Hz]	basis	Std. Dev.	T-con.	Rep.-duc.	NVM 1	NVM 2	sensi-tivity	diff. NVM	DC eff.	sum k=1	
	norm	norm	rect.	rect.	rect.	rect.	rect.	rect.	rect.	norm	
		19									effective degrees of freedom
Step 7: (PTC11+B200mA)-(PTC10+B300mA)											
10000	2.55	0.34	0.00	0.29	0.16	0.49	0.15	0.00	0.58	**2.76**	87092
20000	2.55	0.34	0.00	0.29	0.16	0.49	0.15	0.00	0.58	**2.76**	87092
50000	2.80	0.34	0.00	0.29	0.16	0.49	0.15	0.46	0.58	**3.02**	124773
100000	4.04	0.34	0.00	0.29	0.16	0.49	0.15	1.27	0.58	**4.36**	541315
Step 8: (PTC10+B300mA)-(PTC11+B500mA)											
10000	2.76	0.58	0.00	0.29	0.45	0.17	0.16	0.00	0.87	**3.05**	14306
20000	2.76	0.58	0.00	0.29	0.45	0.17	0.16	0.00	0.87	**3.05**	14306
50000	3.02	0.58	0.00	0.29	0.45	0.17	0.16	0.46	0.87	**3.31**	20079
100000	4.36	0.58	0.00	0.29	0.45	0.17	0.16	1.27	0.87	**4.72**	82409
Step 9: (PTC11+B500mA)-(PTC10+B1A)											
10000	3.05	0.36	0.00	0.29	0.24	0.45	0.15	0.00	0.87	**3.28**	134609
20000	3.05	0.36	0.00	0.29	0.24	0.45	0.15	0.00	0.87	**3.28**	134609
50000	3.31	0.36	0.00	0.29	0.24	0.45	0.15	0.46	0.87	**3.56**	187057
100000	4.72	0.36	0.00	0.29	0.24	0.45	0.15	1.27	0.87	**5.04**	746568
Step 10: (PTC10+B1A)-(PTC11+B2A)											
10000	3.28	0.49	0.00	0.29	0.43	1.18	0.15	0.00	1.15	**3.95**	78916
20000	3.28	0.49	0.00	0.29	0.43	1.18	0.15	0.00	1.15	**3.95**	78916
50000	3.56	0.49	0.00	0.29	0.43	1.18	0.15	0.46	1.15	**4.21**	102058
100000	5.04	0.49	0.00	0.29	0.43	1.18	0.15	1.27	1.15	**5.64**	328253
Step 11: (PTC11+B2A)-(PTC10+B4A)											
10000	3.95	0.27	0.00	0.29	0.05	0.15	0.15	0.00	1.73	**4.34**	1299144
20000	3.95	0.27	0.00	0.29	0.05	0.15	0.15	0.00	1.73	**4.34**	1299144
50000	4.21	0.27	0.00	0.29	0.05	0.15	0.15	0.46	1.73	**4.60**	1644220
100000	5.64	0.27	0.00	0.29	0.05	0.15	0.15	1.27	1.73	**6.05**	4923813

[1] M. Klonz, T. Spiegel, R. Zirpel, B.D. Inglis, G. Hammond, H. Sasaki, K. Takahashi and B. Stojanovic, “Measuring thermoelectric effects in thermal converters with a fast reversed dc”, *IEEE Trans. Instrum. Meas.,* Vol. 44, pp. 379–382, Apr. 1995.

[2] K.-E. Rydler, V. Tarasso, “A method to determine the low frequency behaviour of thermal converters”, CPEM Conference Digest, p. 358 (2002).

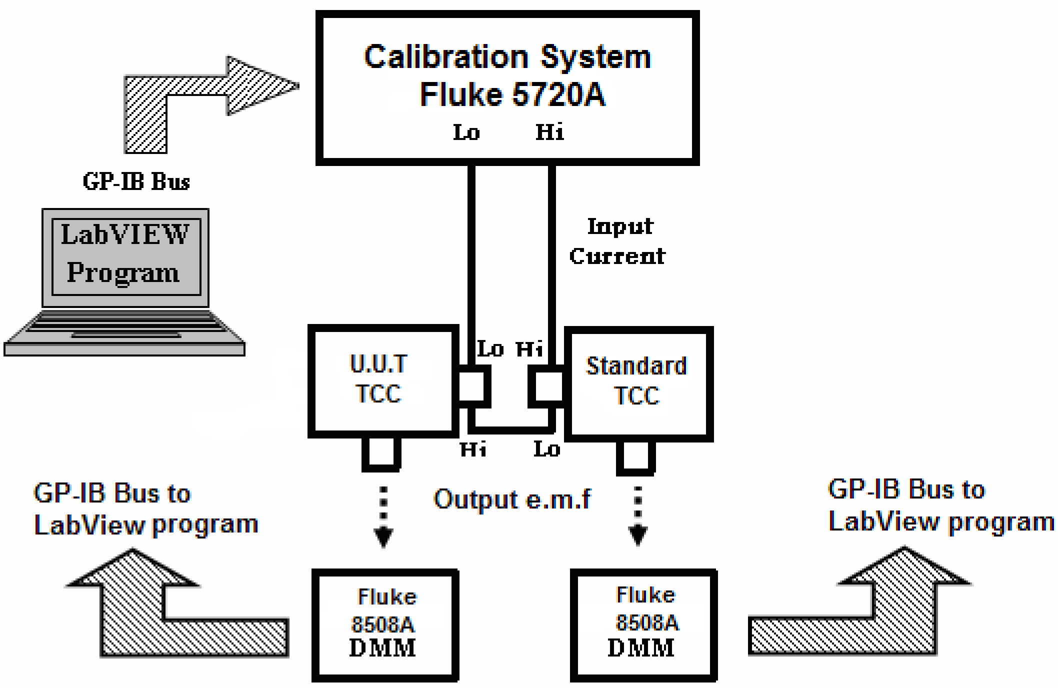
[3] M. Garcocz, G. Heine: “AC-DC Current Transfer Difference at BEV”, Conf. proc. CPEM’08, p.32-33

EURAMET Key International Comparison of AC-DC Current Transfer Standards
EURAMET.EM-K12

Institute: National Institute for Standards (NIS), Egypt

Date of measurements: 5th June 2014 to 3rd July 2014

1. Measurement Setup:



New program using labVIEW software has been performed to automatically calibrate the unit under test (U.U.T) Thermal Current Converter (TCC). A simplified schematic diagram of the automated calibration system is shown in the figure. This system consists of a highly accurate (Fluke 5720A) programmable Calibration System to precisely source both alternating and direct currents, and two devices with similar rating current TCCs; the first is the reference standard TCC and the second is the U.U.T are connected in series. In addition, two similar recently calibrated high sensitive 8.5 digits (Fluke 8508A) digital multimeters to measure the output emfs of the two devices.

2. Reference Standards:

For 10 mA:

The reference standard is multijunction thermal converter. Its rating is 1 V, 10 mA. It is manufactured at PTB, Germany.

For 5 A:

The reference standard is single junction thermal converter connected in parallel with current shunt. Its rating is 5A. It is manufactured at PTB, Germany.

3. Definition of the Measurand:

At each frequency from 10 Hz to 10 kHz, the ac-dc difference measurements are made by recording the output emfs of the two devices at the same sequence of inputs: ac, dc^+, dc^-, ac for the U.U.T TCC. Twenty ac-dc differences have been computed at equal intervals of input currents at the rated value. Noting that, 30 minutes warming up for the 10 mA TCC, and 1 hr. for the 5 A TCC are elapsed by the LabVIEW program at the beginning. In addition, 60 seconds for the settling time before recording the emfs from the two DMMs. The ac-dc difference of each TCC (δt) at each frequency is calculated from the equation:

$$\delta_t = \frac{E_{as} - E_{ds}}{n_s E_{ds}} - \frac{E_{at} - E_{dt}}{n_t E_{dt}} + \delta_s \qquad (1)$$

Where, δ_s is the ac-dc transfer difference of the reference standard unit, E_{as} and E_{at} are the output emfs for the ac input current while, E_{ds} and E_{dt} are the mean emf values for forward (dc^+) and reverse (dc^-) test currents for the standard and the U.U.T respectively. n_s and n_t are the n-factor of the standard and the U.U.T TCCs.

4. Description of the Measurement Procedures:

1. Connect the circuit as shown in the Figure.

2. Wait 30 min. for range 10 mA, and 1 hr. for range 5A to warm up the TCCs.

3. Apply the r.m.s value of the rating ac current to the input terminals of the standard TCC and the U.U.T TCC. Wait the settling time before recording the results from the both DMM's and then record the output e.m.f.

4. Apply the positive value of the current of the stable dc source to the input terminal of the standard TCC and the U.U.T TCC. Also wait the settling time before recording the results from the both DMM's.

5. By reversing the polarity of the dc source currents, the negative value of the current of the stable dc source is applied to the input terminal of the standard TCC and the U.U.T TCC. Also wait the settling before recording the results from the both DMM's.

6. The r.m.s value of current is applied again to the input terminal of the TCCs and records the outputs.

7. The values of ac-dc difference (δ_t) of the U.U.T TCC is determined from equation (1).

8. Repeat the steps from 3 to 7 for 20 times and calculate the ac-dc difference (δ_t) for each time and take the average.

5. Traceability:

Our standards are traceable to PTB, Germany.

6. Measurement Results:

Current	Measured ac-dc current difference (*m*A/A) at frequency			
	10 Hz	55 Hz	1 kHz	10 kHz
10 mA	3.92	0.39	1.3	1.77
5A	-------	1.07	5.38	12.64

Expanded Uncertainty:

Current	Expanded Uncertainty (*m*A/A) at frequency			
	10 Hz	55 Hz	1 kHz	10 kHz
10 mA	7.4	7.2	7.2	7.2
5A	------	28.4	28.2	28.2

7. Environmental Conditions:

It was highly considered during the calibration that the interferences from high field strengths were completely avoided. Also, temperature and relative humidity of the calibration laboratory were adjusted and fairly controlled to (23 ±1) °C and (50% ± 5%) respectively.

8. Complete Uncertainty Budget:

10 mA at 10 Hz frequency as an example

Uncertainty Sources	Standard Uncertainty, (*m*A/A)	Probability distribution	Divider	C_i	Degree of Freedom	Uncertainty contribution, (*m*A/A)
Repeatability	1.03	Normal	1	1	19	1.03
Standard TCC Calibration	2	Normal	2	1	∞	1
DC Current Calibration	3.6	Normal	2	1	∞	1.8
Level Dependence	0.5	Rectangular	$\sqrt{3}$	1	∞	0.29
Connectors	5	Rectangular	$\sqrt{3}$	1	∞	2.9
Freq. Calibration	0.18	Normal	2	1	∞	0.09
Combined standard uncertainty:						±3.7 (*m*A/A)
Effective degrees of freedom:						∞
Expanded Uncertainty at confidence level 95%, **(k = 2)**:						±7.4 (*m*A/A)

LNE report on EURAMET EM-K12 comparison
« AC-DC current transfer »

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Contents :

LNE report on EURAMET EM-K12 comparison

1 Introduction :

From August 20th to September 16th, LNE performed measurements in the frame of the EURAMET EM-K12 comparison on current AC-DC thermal converters. These measurements consisted in the calibration of the travelling standards against LNE reference standards. The travelling standards were :

- a planar multijunction thermal converter, serial number PTC 19, developed by PTB and manufactured by IPHT Jena, for measurement at a current of 10 mA;
- the planar multijunction thermal converter, serial number PTC 19, connected in parallel with a 147 mΩ coaxial shunt, serial number B3A, for measurement at a current of 5 A. The shunt has been manufactured at BEV.

These standards have been provided by BEV.

2 Definition of the measurand :

The quantity to be measured is the AC-DC current transfer difference of the travelling standards. This quantity, noted *d*, is defined as :

$$d = \frac{I_{AC} - I_{DC}}{I_{DC}} \qquad (1)$$

where :

- I_{AC} is an RMS AC current applied to the thermal converter ;
- I_{DC}, the DC current which, when reversed, produces the same output response of the thermal converter as I_{AC}.

AC-DC current differences are expressed in microamperes per ampere (µA/A) and a positive sign signifies that more AC current than DC current was required for the same output response.

Measurements had to be performed under currents of 10 mA and 5 A at frequencies of 10 Hz, 55 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz.

3 AC-DC current transfer standards of LNE :

The AC-DC current transfer standards of LNE are two PTB-IPHT 10 mA planar multijunction thermal converters, each of them associated with a set of shunts covering all the domain up to 20 A. These shunts have been developed and manufactured by the Norwegian National Metrology Institute JV [1].

The AC-DC difference of the LNE standards has been determined by a step-up procedure consisting in calibrating each standard against a standard already calibrated and then using it as the reference standard to calibrate an other standard in the next step of the procedure. In this procedure, each standard is calibrated at a current lower than its nominal current and then used at its nominal current in the next step. The starting point of the step-up is a 3-D PTB multijunction converter which AC-DC difference has been established from [2].

4 Measuring system :

The diagram of the measuring system used at LNE to calibrate AC-DC current thermal converters is given in figure 1.

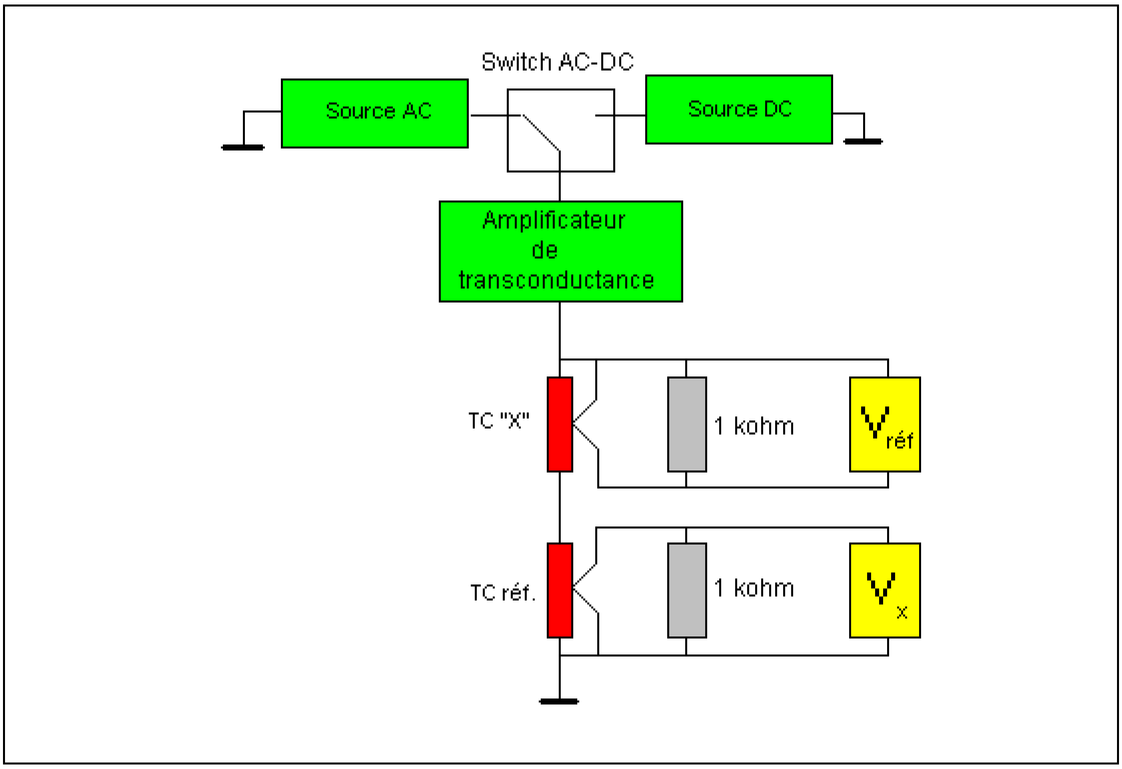

Figure 1 : Diagram of the measuring system used to calibrate AC-DC current thermal converters.

The converters to compare are connected in series at the output of a transconductance amplifier whose input can be connected to an AC or a DC voltage source by means of a switch. Two precision nano-voltmeters measure directly the output voltages of the converters, each of them loaded by a 1 kΩ resistor. The result of the calibration is given by :

$$Y = d_x - d_{réf} = \frac{1}{n_{réf}} \cdot \left[\frac{2.V_{réf,a}}{V_{réf,c+} + V_{réf,c-}} - 1 \right] - \frac{1}{n_x} \cdot \left[\frac{2.V_{x,a}}{V_{x,c+} + V_{x,c-}} - 1 \right] \qquad (2)$$

where :

- d_x is the AC-DC difference of the converter to calibrate;
- d_{ref}, the AC-DC difference of the reference converter ;
- n_{ref} and n_x, characteristic constants of the reference converter and of the device under test ;
- $V_{réf,a}$ and $V_{x,a}$, voltages measured by voltmeters V_{ref} and V_x when the converters are supplied by an AC current ;
- $V_{réf,c+}$ and $V_{x,c+}$, voltages measured by voltmeters V_{ref} and V_x when the converters are supplied by a DC current in the positive polarity ;
- $V_{réf,c-}$ and $V_{x,c-}$, voltages measured by voltmeters V_{ref} and V_x when the converters are supplied by a DC current in the negative polarity ;

The calibration procedure is as follows :

AC and DC currents are successively applied to the converters in the sequence AC, DC+, DC- AC, DC+, DC-, AC, DC+, DC-, AC and voltages measured by nano-voltmeters V_{ref} and V_x each time recorded. From this set of data, quantities $V_{ref,a}$, $V_{x,a}$, $V_{ref,c+}$, $V_{x,c+}$, $V_{ref,c-}$ et $V_{x,c-}$ representing the output voltages of both converters in response to the AC and the DC (in positive and negative polarities) currents corrected for drift are computed by the least squares method. In this computation the drift is modelled by a third degree polynomial. The result is finally calculated using (2). The scattering of the measured output voltages of the converters around the polynomial modelling the drift is characterised by the standard deviation associated with the result.

The final result is the weighted average of four determinations of the AC-DC difference of the travelling standard.

This procedure is fully automated and all calculations are made by the software.

A preliminary procedure allows determination of constants n_{ref} and n_x.

5 Measurement results :

The results of the calibration of the travelling standards are reported in tables 1 and 2.

	AC-DC difference and expanded uncertainty of PTC 19 at 10 mA						
Frequency (kHz)	0,01	0,04	1	10	20	50	100
AC-DC difference (µA/A)	**9,5**	**1,9**	**0,1**	**-0,2**	**0,9**	**2,3**	**3,4**
Uncertainty [k = 2] (µA/A)	*5,4*	*3,8*	*2,8*	*3,2*	*3*	*3,2*	*3,2*

Table 1 : Calibration results at 10 mA.

	AC-DC difference and expanded uncertainty of PTC 19 + shunt B3A at 5 A						
Frequency (kHz)	0,01	0,04	1	10	20	50	100
AC-DC difference (µA/A)	**-11**	**1**	**-4**	**-8**	**-4**	**-18**	**-23**
Uncertainty [k = 2] (µA/A)	*19*	*18*	*14*	*15*	*15*	*16*	*17*

Table 2 : Calibration results at 5 A.

As LNE AC-DC current transfer standards are not calibrated at 55 Hz, the travelling standards were measured at 40 Hz instead of 55 Hz.

Because of malfunction of the LNE set-up at 100 kHz, the travelling standards were also calibrated at 99 kHz instead of 100 kHz.

During the measurements, the ambient conditions were :

- Temperature : (23.0 ± 0.5)°C ;
- Relative humidity : (50 ± 10)°C.

6 Uncertainty budget :

Measurement uncertainty :

The following uncertainty components have been identified and taken into account :

- Uncertainty components linked with the scattering of the measured output voltages of the converters around the polynomial modelling the drift of the system during the measurements. These components noted $u(V_{réf,a})$, $u(V_{x,a})$, $u(V_{réf,c+})$, $u(V_{x,c+})$, $u(V_{réf,c-})$ and $u(V_{x,c-})$ are computed by the software and used to calculate the standard deviation associated with the result of each determination of the AC-DC difference of the device under test.

- Uncertainty component linked with the systematic error C_j of voltmeter $V_{réf}$ and C_{xj} of voltmeter V_x. These errors are assumed to be equal to zero with an uncertainty $u(C_j)=u(C_{xj})=5.10^{-5}$ mV.
- Uncertainty on values of characteristics n_{ref} and n_x : $u(n_{réf})=u(n_x)=5.10^{-4}$.
- Uncertainty due to the adapter used to connect the converters. The value of this component noted $u(C_{connect})$ is given in table 3.
- The difference between the RMS value of the AC current and the value of the DC current applied to the converters can be as large as some tens of µA/A and give rise to a measurement error taken into account by an uncertainty component noted $u(C_{EgalTens})$ whose value is given in table 4.
- Expression (2) has been established using the empiric relation $V_{out}=g.E_{in}^{n}$ linking the output voltage V_{out} of a converter to the signal E_{in} applied at its input. This relation describes properly the behaviour of the converter only if variations of E_{in} and V_{out} are very small. In case of large difference between the reference converter and the converter under test, the difference between V_{out} measured in response for an AC and a DC input can become substantial and be at the origin of a measurement error. The associated uncertainty component $u(C_{approx})$ is estimated to be of the order of $u(C_{approx})=|Y|/20$ where Y is the measurement result (see relation 2).

Fréquency (kHz)	*u(C connect)*	*u(C EgalTens)*
0,01	0,1	1
0,04	0,1	1
1	0,2	0,3
10	0,3	0,5
20	0,3	0,5
50	0,5	0,5
100	0,5	0,5

Table 3 : Estimated standard uncertainties $u(C_{connect})$ and $u(C_{EgalTens})$ (µA/A).

The complete mathematical model is the the following :

$$Y=\frac{1}{n_{réf}}.\left[\frac{2.(V_{réf,a}+C_j)}{V_{réf,c+}+V_{réf,c-}+2.C_j}-1\right]-\frac{1}{n_x}.\left[\frac{2.(V_{x,a}+C_{xj})}{V_{x,c+}+V_{x,c-}+2.C_{xj}}-1\right]+C_{connect}+C_{EgalTens}+C_{approx}$$

$$=f(V_{réf,a},V_{réf,c+},V_{réf,c-},V_{x,a},V_{x,c+},V_{x,c-},C_j,C_{xj},n_{réf},n_x,C_{connect},C_{Egaltens},C_{approx})$$

where $C_j=C_{xj}=C_{connect}=C_{EgalTens}=C_{approx}=0$

The relation giving uncertainty $u(Y)$ of Y can be deduced from this model as follows :

$$u^2(Y)=\left(\frac{\partial f}{\partial V_{réf,a}}\right)^2.u^2(V_{réf,a})+\left(\frac{\partial f}{\partial V_{réf,c+}}\right)^2.u^2(V_{réf,c+})+\left(\frac{\partial f}{\partial V_{réf,c-}}\right)^2.u^2(V_{réf,c-})+\left(\frac{\partial f}{\partial V_{x,a}}\right)^2.u^2(V_{x,a})$$

$$+\left(\frac{\partial f}{\partial V_{x,c+}}\right)^2.u^2(V_{x,c+})+\left(\frac{\partial f}{\partial V_{x,c-}}\right)^2.u^2(V_{x,c-})+2.\left(\frac{\partial f}{\partial V_{réf,a}}\right).\left(\frac{\partial f}{\partial V_{réf,c+}}\right).\mathrm{cov}(V_{réf,a},V_{réf,c+})$$

$$+2.\left(\frac{\partial f}{\partial V_{réf,a}}\right).\left(\frac{\partial f}{\partial V_{réf,c-}}\right).\mathrm{cov}(V_{réf,a},V_{réf,c-})+2.\left(\frac{\partial f}{\partial V_{réf,c+}}\right).\left(\frac{\partial f}{\partial V_{réf,c-}}\right).\mathrm{cov}(V_{réf,c+},V_{réf,c-})$$

$$+2.\left(\frac{\partial f}{\partial V_{x,a}}\right)\left(\frac{\partial f}{\partial V_{x,c+}}\right).\mathrm{cov}(V_{x,a},V_{x,c+})+2.\left(\frac{\partial f}{\partial V_{x,a}}\right)\left(\frac{\partial f}{\partial V_{x,c-}}\right).\mathrm{cov}(V_{x,a},V_{x,c-})$$

$$+2.\left(\frac{\partial f}{\partial V_{x,c+}}\right)\left(\frac{\partial f}{\partial V_{x,c-}}\right).\mathrm{cov}(V_{x,c+},V_{x,c-})+\left(\frac{\partial f}{\partial C_j}\right)^2.u^2(C_j)+\left(\frac{\partial f}{\partial C_{xj}}\right)^2.u^2(C_{xj})$$

$$+\left(\frac{\partial f}{\partial n_{réf}}\right)^2.u^2(n_{réf})+\left(\frac{\partial f}{\partial n_x}\right)^2.u^2(n_x)+\left(\frac{\partial f}{\partial C_{connect}}\right)^2.u^2(C_{connect})$$

$$+\left(\frac{\partial f}{\partial C_{EgalTens}}\right)^2.u^2(C_{EgalTens})+\left(\frac{\partial f}{\partial C_{approx}}\right)^2.u^2(C_{approx})$$

The sum of the 12 first terms represents the variance associated to the result Y. The sum of the other terms represents the type-B uncertainty $u_B(Y)$ of Y.

The final result $\overline{Y}$ is the weighted average of four determinations of Y and is given by:

$$\overline{Y}=\frac{1}{\sum_{i=1}^{i=4}\frac{1}{u_A^2(Y_i)}}.\sum_{i=1}^{i=4}\frac{Y_i}{u_A^2(Y_i)} \qquad (3)$$

where Y_i is the result of determination number i and $u_A^2(Y_i)$ the standard deviation associated with Y_i.

The associated type-A uncertainty $u_A(\overline{Y})$ of the final result is obtained from :

$$u_A(\overline{Y})=\sqrt{\frac{\sum_{i=1}^{i=4}\frac{(Y_i-\overline{Y})^2}{u_A^2(Y_i)}}{\sum_{i=1}^{i=4}\frac{1}{u_A^2(Y_i)}}} \qquad (4)$$

The standard uncertainty $u(\overline{Y})$ of $\overline{Y}$ is finally given by :

$$u(\overline{Y})=\sqrt{u_A(\overline{Y})+u_B^2(Y)} \qquad (5)$$

In the tables below, values of $u_A(\overline{Y})$ and $u_B(Y)$ are reported for each measurement.

Uncertainty of LNE standards :

Corrections of LNE standards have been established by a step-up procedure in which each standard was calibrated against an other standard already calibrated and then served as the reference in the next step of the procedure. The starting point was the LNE primary current AC-DC transfer standard.

Uncertainties of LNE standards at all current level up to 5 A with measurement uncertainty contribution are reported in table 4.

STEP-UP PROCEDURE		10 Hz	40 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Primary standard	**Current : 10 mA**							
PTB 3D-MJTC	**Standard uncertainty :**	**2**	**1**	**1**	**1**	**1**	**1**	**1**
Step n° 1	**Current : 10 mA**							
Measurement uncertainty	Type A :	0,5	0,2	0,5	0,3	0,3	0,3	0,3
	Type B :	1,0	1,0	0,4	0,6	0,6	0,7	0,7
Uncertainty arising from current dependence :		0,0	0,0	0,0	0,0	0,0	0,0	0,0
Resulting standard uncertainty :		**2,4**	**1,5**	**1,3**	**1,3**	**1,3**	**1,3**	**1,3**
Step n° 2	**Current : 30 mA**							
Measurement uncertainty	Type A :	0,8	0,4	0,6	0,4	0,6	0,9	1,2
	Type B :	1,0	1,0	0,4	0,6	0,7	0,8	1,0
Uncertainty arising from current dependence :		3,0	3,0	2,0	2,0	2,0	2,0	2,0
Resulting standard uncertainty :		**4,1**	**3,6**	**2,6**	**2,6**	**2,6**	**2,8**	**2,9**
Step n° 3	**Current : 100 mA**							
Measurement uncertainty	Type A :	1,5	0,8	1,2	1,2	0,5	1,4	1,1
	Type B :	1,0	1,0	0,4	0,6	0,6	0,7	0,7
Uncertainty arising from current dependence :		3,0	3,0	2,0	2,0	2,0	2,0	2,0
Resulting standard uncertainty :		**5,5**	**4,9**	**3,6**	**3,6**	**3,4**	**3,8**	**3,8**
Step n° 4	**Current : 300 mA**							
Measurement uncertainty	Type A :	1,3	0,9	1,3	1,8	0,7	0,8	1,5
	Type B :	1,0	1,0	0,4	0,6	0,6	0,7	0,7
Uncertainty arising from current dependence :		3,0	3,0	2,0	2,0	2,0	2,0	2,0
Resulting standard uncertainty :		**6,5**	**6,0**	**4,4**	**4,6**	**4,1**	**4,5**	**4,7**
Step n° 5	**Current : 1 A**							
Measurement uncertainty	Type A :	0,4	0,8	0,5	1,3	1,6	0,8	0,7
	Type B :	1,0	1,0	0,4	0,6	0,6	0,7	0,7
Uncertainty arising from current dependence :		3,0	3,0	2,0	2,0	2,0	2,0	2,0
Resulting standard uncertainty :		**7,3**	**6,9**	**4,9**	**5,3**	**5,0**	**5,1**	**5,3**
Step n° 6	**Current : 3 A**							
Measurement uncertainty	Type A :	0,7	1,6	0,5	1,1	1,8	0,9	0,9
	Type B :	1,0	1,0	0,4	0,6	0,6	0,7	0,7
Uncertainty arising from current dependence :		3,0	3,0	3,0	3,0	3,0	4,0	4,0
Resulting standard uncertainty :		**8,0**	**7,8**	**5,8**	**6,3**	**6,2**	**6,6**	**6,8**
Step n° 7	**Current : 5 A**							
Measurement uncertainty	Type A :	1,1	1,0	1,7	1,4	0,3	0,7	1,2
	Type B :	1,0	1,0	0,4	0,6	0,6	0,7	0,7
Uncertainty arising from current dependence :		4,0	3,0	3,0	3,0	3,0	4,0	4,0
Resulting standard uncertainty :		**9,1**	**8,5**	**6,8**	**7,2**	**7,0**	**7,8**	**8,1**

Table 4 : Uncertainty of LNE standards (µA/A).

<u>Uncertainty of the 10 mA travelling standard PTC 19</u> :

Corrections of the 10 mA travelling standard have been established by direct comparison with the 10 mA LNE standard. Uncertainty of the 10 mA travelling standard with measurement uncertainty contribution are reported in table 5.

Travelling standard : PTC 19		10 Hz	40 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA LNE standard								
	Standard uncertainty :	**2,4**	**1,5**	**1,3**	**1,3**	**1,3**	**1,3**	**1,3**
	Current : 10 mA							
Measurement uncertainty	Type A :	0,6	0,4	0,2	0,4	0,2	0,3	0,2
	Type B :	1,0	1,0	0,4	0,6	0,6	0,7	0,7
Resulting standard uncertainty :		**2,7**	**1,9**	**1,4**	**1,6**	**1,5**	**1,6**	**1,6**
Expanded uncertainty (k = 2)		**5,4**	**3,8**	**2,8**	**3,2**	**3,0**	**3,2**	**3,2**

Table 5 : Uncertainty of the 10 mA travelling standard PTC 19 (µA/A).

<u>Uncertainty of the travelling standard PTC 19 associated with the 5 A shunt B3A</u> :

Corrections of the travelling standard PTC 19 associated with the 5 A shunt B3A have been established by direct comparison with the 5 A LNE standard. Uncertainty of the 5 A travelling standard with measurement uncertainty contribution are reported in table 6.

Travelling standard : PTC 19 + 5 A shunt B3A		10 Hz	40 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
5 A LNE standard								
	Standard uncertainty :	**9,1**	**8,5**	**6,8**	**7,2**	**7**	**7,8**	**8,1**
	Current : 5 A							
Measurement uncertainty	Type A :	0,8	0,9	1,1	0,5	0,6	0,7	0,7
	Type B :	1,0	1,0	0,4	0,7	0,9	1,5	1,9
Resulting standard uncertainty :		**9,2**	**8,7**	**7,0**	**7,3**	**7,1**	**8,0**	**8,4**
Expanded uncertainty (k = 2)		**19**	**18**	**14**	**15**	**15**	**16**	**17**

Table 6 : Uncertainty of the travelling standard PTC 19 associated with the 5 A shunt B3A (µA/A).

References

[1] K. LIND, T. SORSDAL and H. SLINDE, « Design, modelling and verification of high-performance AC-DC current shunts from inexpensive components », IEEE Trans. Instr. Meas., vol. 57, n°1, January 2008.

[2] M. Klonz, ”AC-DC transfer difference of the PTB multijunction thermal converter in the frequency range from 10 Hz to 100 kHz,” IEEE Trans. Instrum. Meas., vol. 36, pp. 320-327, June. 1987.

Report

Key comparison EURAMET.EM-K12 “AC-DC Current Transfer Standards”

Acronym of institute: Trescal

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Content

1 Introduction

Trescal A/S operates the Danish national laboratory for AC-electricity and RF & microwave measurements. Together with DFM (Danish Institute for Fundamental Metrology in Copenhagen) DPLE, Danish Primary Laboratory for Electricity, has been established. Both laboratories are members of DANIAmet, which is a decentralized metrological organization of Danish primary and reference laboratories nominated by the Danish Agency for Development of Trade and Inustry.

2 Measuring System

The AC-DC current transfer difference δ of a transfer standard is defined as:

$$\delta = \frac{I_{AC} - I_{DC}}{I_{DC}}$$

where:

I_{AC} is the rms value of the input AC current.
I_{DC} is the value of the input DC current which when reversed produces the same mean output rms current as I_{AC}.

The AC-DC current transfer difference of the test object δ_{obj} is calculated as:

$$\delta_{obj} = \frac{E_{AC,ref} - E_{DC,ref}}{n_{ref} E_{DC,ref}} - \frac{E_{AC,obj} - E_{DC,obj}}{n_{obj} E_{DC,obj}} + \delta_{ref}$$

where:

E_{AC} output currents at AC.
E_{DC} output currents at DC, averaged for reversed DC.
δ_{ref} AC-DC current transfer difference of the reference standard.
n power coefficient determined from the output/input correlation of a thermal transfer standard, given by:

$$E = k(IR)^n$$

By measuring the output voltages for input currents about 50 - 100 ppm below and above the nominal input currents, the power coefficient n is determined from:

$$n = \frac{\Delta E}{E} \frac{I}{\Delta I}$$

where ΔE and ΔI are the small changes of output and input values respectively. In this way the value of n was determined to be n = 2 for the travelling standard, which was used for the calculation of δ_{obj} at all currents and frequencies.

Three multijunction thermal converters, MJTC, of the “3-dim.” PTB type are used at the primary level for currents between 10 mA to 2 mA [1]. The calibration is carried out in a two-channel set-up shown schematically in fig. 1. The reference standard and the DUT are connected to the transconductance amplifier using a special T-adaptor. The special guarding due to the Hi-Lo asymmetry of the set-up is shown in fig. 2. To reach higher current levels PTB/IPHT type planar multijunction thermal converters, PMJTC, in combination with a series of Fluke A40 current shunts (20 mA - 5 A) is used in a step-up procedure as depicted in fig. 3.

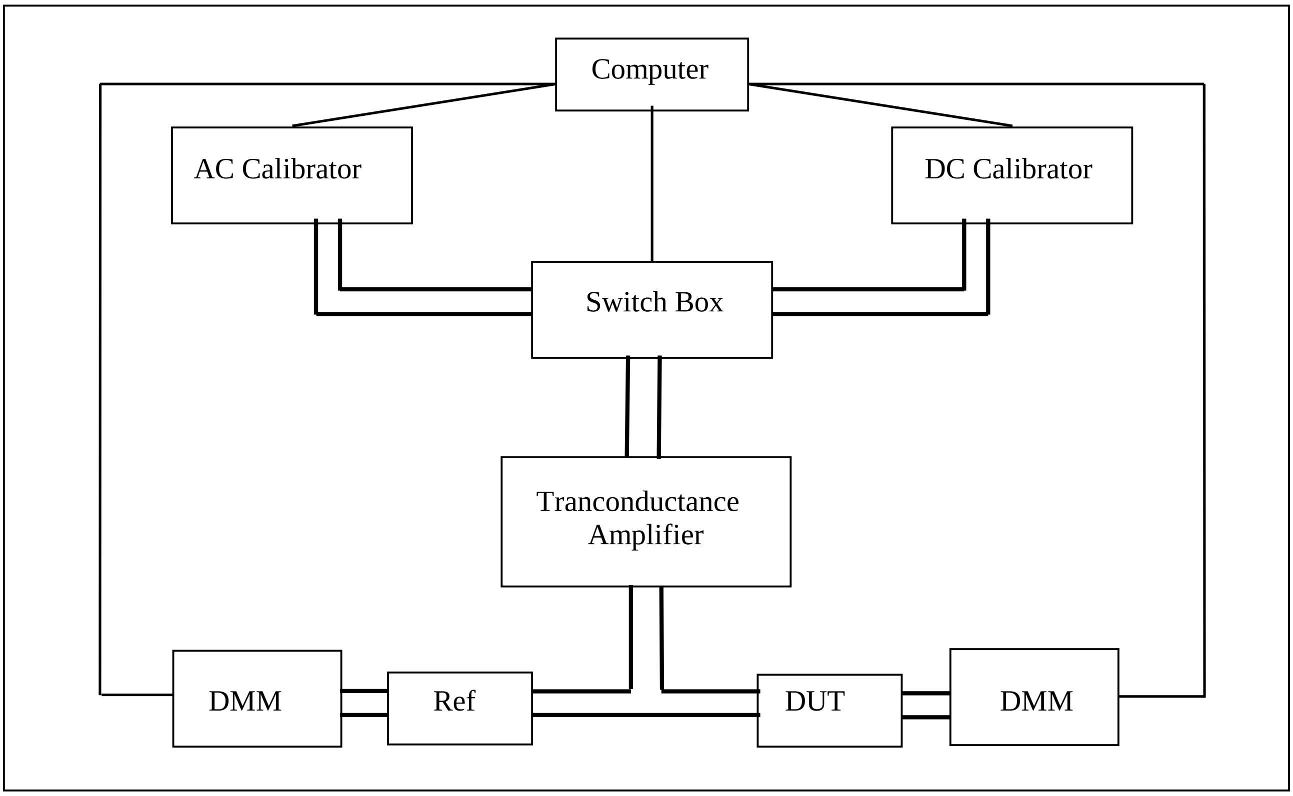

Fig. 1: Measurement set-up for the measurement of the AC-DC transfer difference of a thermal transfer standard.

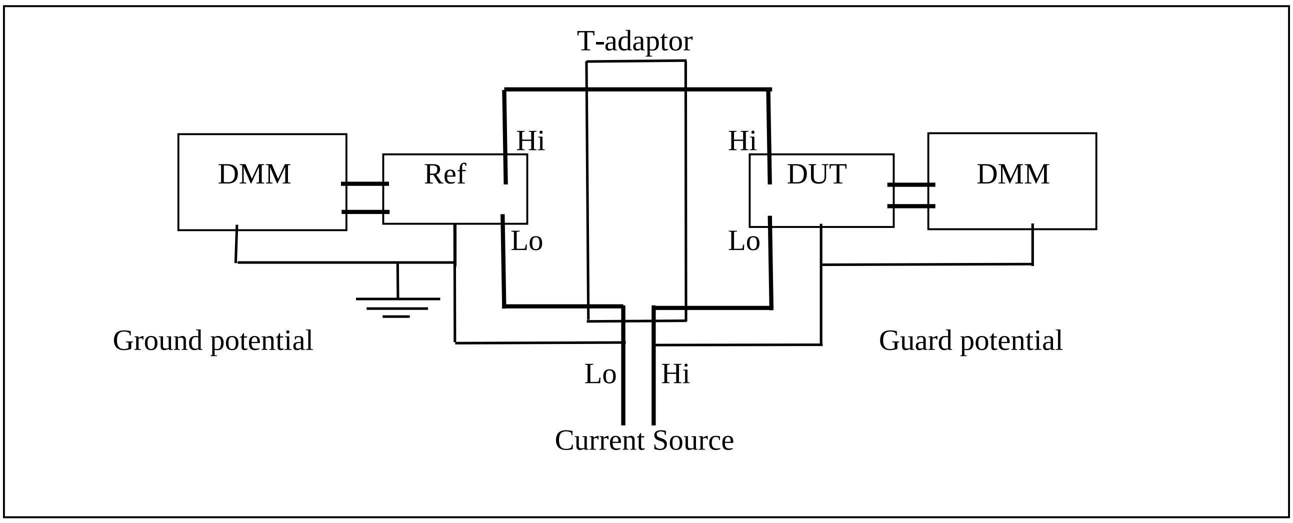

Fig. 2: Diagram for guarding.

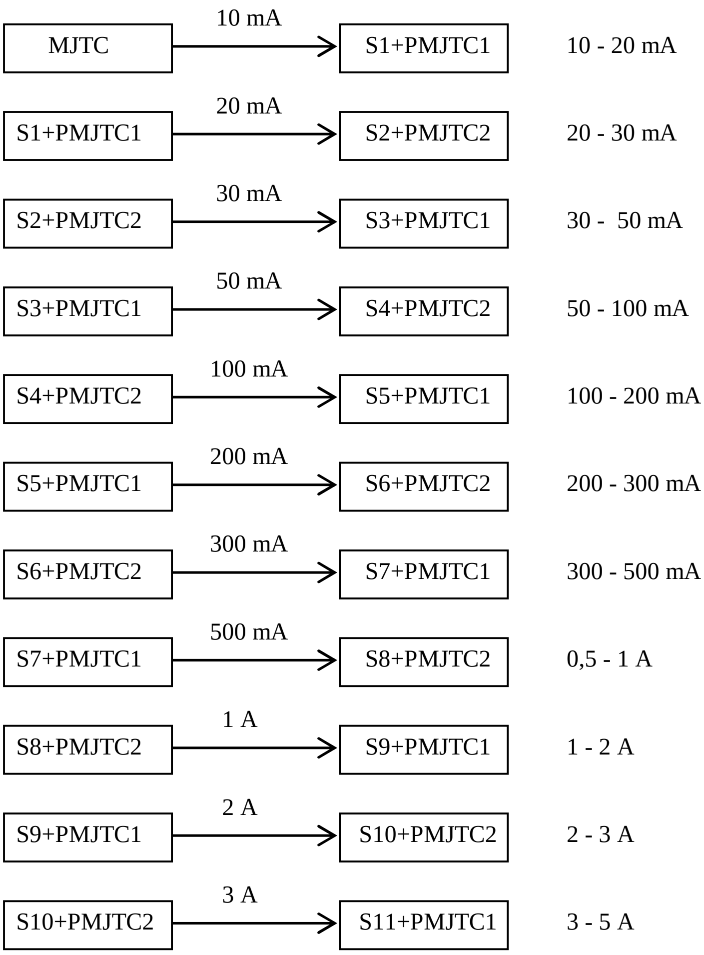

Fig. 3: Step-up procedure.

The AC-DC transfer difference of the travelling standards were measured at 10 mA and 5 A at the frequencies 10 Hz, 55 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz.

The equipment used includes the following:

MJTC, of the “3-dim.” PTB type (190 ohm heater resistance) [1].
PMJTC, PTB/IPHT type (90 ohm heater resistance) & Fluke A40 5 A current shunt.
Datron 4000A calibrator used as DC source.
Fluke 5720 A calibrator used as AC source.
Hewlett Packard 34420 Nanovoltmeter used to measure the output voltage of the reference standard.
Keithley 182 Nanovoltmeter used to measure the output voltage of the travelling standard.
Clarke Hess 8100 Transconductance Amplifier.
An automated AC-DC switchbox.

Travelling standards:
10 mA: PMJTC type PTB/IPHT, sn. PTC 17
5 A: BEV 147 mΩ coaxial shunt, sn. B3A, connected in parallel to the PMJTC, sn. PTC 17.

In order to protect the travelling standards, measurements were carried out with the travelling standards connected to the Lo side of the T-piece only, and therefore with both input and output connected to earth at all times.

Before any measurement the reference standard and the travelling standard was allowed to warm-up for 30 minutes with DC current applied.

After this the AC-DC transfer difference is determined by use of the measuring sequence AC - DC+ - AC - DC– - AC, which is chosen in order to compensate for errors due to drift of the output voltage of transfer standards. After each switching event the thermal transfer standards are allowed to stabilize for 30 seconds before taking five readings five seconds apart of both nV-meters, so that every E_{AC}, E_{DC+} and E_{DC-} is the average five readings.

In order to minimize errors due to the non-linear output/input correlation of the transfer standards, the first sequence is used to adjust the output of the AC calibrator, so that the AC-DC difference measured at the output of the test object is minimized.

At each frequency and current the measurement sequence was repeated 12 times, and the arithmetic mean and the corresponding experimental standard deviation is calculated.

3 Measurement Result

The intercomparison was performed in a laboratory with stabilised environmental conditions 23 °C ± 1 °C and 45 %RH ± 5 %RH. The minimum and maximum values recorded during the measurements are given in the following table:

Table 1: Minimum and maximum temperature and humidity values.

	Min	Max	Unc.
Ambient temperature / ºC	22,7	23,4	1
Relative humidity / %	40,8	45,2	5

The measurements were performed with only weak air streams due to air-conditioning, and the calibrators were placed with the air-cooling pointing away from the set-up.

The measured AC-DC transfer differences of the travelling standards at the required currents and frequencies are given in the following table 2, while the measurement frequencies incl. uncertainty is shown in table 3.

Table 2: Measurement results.

Current	Measured ac-dc current difference (*m*A/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	3	0	0	0	1	5	10
5 A	–2	0	0	–4	–10	–24	–30

Table 3: Measurement frequency.

Current	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. Frequency	10,00018	55,0010	1,000018	10,00018	20,0004	50,0009	100,0018
Expanded Uncertainty	100 ppm	100 ppm	100 ppm	100 ppm	100 ppm	100 ppm	100 ppm

4 Uncertainty

The overall uncertainties of the measurement results are estimated in accordance with EA-4/02. It has been distinguished between category A and B uncertainties. The category A uncertainty is stated as the estimated value of the experimental standard deviation. Estimates of the category B uncertainties are based either on experience or on stated specifications of the manufacturers. Here the limits of errors are estimated. In this case a suitable population distribution is assumed and the standard deviation is estimated by multiplying the error estimate with the corresponding factor.

The expanded uncertainties (k = 2) of the measured AC-DC differences of the travelling standards, consistent with the BIPM Appendix C entries, are stated in table 4, whereas table 5 contains the uncertainty budget for the AC-DC current transfer difference of the primary standards as the starting point of the traceability chain [1].

Assuming that all the uncertainty contributions (u_i) are uncorrelated the standard uncertainty u is calculated as:

$$u = \sqrt{\sum u_i^2}$$

The expanded uncertainty U is determined by:

$$U = ku$$

where the coverage factor k for a coverage probability of 95% is found from the effective number of degrees of freedom ν_{eff} and a t-distribution:

$$\nu_{eff} = \frac{u^4}{\sum \frac{u_i^4}{\nu_i}}$$

Table 4: Expanded uncertainty (k = 2).

Current	Expanded Uncertainty (μA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	5	5	5	5	7	10	20
5 A	18	18	18	22	27	45	70

Table 5: Uncertainty budget for AC-DC transfer difference δ of the primary standards [1].

Contribution of:	10 Hz δ	10 Hz Unc	55 Hz δ	55 Hz Unc	1 kHz δ	1 kHz Unc	10 kHz δ	10 kHz Unc	Type A or B	Distri-bution	Degrees of freedom
Th.-el. effect, FRDC	-0,03	0,2	-0,03	0,2	-0,03	0,2	-0,03	0,2	A	Gauss k=1	10
Heater, dielectric loss	0	0	0	0	0,02	0,05	0,06	0,05	B	Uniform	∞
Heater, capacitance	0	0	0	0	0	0,02	0	0,02	B	Uniform	∞
Heater, inductance	0	0	0	0	0	0,02	0	0,02	B	Uniform	∞
Leads, dielectric loss	0	0	0	0	0,02	0,05	0,1	0,05	B	Uniform	∞
Leads, capacitance	0	0	0	0	0	0,02	0	0,02	B	Uniform	∞
Leads, inductance	0	0	0	0	0	0,02	0	0,02	B	Uniform	∞
Low frequency effect	3,1	3	0,6	1	0	0	0	0	B	Uniform	∞
Connector & leads	0	0,1	0	0,1	0,05	0,1	0,5	0,1	B	Uniform	∞
Comp. diff. standards	0	1	0	1	0	1	0	1	B	Uniform	∞
AC-DC difference δ	3,1		0,6		0,1		0,6				
Standard unc. (k = 1):		1,9		0,9		0,7		0,7			
Expanded unc. (k = 2):		3,8		1,8		1,4		1,4			
Eff. Deg. Of freedom:	> 100		> 100		> 100		> 100				

Table 5 - continued: Uncertainty budget for AC-DC transfer difference δ of the primary Standards [1].

Contribution of:	20 kHz δ	20 kHz Unc	50 kHz δ	50 kHz Unc	100 kHz δ	100 kHz Unc		Type A or B	Distri-bution	Degrees of freedom
Th.-el. effect, FRDC	-0,03	0,2	-0,03	0,2	-0,03	0,2		A	Gauss k=1	10
Heater, dielectric loss	0,14	0,05	0,42	0,05	0,91	0,5		B	Uniform	∞
Heater, capacitance	0	0,02	0,01	0,02	0,03	0,3		B	Uniform	∞
Heater, inductance	0	0,02	-0,02	0,02	-0,06	0,3		B	Uniform	∞
Leads, dielectric loss	0,3	0,05	0,89	0,05	1,97	0,5		B	Uniform	∞
Leads, capacitance	0	0,02	0,02	0,02	0,09	0,3		B	Uniform	∞
Leads, inductance	0	0,02	0,01	0,02	0,04	0,3		B	Uniform	∞
Low frequency effect	0	0	0	0	0	0		B	Uniform	∞
Connector & leads	1,0	0,1	1,97	0,3	5,79	0,5		B	Uniform	∞
Comp. diff. standards	0	1,5	0	2	0	3		B	Uniform	∞
AC-DC difference δ	1,4		3,3		8,7					
Standard unc. (k = 1):		0,9		1,2		1,9				
Expanded unc. (k = 2):		1,8		2,4		3,8				
Eff. Deg. Of freedom:	> 100		> 100		> 100					

With the expanded uncertainties in table 5 as a starting point the uncertainty budget for the calibration of the travelling standard at 10 mA is shown in table 6. The following tables, 7 - 17 show the additional and varying uncertainties for each step in the step-up procedure up to 5 A, which means that those contributrions given in table 6 that remain unchanged for each step are not reported again in the following tables. The resulting expanded uncertainty for each step is used as the “Reference” contribution in the next step. Table 18 shows the uncertainty budget for the travelling standard at 5 A.

The uncertainty of each frequency is ± 100 ppm (k = 2), so that the uncertainty contribution due to the frequency dependence may be neglected.

Table 6: Uncertainty budget, 10 mA, travelling standard - MJTC (ref)

Contribution of:	Unc. 10 Hz	Unc. 55 Hz	Unc. 1 kHz	Unc. 10 kHz	Type A or B	Distri-bution	Degrees of freedom
Reference	3,8	1,8	1,4	1,4	B	Gauss k=2	> 100
Standard deviation	0,7	0,7	0,7	0,7	A	Gauss k=1	11
Power coefficients	0,05	0,05	0,05	0,05	B	Uniform	∞
Linearity (DMM’s)	0,5	0,5	0,5	0,5	B	Uniform	∞
Noise	1	1	1	1	B	Uniform	∞
Resolution (DMM’s)	0,5	0,5	0,5	0,5	B	Uniform	∞
T-adaptor	0,5	0,5	0,5	1	B	Uniform	∞
Hi-Lo asymmetry	0,5	0,5	0,5	1,5	B	Uniform	∞
Different references	1	1	1	1	B	Uniform	∞

Standard unc. (k = 1):	2,3	1,6	1,5	1,7
Expanded unc. (k = 2):	4,6	3,2	3,0	3,4
Eff. Deg. Of freedom:	> 100	> 100	> 100	> 100

Table 6 - continued: Uncertainty budget, 10 mA, travelling standard - MJTC (ref)

Contribution of:	Unc. 20 kHz	Unc. 50 kHz	Unc. 100 kHz		Type A or B	Distri-bution	Degrees of freedom
Reference	1,8	2,4	3,8		B	Gauss k=2	> 100
Standard deviation	0,7	0,7	0,7		A	Gauss k=1	11
Power coefficients	0,05	0,05	0,05		B	Uniform	∞
Linearity (DMM's)	0,5	0,5	0,5		B	Uniform	∞
Noise	1	1	1		B	Uniform	∞
Resolution (DMM's)	0,5	0,5	0,5		B	Uniform	∞
T-adaptor	2	5	10		B	Uniform	∞
Hi-Lo asymmetry	3	5	10		B	Uniform	∞
Different references	1,5	2	3		B	Uniform	∞

Standard unc. (k = 1):	2,7	4,6	8,7	
Expanded unc. (k = 2):	5,4	9,2	18	
Eff. Deg. Of freedom:	> 100	> 100	> 100	

Table 7: Additional/varying uncertainties, step-up 10 - 20 mA.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	1	0,2	2,7
55 Hz	0,7	1	0,2	2,1
1 kHz	0,7	1	0,2	2,0
10 kHz	0,7	1	1	2,5
20 kHz	0,7	1	1,5	3,8
50 kHz	0,7	1	3	6,6
100 kHz	0,7	1	7	12,8

Table 8: Additional/varying uncertainties, step-up 20 - 30 mA.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	1	0,2	3,0
55 Hz	0,7	1	0,2	2,5
1 kHz	0,7	1	0,2	2,4
10 kHz	0,7	1	1	3,1
20 kHz	0,7	1	1,5	4,6
50 kHz	0,7	1	3	8,1
100 kHz	0,7	1	7	15,8

Table 9: Additional/varying uncertainties, step-up 30 - 50 mA.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	1	0,2	3,3
55 Hz	0,7	1	0,2	2,8
1 kHz	0,7	1	0,2	2,8
10 kHz	0,7	1	1	3,5
20 kHz	0,7	1	1,5	5,4
50 kHz	0,7	1	3	9,4
100 kHz	0,7	1	7	18,4

Table 10: Additional/varying uncertainties, step-up 50 - 100 mA.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	1	0,2	3,6
55 Hz	0,7	1	0,2	3,2
1 kHz	0,7	1	0,2	3,1
10 kHz	0,7	1	1	3,9
20 kHz	0,7	1	1,5	6,0
50 kHz	0,7	1	3	10,5
100 kHz	0,7	1	7	20,6

Table 11: Additional/varying uncertainties, step-up 100 - 200 mA.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	1	0,2	3,8
55 Hz	0,7	1	0,2	3,4
1 kHz	0,7	1	0,2	3,4
10 kHz	0,7	1	1	4,3
20 kHz	0,7	1	1,5	6,6
50 kHz	0,7	1	3	11,5
100 kHz	0,7	1	7	22,6

Table 12: Additional/varying uncertainties, step-up 200 - 300 mA.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	1	0,2	4,1
55 Hz	0,7	1	0,2	3,7
1 kHz	0,7	1	0,2	3,7
10 kHz	0,7	1	1	4,7
20 kHz	0,7	1	1,5	7,1
50 kHz	0,7	1	3	12,5
100 kHz	0,7	1	7	24,5

Table 13: Additional/varying uncertainties, step-up 300 - 500 mA.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	1,5	0,2	4,3
55 Hz	0,7	1,5	0,2	4,0
1 kHz	0,7	1,5	0,2	4,0
10 kHz	0,7	1,5	1	5,0
20 kHz	0,7	1,5	1,5	7,6
50 kHz	0,7	1,5	3	13,4
100 kHz	0,7	1,5	7	26,2

Table 14: Additional/varying uncertainties, step-up 0,5 - 1 A.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	0,7	2	0,2	4,7
55 Hz	0,7	2	0,2	4,3
1 kHz	0,7	2	0,2	4,3
10 kHz	0,7	2	1	5,4
20 kHz	0,7	2	1,5	8,1
50 kHz	0,7	2	3	14,2
100 kHz	0,7	2	7	27,9

Table 15: Additional/varying uncertainties, step-up 1 - 2 A.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	1	3	0,2	5,2
55 Hz	1	3	0,2	4,9
1 kHz	1	3	0,2	4,9
10 kHz	1	3	1	6,0
20 kHz	1	3	1,5	8,8
50 kHz	1	3	3	15,1
100 kHz	1	3	7	29,5

Table 16: Additional/varying uncertainties, step-up 2 - 3 A.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	1	5	0,2	6,1
55 Hz	1	5	0,2	5,9
1 kHz	1	5	0,2	5,8
10 kHz	1	5	1	6,9
20 kHz	1	5	1,5	9,6
50 kHz	1	5	3	16,1
100 kHz	1	5	7	31,0

Table 17: Additional/varying uncertainties, step-up 3 - 5 A.

Contribution of:	Standard Deviation Gauss k=1	Step-up Uniform	Mutual Inductance Uniform	Std. Uncertainty k=1
10 Hz	1	7	0,2	7,5
55 Hz	1	7	0,2	7,3
1 kHz	1	7	0,2	7,2
10 kHz	1	7	1	8,2
20 kHz	1	7	1,5	10,8
50 kHz	1	7	3	17,2
100 kHz	1	7	7	32,7

Table 18 Uncertainty budget, 5A, travelling standard.

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference	14,9	14,4	14,4	16,3	21,5	34,4	65,3	B	Gauss k=2
Standard deviation	1	1	1	1	1	1	1	A	Gauss k=1
Power coefficients	0,05	0,05	0,05	0,05	0,05	0,05	0,05	B	Uniform
Linearity (DMM’s)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Uniform
Noise	1	1	1	1	1	1	1	B	Uniform
Resolution (DMM’s)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	B	Uniform
T-adaptor	0,5	0,5	0,5	1	2	5	10	B	Uniform
Hi-Lo asymmetry	0,5	0,5	0,5	1,5	3	5	10	B	Uniform
Different references	1	1	1	1	1,5	2	3	B	Uniform
Step-up	7	7	7	7	7	7	7	B	Uniform
Mutual Inductance	0,2	0,2	0,2	1	1,5	3	7	B	Uniform
Standard unc.:	8,6	8,4	8,4	9,3	11,8	18,3	34,2		
Expanded unc.:	18	17	17	19	24	37	69		
Coverage factor k:	2	2	2	2	2	2	2		

[1] M. Klonz, “Entwicklung von Vielfachthermoconvertern zur genauen Rückführung von Wechselgrößen auf äquivalente Gleichgrößen”, PTB-Bericht E 29, Fakultät für Maschinenbau und Elektrotechnik, Technische Universität Carolo Wilhelmina, Braunschweig, 1987.

EURAMET Key International Comparison of AC-DC Current Transfer Standards

EURAMET.EM-K12

Measurement Report

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Contents

1. Introduction

INRiM was one of the participants of the EURAMET Key International Comparisons of AC-DC Current Transfer Standards: EURAMET.EM - K12. The measurements on the travelling standard, composed of a thermal converter of PMJTC type having current nominal of 10 mA and a coaxial current shunt of 5 A of current nominal, were performed during the period from 3/11/2014 to 24/11/2014. The travel standards arrived at INRiM from Trescal A/S (Denmark), in good physical and working conditions, and were sent to SIQ (Slovenia) on 25/11/2014 after being verified.
The electrical parameters of the thermal convert were measured after a day of stabilization once the travel standard packing was placed within the primary ac-dc transfer laboratory. The input and output resistance as well as the insulation resistance were about 93 Ω, 7.3 kΩ and 2 GΩ, respectively.

2. Description of the measurement setup and the reference standards

4.2. Measurement setup

The new measurement system used during the EURAMET.EM-K12 international comparison is suitable for direct comparison between thermal current converts and current standards, i.e., current shunts connected in parallel to thermal converters. It is fully automated and used for realization, maintenance and dissemination of primary alternating current scale in a wide range of currents ranging from 10 mA to 50 A and frequencies from 10 Hz up to 100 kHz. It performs precise comparison in terms of ac-dc current transfer difference between the unknown/travelling standard and the known standard. The measured quantity at a particular frequency is $\delta_d = \delta^{TS}_{ac\text{-}dc} - \delta^{RS}_{ac\text{-}dc}$ where $\delta_{ac\text{-}dc} = I_{ac} \text{-} I_{dc}/I_{dc}$ is the ac-dc current transfer difference (TS is the travelling/unknown standard and RS is the reference standard).
The measurement setup employs the following instruments:

Instrument type	Quantity	Model	Notes
Programmable Multifunction Calibrator	1	Wavetek 4808	DC Calibrator
Programmable Multifunction Calibrator	1	DATRON 4200A	AC Calibrator
Coaxial Switch	1	Home build	Control Unit "Electronics corporation (ICS) model 4833"
Transconductance Amplifier	1	Clarke-Hess 8100	Used from 10 mA up to 5 A
Nanovoltmeter	2	Keithley 2182A	Full-scale set to 10 mV and 100 mV
Personal computer	1	HP workstation xw4000	
Automatic control software	1	Developed in Labwindows/CVI	

A simplified schematic of the measurement setup is given in Fig. 1. The main current loop is composed of a voltage controlled transconductance amplifier (TA), a current choke (Ch), a T-current node (CN) which connects in series the devices to be compared: thermal converts from currents from 5 mA up to 15 mA of three different models SJTC, 3D-MJTC and PMJTC; current shunts connected in parallel with thermal converts of PMJTC type where SH_S indicates the known standard whereas the unknown shunt to be calibrated is indicated with SH_X. A guarded arrangement has been employed in order to make negligibly small and equal any leakage impedance. In order to reduce the differences depending on the potential between the devices under comparison, all measurements are repeated by interchanging the position of the devices with respect to the current node. The final result of the comparison, at the frequency *f*, includes the average between the direct and reverse measurements and the calculation of the uncertainty budged.

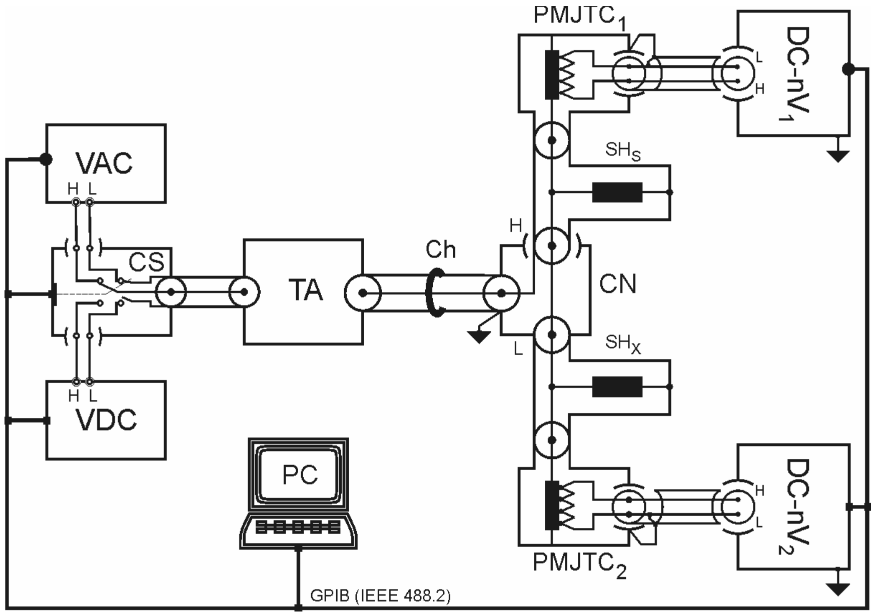

Fig 1. Measurement setup for ac-dc current transfer difference determination between current standards.

4.2. Reference standards

At INRiM, the reference standards for currents higher than 10 mA are made of coaxial shunts connected in parallel to the Planar Multi-Junction Thermal Converter.
A group of thermal converts (TVCs) composed of a SJTC used as frequency standards, a calculable 3D-MJTC and five PMJTC were employed for the realization of the traceability at rated current of 10 mA. Table 1 reports the main electric parameters of the TVCs employed for this purpose.
The route to establish the traceability at a rated current of 10 mA is based on a group of five PMJTCs and on the ability to track property the frequency behaviour of the ac-dc current transfer difference (δ_i) of each converter of the group. For this purpose different approaches have been pursued by checking the consistency of the results. It was also useful to introduce two additional thermal converters: a calculable 3D-MJTC for which the frequency dependence of the ac-dc current transfer difference is calculable [1]; a SJTC under assumption that its ac-dc current transfer difference is as flat as possible for frequencies beyond 10 kHz. The methods employed are valid only for a certain frequency range band and may be divided as follows:

- *from 10 Hz up to 100 Hz* three different approaches are employed and their consistency has been checked:
    a) PMJTCs compared directly against the 3D–MJTC at rated current of 10 mA (the ac-dc current transfer difference of the 3D-MJTC has been computed theoretically [1]);
    b) PMJTCs compared directly against the 3D–MJTC or between them by using the principle of power adaptation [2] (one of the two thermal converts works at lower power level by connecting a suitable resistor in parallel to the heater resistance);
    c) PMJTC compared directly against a current shunt by using the sampling strategy;

- *from 100 Hz up to 10 kHz*: PMJTCs were compared against the calculable 3D-MJTC (from 1 kHz up to 10 kHz the ac-dc current transfer difference of the 3D-MJTC is assumed zero);
- *from 10 kHz up to 100 kHz*: the PMJTCs were compared against the calculable 3D-MJTC and between them at rated current of 10 mA. The frequency behaviour of the 3D-MJTC and one of the PMJTC from 10 kHz up to 100 kHz has been verified by means of a SJTC which is also used to verify the behaviour of PMJTCs. The discrepancy founded between the model and the experiment was treated as a component of uncertainty in the overall uncertainty budged.

The reference standards for current of 5 A are composed of coaxial current shunts connected in parallel to specific PMJTCs, which work in voltage mode.
Table I reports the nominal parameters of the following reference standard employed at rated current of 10 mA and 5 A, respectively.

Table I. INRiM reference standards employed for the realization of the traceability of alternating current at 10 mA level (based on a group of thermal converters) and 5 A reference standards based on current shunts.

Thermal Converters Serial No.	Rated Input Current	Frequency range	Heater Resistance	Thermocouple resistance	Output voltage at rated current
PMJ2	10 mA	10 Hz ÷ 100 kHz	112.6 Ω	11.9 kΩ	103 mV
PMJ3	10 mA	10 Hz ÷ 100 kHz	118.4 Ω	12.9 kΩ	103 mV
PMJ4	10 mA	10 Hz ÷ 100 kHz	93.7 Ω	7.4 kΩ	100 mV
PMJ29	10 mA	10 Hz ÷ 100 kHz	93.7 Ω	7.5 kΩ	100 mV
PMJ30	10 mA	10 Hz ÷ 100 kHz	93.9 Ω	7.9 kΩ	100 mV
3D - MJTC	15 mA	10 Hz ÷ 100 kHz	190 Ω	860 Ω	100 mV
SJTC-18140	5 mA	10 kHz ÷ 100 kHz	50 Ω	25 Ω	7 mV
Current Shunt	Rated Input Current	Frequency range	Shunt Resistance	Output voltage at rated current	
Shunt Fluke A40B_I1 (S. No 228066429)	5A	10 Hz ÷ 100 kHz	0.16 Ω	800 mV	
Shunt Fluke A40B_I2 (S. No 142761358)	5 A	10 Hz ÷ 100 kHz	0.16 Ω	800 mV	

3. Definition of the measurand

Ac-dc current transfer difference is defined as:

$$\delta = \left[\frac{I_{ac} - I_{dc}}{I_{dc}} \right]_{E_{ac} = E_{dc}} \tag{1}$$

where: I_{ac} is an rms ac current; I_{dc} is a dc current, when reversed, it produces the same mean output response as the rms ac current (E_{ac}=E_{dc}).
The definition (1) can be rewritten while taking the operating condition into account and [5] as:

$$\delta = \left[\frac{I_{ac} - I_{dc}}{I_{dc}} \right]_{E_{ac}=E_{dc}} \equiv -\left[\frac{E_{ac} - E_{dc}}{s \cdot E_{dc}} \right]_{I_{ac}=I_{dc}} \qquad (2)$$

The definition (2) is particularly suitable when the measurement system performs direct comparison and the measured quantity is the difference between the ac-dc current transfer difference of thermal converters.

4. Description of the measurement procedure

The measurement procedure is composed of several steps:

- insertion of the standards to be compared into the measuring system: it consists in connecting the current port of the current standards in series through a suitable home made T-current node with the aim of reducing current leakage at high frequencies;
- connection of the output connectors of the thermal converters TC_1 and TC_2, supporting electromotive force signals, to the input of digital nanovoltmeters NV_1 and NV_2; symmetrization of each mesh voltage by connecting the low voltage (LV) terminals of the nanovoltmeters NV_1, that operates at high voltage, to the respective potential voltage in order to minimize leakage currents at higher frequencies due to parasitic capacitances;

The measurement procedure is performed automatically and a control program enables the possibility of remotely controlling the measuring instruments by means of a Graphical User Interface (GUI). The parameter namely *initializing constants* are inserted within the GUI as follows:

- Identification of the current standards;
- Working current and AC frequencies of the standards to be compared;
- Global heating time, typically in the range 30 min – 60 min;
- Stabilization time, typically greater than 30 s;
- Alignment factor, typically within 1 µV/V;
- Measuring time, typically 40 s;
- Number of ac-dc cycles, typically 10 consecutive measurements.

The measurement procedure consists in:

a) setting and switching on the DC and AC calibrators;
b) setting and switching on the transconductance amplifier at the value $I_{dc}(+)$ according to the step-up level;
c) waiting for temperature stabilization of TVCs by monitoring its electromotive forces;
d) determination of the sensitivity at a specific working point in dc, $s = \frac{\Delta\varepsilon / \varepsilon}{\Delta I / I}$;
e) automatic alignment of $I_{dc}^{(-)}$ level to the $I_{dc}(+)$ level of the calibrator in DC by means of a convergence algorithm;
f) automatic alignment of I_{ac} level to the mean of $I_{dc}(+)$ and $I_{dc}(-)$ levels by means of a convergence algorithm;
g) starting of the ac-dc transfer sequence ($I_{ac} - I_{dc}^{(+)} - I_{ac} - I_{dc}^{(-)} - I_{ac}$); after each commutation a stabilization time greater than 30 s occurs; the transfer sequence at a specific frequency is repeated more than 10 times;
h) steps (f-g-h) are repeated at the following frequencies: 10 Hz, 55 Hz, 1 kHz, 20 kHz, 50 kHz, 100 kHz.

Steps (a-b-c-d-e-f-g-h) are repeated twice (direct and reverse measurements) with respect to the interchange of the standards insertion in the current node.

4.2. Measurement at 10 mA level

The measurements at 10 mA level were performed by comparing directly the travelling standard PMJTC namely PTC19-BEV with a group of INRiM thermal converts of PMJTC type having the same rated input current as the travelling standard. The ac-dc transfer difference was measured for the "Lo" position of the travelling standard and the connection to earth must always be present in order to protect the output of the PMJTC. With reference to Fig. 2 the $PMJTC_{1\text{-}2}$ to be compared are connected directly to the current node and their outputs are connected to the respective digital nanovoltmeters $DC\text{-}nV_{1\text{-}2}$.
The ac and dc currents are provided by a transconductance amplifier (TA) controlled by means of two multifunction calibrators imposed in AC and DC voltage mode. A coaxial switch allows applying sequentially AC and DC voltage to the TA amplifier.
Fig. 2 shows the measurement setup employed for ac-dc current transfer difference measurements at 10 mA current level.

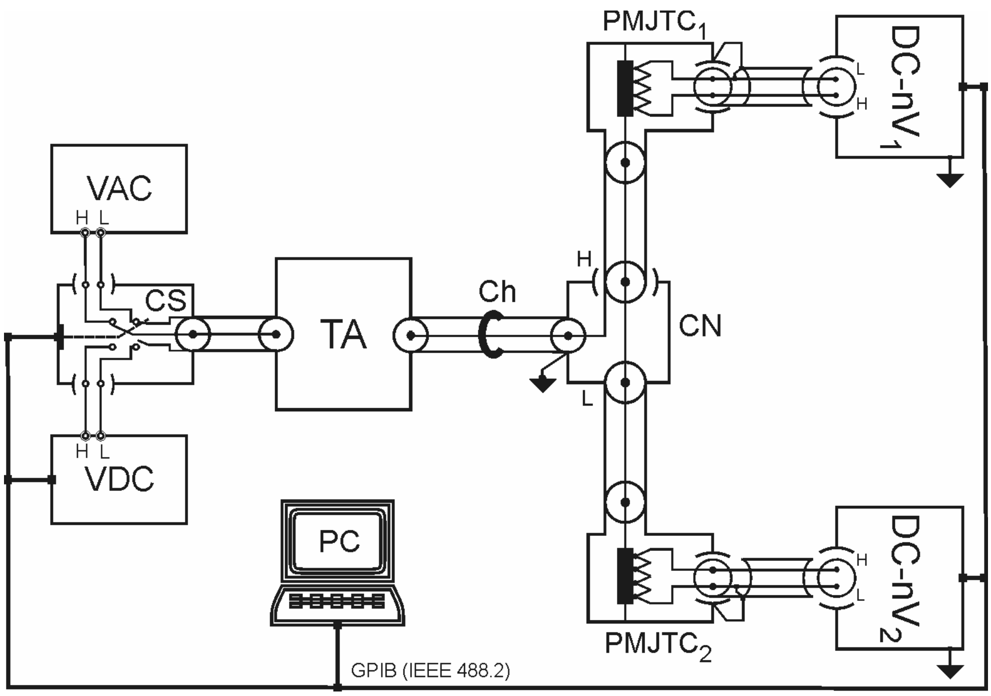

Fig 2. Measurement setup for ac-dc current transfer difference measurements at 10 mA.

Table II, reports an example of three repeated comparisons performed at 10 mA level between an INRiM PMJTC ac-dc current standard (model PMJ4) and the ac-dc travelling current PTC19-BEV standard. Some of the planar multi-junction thermal converters supplied by INRiM, during the EURAMET.EM-K12, against which the 10 mA travelling standard was compared is given in table I.

Table II. Example of comparison between the ac-dc travelling current transfer standard (PTC19_BEV) and an ac-dc current transfer (PMJTC_PMJ29) INRiM at 10 mA current level.

Devices under comparison		Measured quantity (µA/A)	Frequency						
TC1	TC2		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
$PMJ29_{INRiM}$ (High)	$PTC19_{BEV}$ (Low)	$\delta_d = \delta_{TC2}^H - \delta_{TC1}^L$ Date: 03/11/2014	0.85	0.28	0.46	0.28	0.61	0.65	0.74
		$u(\delta_d)$ (computed from a set of 10 measurements)	0.16	0.18	0.12	0.19	0.10	0.20	0.23
$PMJ29_{INRiM}$ (High)	$PTC19_{BEV}$ (Low)	$\delta_d = \delta_{TC2}^H - \delta_{TC1}^L$ Date: 04/11/2014	0.77	0.06	-0.04	0.40	0.28	0.42	0.31
		$u(\delta_d)$ (computed from a set of 10 measurements)	0.10	0.15	0.19	0.11	0.13	0.11	0.22
$PMJ29_{INRiM}$ (High)	$PTC19_{BEV}$ (Low)	$\delta_d = \delta_{TC2}^H - \delta_{TC1}^L$ Date: 06/11/2014	0.71	-0.02	0.09	-0.04	0.38	0.26	0.98
		$u(\delta_d)$ (computed from a set of 10 measurements)	0.19	0.15	0.12	0.10	0.11	0.09	0.12
$\delta_{PTC19_{BEV}} - \delta_{PMJ29_{INRiM}}$ @ 10 mA		$\delta_M = \sum_{i=1}^{n} \frac{1}{n} \delta_d^i$ (with n=3)	0.78	0.11	0.17	0.21	0.42	0.44	0.68
		$u(\delta_M)$ (computed from a set of 3 repeated measurements)	0.04	0.09	0.15	0.13	0.10	0.12	0.19

The INRiM standards against which the 10 mA travelling standard has been compared were four, one 3D-MJTC and three PMJTCs. The PMJTCs standards were chosen in order to have the heater resistance as near as possible that of the travelling standard.

Table III, reports the final single comparison between the standard involved to assign the ac-dc current transfer difference of the travelling standard.

Table III. Results of the comparisons between the ac-dc travelling current transfer standard (PTC19_BEV) and the set of standards INRiM used at 10 mA current level.

Devices under comparison @ 10 mA	Measured quantity (µA/A)	Frequency						
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
$\delta_{PTC19_{BEV}} - \delta_{PMJ4_{INRiM}}$	$\delta_M = \sum_{i=1}^{n} \frac{1}{n} \delta_d^i$ (with n=3)	0.57	-0.01	0.00	0.33	0.08	0.39	0.52
	$u(\delta_M)$ (computed from a set of 3 repeated measurements)	0.10	0.05	0.05	0.05	0.12	0.21	0.23
$\delta_{PTC19_{BEV}} - \delta_{PMJ29_{INRiM}}$	$\delta_M = \sum_{i=1}^{n} \frac{1}{n} \delta_d^i$ (with n=3)	0.78	0.11	0.17	0.21	0.42	0.44	0.68
	$u(\delta_M)$ (computed from a set of 3 repeated measurements)	0.04	0.09	0.15	0.13	0.10	0.12	0.19

$\delta_{PTC19_{BEV}} - \delta_{PMJ30_{INRiM}}$	$\delta_M = \sum_{i=1}^{n} \frac{1}{n} \delta_d^i$ (with n=3)	0.69	0.03	-0.02	0.20	0.14	0.25	0.35
	$u(\delta_M)$ (computed from a set of 3 repeated measurements)	0.09	0.06	0.12	0.10	0.06	0.08	0.02
$\delta_{PTC19_{BEV}} - \delta_{3D\text{-}MJTC_{INRiM}}$ @ 10 mA	Single measurements	3.60	-0.27	0.01	0.42	0.17	0.05	-0.71
	$u(\delta_M)$ (computed from a set of 10 measurements)	0.18	0.18	0.15	0.12	0.14	0.18	0.19

The final assignment of the value of the travelling standard is computed starting from the ac-dc current transfer difference of the INRiM standards involved. For low frequencies we also perform a single measurement by employing the principle of power adaption, i.e., PTC19-BEV operates at its full input power levels whereas the standard INRIM - the 3D-MJTC – is connected in parallel with a low temperature coefficient resistor and operates near 19 % of its input power level. Table IV summarizes the ac-dc current transfer difference assigned to the travelling standards at rated current of 10 mA by using different from single determinations. The final value was assigned as the mean of the single determinations.

Table IV. ac-dc current transfer differences of the PTC19-BEV assigned from the reference standards INRIM at rated current of 10 mA.

Devices under comparison		Measurement method	Frequency						
Unknown standard	Reference standard		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
$PTC19_{BEV}$ (Low)	$PMJ4_{INRiM}$ (High)	Direct comparison	5.50	0.09	0.04	0.48	0.49	1.25	1.86
PTC19BEV (Low)	$PMJ29_{INRiM}$ (High)	Direct comparison	5.81	0.18	0.05	0.55	0.80	1.03	2.19
PTC19BEV (Low)	$PMJ30_{INRiM}$ (High)	Direct comparison	5.92	0.14	-0.05	0.30	0.51	1.08	1.60
$PTC19_{BEV}$ (Low)	$3D\text{-}MJTC_{INRiM}$ (High)	Direct comparison	5.90	0.23	0.01	0.42	0.56	0.92	1.24
$PTC19_{BEV}$ (Low)		Mean value	5.85	0.20	0.01	0.44	0.59	1.07	1.72

4.2. Measurement at 5 A level

The measurements at 5 ampere level between the travelling standard (Serial No B3A connected in parallel to the PMJTC (Serial No PTC19)) and maintained national INRiM standards were performed at a rated current of 5 A. Table V(a) shows the INRiM standards employed during the comparison. The measurement setup employed is reported in Fig. 1.

Table V(a). Standards involved for comparisons at 5 A rated current during the EURAMET.EM-K12.

5 ampere travelling standard	5 ampere maintained standards by INRiM	Measurement method	Rated current	TA full-scale
Coaxial shunt (Serial No B3A) connected in parallel to the PMJTC (Serial No PTC19)	Coaxial shunt A40B-5A_I1 (Serial No 228066429) connected in parallel to PMJTC (Serial No PMJ29)	Direct	5 A	20 A
	Coaxial shunt A40B-5A_I2 (Serial No 142761358) connected in parallel to PMJTC (Serial No PMJ4)	Direct	5 A	20 A

INRIM standards at 5 A rated current are of Fluke design and are used for primary ac current scale realization beyond 2 A.

Table V(b). Comparisons performed at rated current of 5 A .

TA Full-scale	Measured quantity $\delta_d = \delta^x_{TC2} - \delta^s_{TC1}$		Rated current	Frequency (kHz)						
	TC2	TC1		0.01	0.55	1	10	20	50	100
20 A	B3A_PTC19 (BEV)	A40B-5A_I1_PMJ29	5 A	-2.5	-0.6	0.3	-7.7	-17.7	-35.5	-42.1
20 A	B3A_PTC19 (BEV)	A40B-5A_I2_PMJ4	5 A	-2.6	-1.0	0.3	-7.9	-17.6	-35.5	-40.7

The differences reported in Table V(b) represent the mean values computed from a set of three repeated measurements. The value assigned of the 5 ampere travelling standard (Serial No B3A) connected in parallel to the PMJTC (Serial No PTC19) is computed as the mean value of both determination.

5. Statement of the traceability

At INRiM, the national standard of ac-dc current transfer standard is considered to be a primary standard. It is composed of a group of thermal converters.
Table VI shows the construction of the traceability maintained by a group of ac-dc current transfer based on thermal converters.

Table VI. Standards employed for the construction of the traceability at 10 mA level.

Thermal converter	Nominal parameters	Frequency range	Assignment method	Verification method
3D-MJTC	Rated Input Current: 15 mA Heater resistance: 198 Ω Thermocouple resistance: 860 Ω Output voltage: 100 mV	10 Hz ÷ 100 kHz	Theoretical calculation	For frequencies from 10 Hz up to 100 Hz by direct comparison with PMJTC operating at reduced power level. For frequencies beyond 20 kHz by direct comparison with SJTC (single junction thermal converter)
PMJTC	Rated Input Current: 10 mA Heater resistance: 90-111 Ω Thermocouple resist.: 7.5 – 12 kΩ Output voltage: 100 mV	10 Hz ÷ 100 kHz	Direct comparison with 3D-MJTC and between them	For frequencies from 10 Hz up to 100 Hz by direct comparison of PMJTCs at different power levels.

The steps employed for traceability construction at rated current of 10 mA level are as follows:

a) direct comparison between the 3D-MJTC and SJTC from 10 kHz up to 100 kHz (in this frequency range the ac-dc current transfer difference of the SJTC is considered to be as flat as possible);
b) direct comparison between a 3D-MJTC and a group of 4 PMJTCs at rated current of 10 mA for frequencies ranging from 10 Hz to 100 kHz;
c) direct comparison between the elements of the PMJTC group at 10 mA rated input current and currents ranging from 10 Hz to 100 kHz;
d) direct comparison between 3D-MJTC and the group of PMJTCs performed at different power levels by connecting in parallel low temperature coefficient resistors;
e) from the set of redundant measurements performed during b) and c) steps and resolving the set of equations $[\mathrm{L}]\cdot[\delta]=[\delta_{\mathrm{d}}]$, where [L] is a rectangular matrix ((m+1)×n) (m=number of comparison; n=number of elements) namely connection matrix with elements (-1, 0, +1), $[\delta]$ is a column matrix containing the ac-dc differences of the TVCs and $[\delta_{\mathrm{d}}]$ is a column matrix containing the measured differences determined experimentally. By using the last squares method, [2-3-4], one finds the best solution of $[\mathrm{L}]\cdot[\delta]=[\delta_{\mathrm{d}}]$;
f) by applying the step-up procedure, the calibration of maintained national standards is performed up to 5 ampere level and beyond that. Fig. 3 reports an example of step-up procedure performed at 1 ampere level where two unknown AC current standards of 2 A nominal value are directly compared with two known AC current standards of 1 A nominal value. The verification method consists in checking the triangle enclosure, preferability below 1 µA/A level.

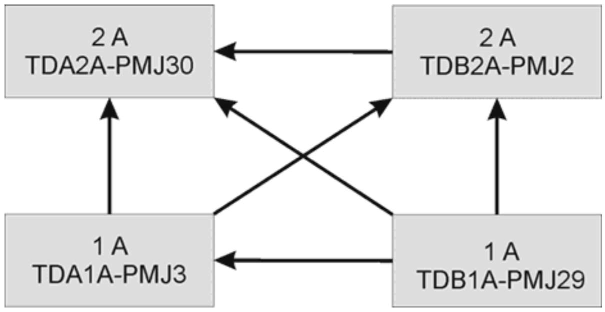

Fig. 3. Block diagram of comparisons performed at rated current of 1 A during the step-up procedure.

Fig. 4 reports the INRiM traceability chain based on step-up procedure for currents ranging from 10 mA to 20 A.

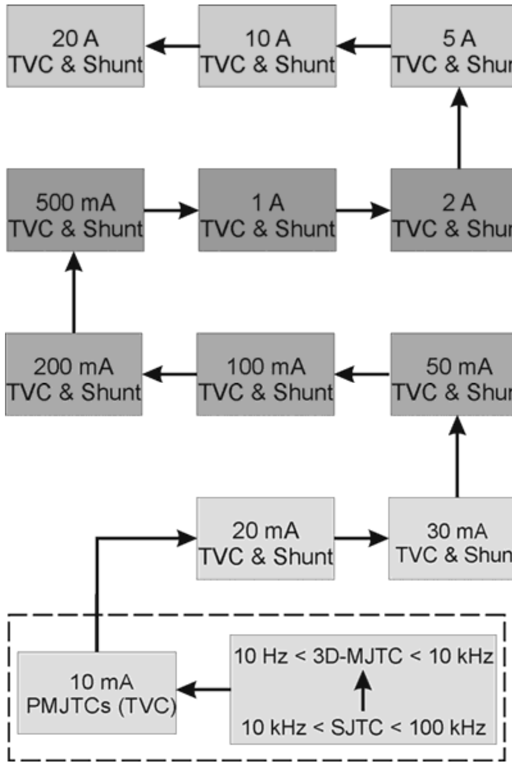

Fig. 4. Step-up INRiM traceability chain for AC current ranging from 10 mA up to 20 A.

6. Measurement results

The 10 mA travelling standard is a Planar Multi-Junction Thermal Converter (PMJTC), type PTB/IPHT34 Serial No PTC19. It was compared with four thermal converters, one 3D-MJTC and three PMJTC type PTB/IPHT Serial No PMJ2, PMJ3, PMJ29 and PMJ30. The measurements are given in terms of mean value computed from the four comparisons.
The travelling standard for the current of 5 ampere is a coaxial shunt (Serial No B3A) connected in parallel to the PMJTC (Serial No PTC19). It was compared with two coaxial shunts of 5 ampere type A40B-5A (Serial No 228066429 and No 228066374) calibrated by INRiM at 5 A which are also connected in parallel with PMJ29 and PMJ4 thermal converters.
The tables below show the measurement results, expanded uncertainty and the measured frequency of the travelling standard at 10 mA and 5 A rated currents.

Measurement Results:

Current	Measured d ac-dc current difference (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	5.8	0.2	0.0	0.4	0.6	1.1	1.7
5A	3.7	-0.9	-0.6	-8.4	-18.3	-36.6	-48.7

Expanded Uncertainty:

Current	Expanded Uncertainty (*k*=2) (µA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	3.3	2.4	2.4	2.4	2.8	3.0	3.4
5A	6.5	5.6	4.3	5.8	7.1	10.3	16.0

Measurement Frequency:

	Nominal frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. Frequency	9.99962	54.9993	0.9999865	9.999865	19.99973	49.99933	99.99866
Expanded Unc. (k=2) (µHz/Hz)	4	2	0.5	0.5	0.5	0.5	0.5

7. Ambient conditions of the measurements

Measures were carried out during the 3 weeks from 3/11/2014 to 24/11/2014 at the ac-dc primary transfer laboratory of INRiM, which is part of the complex shielded room laboratories situated underground, which have automatic temperature control. The table below shows the variations of temperature and relative humidity fluctuation within a period of 3 weeks in November.

	Min	Max	Remarks
Ambient temperature (°C)	22.3	22.9	Maximum variation within 3 weeks in November
Relative humidity (%)	33.3	45.0	Maximum variation within 3 weeks in November

8. Uncertainty budget

The ac-dc transfer difference, in accordance with the method of comparison, is computed from (1) as

$$\delta_{\mathrm{d}} = \delta_{\mathrm{x}} - \delta_{\mathrm{s}} \qquad (1)$$

where δ_x is the ac-dc difference of the unknown TVC_x and δ_s of the known TVC_s.
The ac-dc current transfer difference, δ, is expressed as follow:

$$\delta = \left[\frac{I_{ac} - I_{dc}}{I_{dc}}\right]_{E_{ac}=E_{dc}} \equiv -\left[\frac{E_{ac} - E_{dc}}{s \cdot E_{dc}}\right]_{I_{ac}=I_{dc}} \qquad (2)$$

where I_{ac} and I_{dc} are the AC and DC currents, respectively; E_{ac} and E_{dc} are electromotive forces and s the sensitivity. With respect to experiment in which the measured quantities are electromotive forces and by inserting equation (2) into (1) the following operating equation is obtained

$$\delta_d = \left(\left[\frac{E_{ac}^s - E_{dc}^s}{s^s \cdot E_{ac}^s}\right] - \left[\frac{E_{ac}^x - E_{dc}^x}{s^x \cdot E_{ac}^x}\right]\right)_{\substack{I_{ac}^s = I_{dc}^s \\ I_{ac}^x = I_{dc}^x}} \qquad (3)$$

In order to foster the condition $I_{ac}=I_{dc}$ the term $\Delta = E_{ac} - E_{dc}$ is made small enough, typically below 2 µV/V, by adjusting I_{ac} near the mean value of $I_{dc}(+)$ and $I_{dc}(-)$; this condition is performed automatically by means of a convergence algorithms with respect to the transfer standard thermal converter TVC_s. The known TVC_s is connected to the TC1 nanovoltmeter and the unknown standard TVC_x to the TC_2 nanovoltmeter.
The comparisons between the primary ac-dc current standards of INRiM are made twice: i.e., during the step-up procedure the configuration in which TVC_x is inserted to the *high* position of the current node and TVC_s is inserted to the low position of the current node is named *direct measurement*, δ_d^D; the *reverse measurement*, δ_d^R, consists in changing the position of standards under comparison respect to the current node. The results carried out are given as the mean value of both direct and reverse measures $\bar{\delta} = \left(\delta_d^D + \delta_d^R\right)/2$.
Instead, according to the technical report of the EURAMET EM-K12, the travelling standard during the measurements was inserted always in the low side of the measuring system and compared against INRiM standards at 10 mA and 5 A and frequencies ranging from 10 Hz to 100 kHz.
According to the measurement model the value of the ac-dc transfer difference of the unknown standards δ_x, operating in current mode, and its standard uncertainty $u(\delta_x)$ at a specific current step of the step-up current chain is computed as:

$$\begin{aligned} \delta_{\mathrm{x}}^{\mathrm{i}} &= \delta_{\mathrm{d}}^{\mathrm{i}} + \delta_{\mathrm{S}}^{\mathrm{i-1}} \\ u\left(\delta_{\mathrm{x}}^{\mathrm{i}}\right) &= \sqrt{u^2\left(\delta_{\mathrm{d}}^{\mathrm{i}}\right) + u^2\left(\delta_{\mathrm{S}}^{\mathrm{i-1}}\right)} \end{aligned} \qquad (4)$$

Where the index, i, represents the step at higher current level and (i-1) is the index related to the previous step.
Typically, the influence quantities that contribute to δ_d determination during each step of the AC current traceability chain are as follows:

$$\delta_d = \delta_A + \delta_R + \delta_P + \delta_L + \delta_M + \delta_{TC} + \delta_D + \delta_{CBL} \qquad (5)$$

end the standard uncertainty of $u(\delta_{\mathrm{d}})$ is

$$u(\delta_{\mathrm{d}}) = \sqrt{u^2(\delta_{\mathrm{A}}) + u^2(\delta_{\mathrm{R}}) + u^2(\delta_{\mathrm{P}}) + u^2(\delta_{\mathrm{L}}) + u^2(\delta_{\mathrm{M}}) + u^2(\delta_{\mathrm{TC}}) + u^2(\delta_{\mathrm{D}}) + u^2(\delta_{\mathrm{CBL}})} \qquad (6)$$

A description of each component and assessment is given in Table VII.

Table VII. Uncertainty contributions taken into account of the measured difference between devices during the step-up procedure.

Influence quantity	Description	Type	Notes	D.o.F
$u(\delta_{\mathrm{A}})$	Standard deviation of the mean calculated computed from a set al least 10 measurements	A - Normal	Computed from a set al least of 10 measurements	9
$u(\delta_{\mathrm{R}})$	Standard deviation of the mean of repeated measurements	A - Normal	Computed from a set al least 4 different measurements within a certain time period by removing and reinserting of the standards inside the measuring setup	3
$u(\delta_{\mathrm{P}})$	Potential difference between the known and unknown TCs and/or shunts	B - Rectangular	Exchanging the TCs with respect the current node position and computing $u(\delta_P) = \frac{1}{\sqrt{3}}\left(\frac{\delta_d^{Dir} - \delta_d^{\mathrm{Rev}}}{2}\right)$	∞
$u(\delta_{\mathrm{L}})$	Current-level effect during the step-up procedure	B - Rectangular	Computed as the half of the maximum differences measured with different shunts at different currents $u(\delta_M) = \frac{1}{\sqrt{3}}\left(\frac{\delta_d^{step(i)} - \delta_d^{step(i-1)}}{2}\right)$	∞
$u(\delta_{\mathrm{M}})$	Measurement setup employed to measure the electromotive force of the thermal converters	B-Rectangular	Computed as the half of the sum with respect to interchange of the nV-meters. $u(\delta_L) = \frac{1}{\sqrt{3}}\left(\frac{\delta_{TC2-TC1}^{step(i)} + \delta_{TC1-TC2}^{step(i)}}{2}\right)$	∞
$u(\delta_{\mathrm{TC}})$	Behavior of PMJTC at low frequencies	B-Rectangular	Computed according to the principle of linear behavior of Joule heat dissipated in the heater at low frequencies when PMJTC connected in parallel to the current shunt works between different power levels during the step-up procedure. $u(\delta_{TC}) = \frac{1}{\sqrt{3}}\left(\frac{\delta_{TC+Shunt}^{step(i)} - \delta_{TC+shunt}^{step(i-1)}}{2}\right)$	2
$u(\delta_{\mathrm{D}})$	Deviation from different determinations	A - Normal	Computed as standard deviation of the mean of a certain number of determinations by using a group of maintained standards	3 (10 mA) 1 (5 A)
$u(\delta_{\mathrm{CBL}})$	Contribute due to connectors and bad leakages	B-Rectangular	From literature	2

Measurement Current 10 mA:

The travelling standard PMJTC (Serial No. PTC19) was compared against four INRIM standards, one 3D-MJTC and three PMJTCs (Serial No. PMJ4, PMJ29 and PMJ30).
The main uncertainty contributions involved during the comparison are:
$u(\delta_{RS})$: uncertainty of the reference standard(s) 10 mA of INRiM
$u(\delta_{Comparison\ Measurements})$: uncertainty of the comparison measurements which can be decomposed into the following components $\{u(\delta_A), u(\delta_R), u(\delta_M), u(\delta_L), u(\delta_{CBL}), u(\delta_D)\}$ as shown in Table VIII.

Table VIII. 10 mA, budget uncertainty from 10 Hz to 100 kHz.

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
$u(\delta_{RS\text{-}10\ mA})$: Reference standard(s) 10 mA of INRiM	1.2	0.6	0.5	0.6	0.9	1.0	1.2	B	Normal
$u(\delta_A)$: Standard deviation of the mean of 10 measurements	0.2	0.2	0.2	0.2	0.2	0.2	0.2	A	Normal
$u(\delta_R)$: Repeated measurements	0.3	0.2	0.2	0.2	0.2	0.2	0.3	B	Rectangular
$u(\delta_M)$: Measurement setup	0.1	0.1	0.1	0.1	0.1	0.1	0.2	B	Rectangular
$u(\delta_P)$: Potential difference	0.3	0.2	0.2	0.2	0.2	0.3	0.5	B	Rectangular
$u(\delta_{CBL})$: Connectors + bead lackages	1.0	1.0	1.0	1.0	1.0	1.0	1.0	B	Rectangular
$u(\delta_D)$: Deviation from different determination	0.1	0.1	0.1	0.1	0.1	0.1	0.2	A	Normal
Standard unc.:	1.6	1.2	1.2	1.2	1.4	1.5	1.7		
Expanded unc.:	3.3	2.4	2.4	2.4	2.8	3.0	3.4		
Coverage factor *k*:	2	2	2	2	2	2	2		

Measurement Current 5 A:

The travelling standard of 5 ampere was a coaxial shunt (Serial No. B3A) connected in parallel with PMJTC (Serial No PTC19) which was compared against two INRIM standards classified as A40B-5A_I1 connected in parallel with PMJ29 and A40B-5A_I2 connected in parallel with PMJ4.
The main uncertainty contributions at each frequency during the comparison are:
$u(\delta_{RS\_5A})$: total uncertainty resulting from AC current step-up procedure;
$u(\delta_{Comparison\ Measurements})$: uncertainty of the comparison measurements which can be decomposed into the following components $\{u(\delta_A), u(\delta_R), u(\delta_M), u(\delta_D), u(\delta_{TC}), u(\delta_L), u(\delta_{CBL})\}$ as shown in table IX.

Table IX. 5 A, budget uncertainty from 10 Hz to 100 kHz.

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
$u(\delta_{RS})$: 5 A INRiM standards	2.9	2.6	1.9	2.1	2.9	4.2	6.3	B	Normal
$u(\delta_{A})$: Standard deviation of 10 measurements	0.3	0.2	0.2	0.2	0.2	0.2	0.3	A	Normal
$u(\delta_{R})$: Repeated measurements	0.2	0.1	0.1	0.1	0.1	0.1	0.2	A	Normal
$u(\delta_{M})$: Measurement setup	0.2	0.2	0.2	0.2	0.2	0.2	0.3	B	Rectangular
$u(\delta_{P})$: Potential difference between standards	0.2	0.1	0.1	0.1	0.1	0.2	0.3	B	Rectangular
$u(\delta_{D})$: Deviation from different determination	0.8	0.2	0.2	0.2	0.3	0.5	0.7	A	Normal
$u(\delta_{L})$: Level dependence	0.2	0.2	0.2	0.2	0.2	0.2	0.2	B	Rectangular
$u(\delta_{CBL})$: Connectors + bead lackages	1.0	1.0	1.0	2.0	2.0	3.0	5.0	B	Rectangular
$u(\delta_{TC})$: Low frequency behavior of PMJTC	0.8	0.1	0.0	0.0	0.0	0.0	0.0	B	Rectangular
Standard unc:	3.3	2.8	2.1	2.9	3.5	5.1	8.0		
Expanded Unc:	6.6	5.5	4.3	5.8	7.1	10.3	16.0		
Coverage factor *k*:	2	2	2	2	2	2	2		

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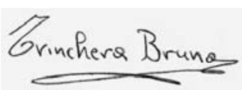
Author

Trinchera Bruno, Ph.D. Date 23/12/2014



EURAMET.EM-K12

Intercomparison report

Prepared by: Boštjan Voljč 2015-01-16

1 Introduction

In the December 2014 SIQ performed EURAMET international comparison of AC/DC current transfer standards EURAMET.EM-K12. In this document are presented all relevant data regarding the intercomparison and results along with the corresponding measuring uncertainty.

2 Reference standards

2.1 PMJTC

One planar multi-junction thermal converter (PMJTC), Type PTB/IPHT (s.n.: 28) was used as reference AC/DC current transfer standard for current 10 mA and for measurement of output voltage from reference 5 A coaxial shunt. The PMJTC was periodically calibrated in PTB for its AC/DC current and voltage transfer difference.

PMJTC has the following parameters:

- input current: 10 mA,
- input voltage: 1 V,
- output voltage: approx. 100 mV,
- heater resistance: approx. 90 Ω.

2.2 Coaxial current shunt 5 A

For measurements at current 5 A the reference coaxial current shunt SIQ MU-5A (s.n.: SIQ07023) together with the PMJTC described above were used. The reference coaxial current shunt has the following parameters:

- design: coaxial cage design,
- rated input current: 5 A,
- output voltage at rated current: approx. 715 mV
- nominal resistance: approx. 143 mΩ.

The current shunt is periodically calibrated for its AC/DC transfer difference in PTB.

2.3 Multimeter HP 3458A

For reading the output voltage of PMJTC's two digital multimeters HP 3458A (s.n.: 2823A20702 and US28028518) were used. Both are periodically calibrated at SIQ according to internal procedures.

2.4 Source

As current source voltage driven trans-conductance amplifier Clarke-Hess 8100 (s.n.: 266) was used. As voltage source Fluke 5440B (s.n.: 4270011) for DC voltage and Fluke 5700A (s.n.: 5215008) for AC voltage were used. Both universal calibrators are periodically calibrated in SIQ according to internal procedures.

To switch between AC and DC voltage that was fed to trans-conductance amplifier an isolated driver unit RBDK Type PIF8 (s.n: 3134) with 2-terminal switching unit RBDK Type TF2 (s.n.: 3136) were used.

3 Measurement

3.1 Definition of measurand

AC/DC current transfer difference on input is defined as

$$\delta = \frac{I_{AC} - I_{DC}}{I_{DC}}$$

where

I_{AC} rms ac current,

I_{DC} dc current which, when reversed, produces the same mean output response as the rms ac current.

Differences are expressed in microamperes per ampere (μA/A) and a positive sign means that more ac than dc current was required for the same output response.

3.2 Measurement setup

On the following figures are shown block diagrams for calibration of AC/DC current transfer standards (Figure 3.1 for 10 mA – PMJTC and Figure 3.2. for 5 A – PMJTC with 5 A current shunt).

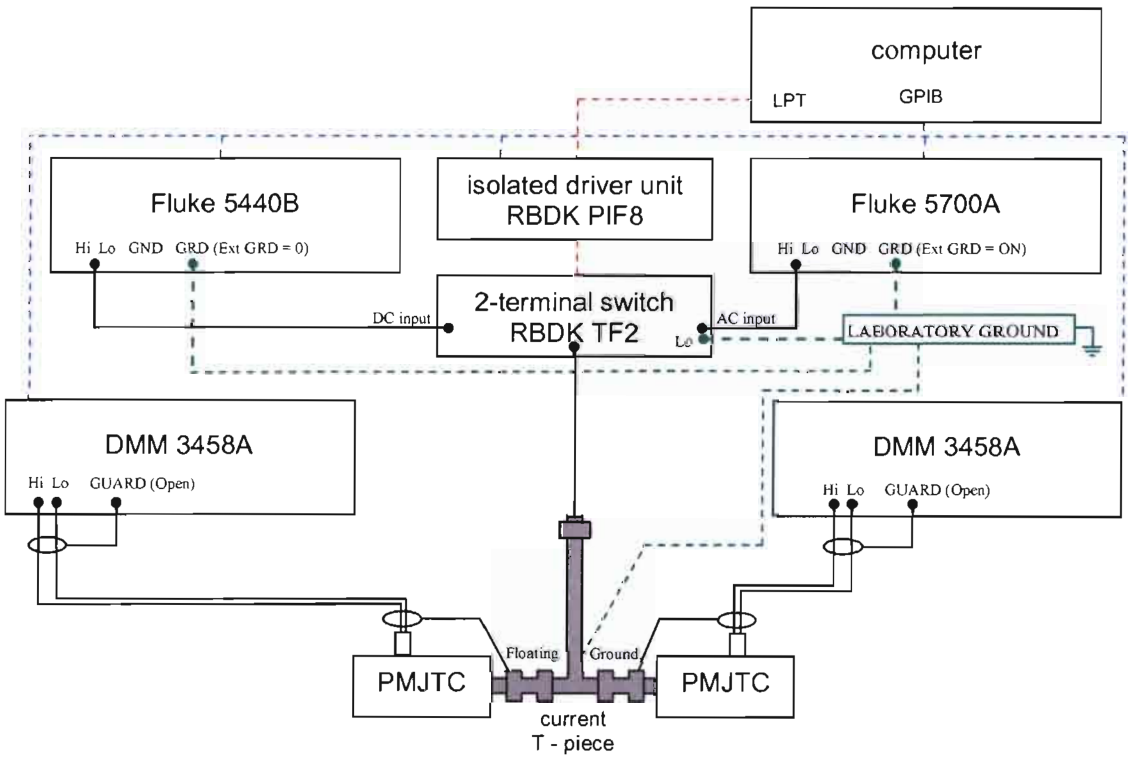


Figure 3.1: Setup for calibration of 10 mA current (PMJTC)

PMJTC was calibrated at 10 mA in voltage mode. The voltage that generates 10 mA current over the reference PMJTC and PMJTC under calibration was generated with two universal calibrators (Fluke 5440B for DC voltage and Fluke 5700A for AC voltage). To switch between AC and DC voltage two-terminal switch was used. Output of the switch was connected directly to current T-piece. Reference PMJTC was connected to floating side of T-piece and PMJTC under calibration to grounded side. Output of both PMJTCs was measured with two DMM's (Agilent 3458A). Shielding of the cable that connects

PMJTC and DMM was connected to GUARD on DMM (GRD set to Open) and to input of the PMJTC. Laboratory's GROUND was connected to both calibrators GRD (GND and GRD was not connected and both calibrators were set to EXT GRD). Laboratory's GROUND was also connected to Lo terminal of the switch (switch has common Lo for both inputs and output) and to the T-Piece.

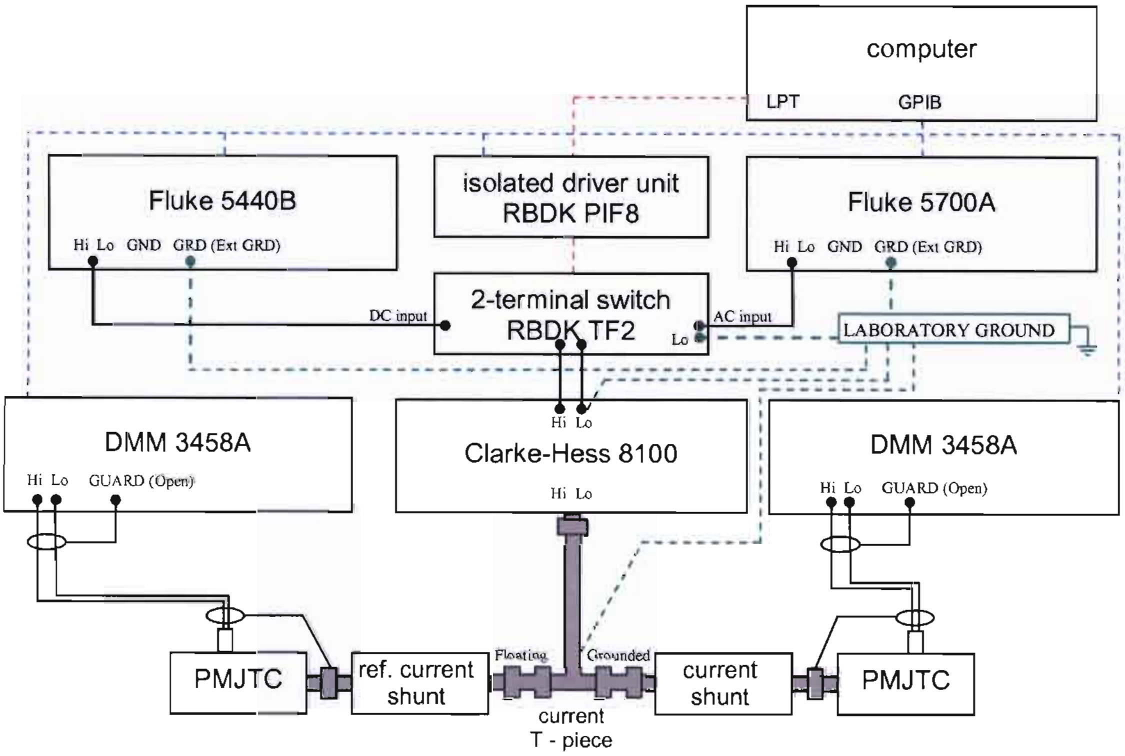


Figure 3.2: Setup for calibration of 5 A current (PMJTC + 5 A current shunt)

To calibrate 5A current (PMJTC with 5 A current shunt) the same setup as described above was used. The only difference is that the trans-conductance amplifier Clarke Hess 8100 was used between the switch and T-piece to generate AC and DC currents. Laboratory's GROUND was connected also to the Lo input of the trans-conductance amplifier.

When the current is applied to the measuring setup for the first time the time of stabilization was more than 30 minutes.

All readings from readout instruments are taken simultaneously over the GPIB.

3.3 Measurement procedure

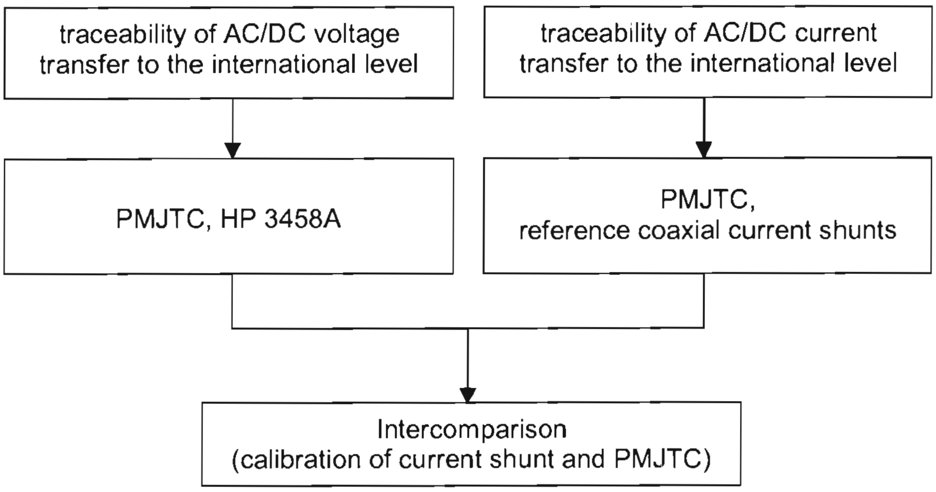
A set of AC1, DC+, AC2, DC-, AC3 measurements was repeated five times. From each set an AC/DC difference is calculated.

Three measured values are obtained in this way (minimum and maximum value from set of five was abandoned) and the actual AC/DC difference is calculated as their mean, while the standard deviation is used to calculate the type A uncertainty contribution.

At the beginning DC+, DC- and AC sequence is measured. On that basis first the generated DC- current is correct in the way that the output at DC+ and DC- are equal. Then also the generated AC current is corrected in the way that the output of the PMJTC at AC current is the same as it would be for the average of DC+ and DC- current. In this way it is assured that the PMJTC's are working as much as possible in the same working point for all three voltages, DC+, DC- and AC.

3.4 Traceability

Traceability is ensured over the accredited calibration of reference PMJTC and current shunts in foreign PTB. For readout two calibrated reference multimeters HP 3458A are used. Multimeters are calibrated in SIQ.



3.5 Ambient conditions

During the intercomparison the ambient conditions in the laboratory were within the limits:

- temperature: 23°C ± 2°C,
- relative humidity: 50 % ± 20 %.

4 Results

Time of comparison: 01.12.2014 – 12.12.2014

Measurement results:

Current	Measured ac/dc current difference (μA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	7	0	0	0	0	1	3
5 A	-2	0	1	-10	-21	-46	-59

Expanded uncertainty:

Current	Expanded uncertainty (μA/A) at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA	8	4	4	4	4	4	5
5 A	14	13	13	13	13	16	26

Measurement frequency:

	Nominal frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Measured frequency	9,99997 Hz	54,9998 Hz	0,999997 kHz	9,99997 kHz	19,99994 kHz	49,9998 kHz	99,9997 kHz
Expanded uncertainty	0,00012 Hz	0,0007 Hz	0,000012 kHz	0,00012 kHz	0,00024 kHz	0,0006 kHz	0,0012 kHz

Environmental parameters:

	Min	Max	Remarks
Ambient temperature (°C)	22,3°C	23,4°C	Two weeks min/max value
Relative humidity (%)	35%	42%	Two weeks min/max value

5 Measurement uncertainty

Parameters description:

δ_{AVG} average value of measured ac/dc transfer differences,

st.dev. standard deviation of measured ac/dc transfer difference,

δ_S ac/dc transfer difference of reference shunt,

δ_{PMJTC} ac/dc transfer difference of reference PMJTC,

u_{RESS} uncertainty due to the resolution of DMM1,

u_{RESX} uncertainty due to the resolution of DMM2,

u_{LTS} uncertainty due to the long term stability of reference current shunt,

u_{LD} uncertainty due to the level dependence of the thermal converter,

u_{REP} uncertainty due to the reproducibility of the measurement,

u_{TD} uncertainty due to temperature dependence.

5.1 10 mA @ 10 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	0,7 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
δ_{AVG}	0,7 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	6,0 ppm	2,0 ppm	normal	2	1	-	2,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	1,7 ppm	rectangular	1,73	1	-	1,73 ppm	1E+99
u_{LD}	0 ppm	1,7 ppm	rectangular	1,73	1	-	1,73 ppm	1E+99
u_{REP}	0 ppm	1,7 ppm	rectangular	1,73	1	-	1,73 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	6,7 ppm						3,7 ppm	687494
			Expanded uncertainty of measurement:				7,4 ppm	

5.2 10 mA @ 55 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	0,2 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	0,2 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	0,0 ppm	1,5 ppm	normal	2	1	-	1,50 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	0,2 ppm						1,9 ppm	53865
			Expanded uncertainty of measurement:				3,9 ppm	

5.3 10 mA @ 1 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	-0,2 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	-0,2 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	0,0 ppm	1,5 ppm	normal	2	1	-	1,50 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	-0,2 ppm						1,9 ppm	53865
			Expanded uncertainty of measurement:				3,9 ppm	

5.4 10 mA @ 10 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	0,0 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	0,0 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	0,0 ppm	1,5 ppm	normal	2	1	-	1,50 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	0,0 ppm						1,9 ppm	53865
			Expanded uncertainty of measurement:				3,9 ppm	

5.5 10 mA @ 20 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	0,1 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	0,1 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	0,0 ppm	1,5 ppm	normal	2	1	-	1,50 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	0,1 ppm						1,9 ppm	53865
			Expanded uncertainty of measurement:				3,9 ppm	

5.6 10 mA @ 50 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	0,2 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	0,2 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	1,0 ppm	1,5 ppm	normal	2	1	-	1,50 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	1,2 ppm						1,9 ppm	53865
		Expanded uncertainty of measurement:					3,9 ppm	

5.7 10 mA @ 100 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	0,9 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	0,9 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	2,0 ppm	2,0 ppm	normal	2	1	-	2,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	2,9 ppm						2,4 ppm	115094
		Expanded uncertainty of measurement:					4,7 ppm	

5.8 5 A @ 10 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	-0,6 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	-0,6 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	1,8 ppm	6,0 ppm	normal	2	1	-	6,00 ppm	1E+99
δ_{TC}	1,0 ppm	3,0 ppm	normal	2	1	-	3,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	2,2 ppm						6,8 ppm	8122394
					Expanded uncertainty of measurement:		13,6 ppm	

5.9 5 A @ 55 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	-0,5 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	-0,5 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	0,0 ppm	6,0 ppm	normal	2	1	-	6,00 ppm	1E+99
δ_{TC}	1,0 ppm	2,0 ppm	normal	2	1	-	2,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	0,5 ppm						6,4 ppm	6470894
					Expanded uncertainty of measurement:		12,9 ppm	

5.10 5 A @ 1 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	-0,4 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	-0,4 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	0,0 ppm	6,0 ppm	normal	2	1	-	6,00 ppm	1E+99
δ_{TC}	1,0 ppm	2,0 ppm	normal	2	1	-	2,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	0,6 ppm						6,4 ppm	6470894
			Expanded uncertainty of measurement:				12,9 ppm	

5.11 5 A @ 10 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	-9,0 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	-9,0 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	0,3 ppm	6,0 ppm	normal	2	1	-	6,00 ppm	1E+99
δ_{TC}	-1,0 ppm	2,0 ppm	normal	2	1	-	2,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	-9,7 ppm						6,4 ppm	6470894
			Expanded uncertainty of measurement:				12,9 ppm	

5.12 5 A @ 20 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	-20,3 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	-20,3 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	1,5 ppm	6,0 ppm	normal	2	1	-	6,00 ppm	1E+99
δ_{TC}	-2,0 ppm	2,0 ppm	normal	2	1	-	2,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	-20,8 ppm						6,4 ppm	6470894
			Expanded uncertainty of measurement:				12,9 ppm	

5.13 5 A @ 50 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	-40,7 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Div.	Sensitivity coefficient c_i		Uncertainty contribution $u_i(y)$	Effective degr. of freedom v_i
δ_{AVG}	-40,7 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_S	4,1 ppm	7,5 ppm	normal	2	1	-	7,50 ppm	1E+99
δ_{TC}	-9,0 ppm	2,0 ppm	normal	2	1	-	2,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_X	-45,6 ppm						7,9 ppm	14317515
			Expanded uncertainty of measurement:				15,7 ppm	

5.14 5 A @ 100 kHz

Mathematical model of measurement:

	result	
δ_{AVG}	-49,9 ppm	
st.dev.	0,2 ppm	(value based on validation)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*
δ_{AVG}	-49,9 ppm	0,2 ppm	normal	1	1	-	0,20 ppm	6
δ_{S}	9,0 ppm	12,5 ppm	normal	2	1	-	12,50 ppm	1E+99
δ_{TC}	-18,0 ppm	3,0 ppm	normal	2	1	-	3,00 ppm	1E+99
u_{RESS}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{RESX}	0 ppm	0,3 ppm	rectangular	1,73	1	-	0,29 ppm	1E+99
u_{LTS}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{LD}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{REP}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
u_{TC}	0 ppm	0,6 ppm	rectangular	1,73	1	-	0,58 ppm	1E+99
δ_{X}	-58,9 ppm						12,9 ppm	104320890
			Expanded uncertainty of measurement:				25,8 ppm	

6 Measurement uncertainty - summary

Measurement current: 10 mA

Contribution of:	Standard uncertainty (µA/A) at frequency							Type A / Type B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Standard deviation of ac/dc difference	0,2	0,2	0,2	0,2	0,2	0,2	0,2	A	normal
Unc. of PMJTC from cerfiticate	4,0	3,0	3,0	3,0	3,0	3,0	4,0	B	normal
Resolution on ref DMM	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Resolution on UUT DMM	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Long term stability of ref. current shunt	3,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Level dependence of thermal converter	3,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Reproducibility of measurement	3,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Temperature dependance	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular

Standard uncertainty:	3,7	1,9	1,9	1,9	1,9	1,9	2,4
Expanded Uncertainty:	7,4	3,9	3,9	3,9	3,9	3,9	4,7
Coverage factor *k* :	2	2	2	2	2	2	2

Measurement current: 5 A

Contribution of:	Standard uncertainty (µA/A) at frequency							Type A or Type	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Standard deviation of ac/dc difference	0,2	0,2	0,2	0,2	0,2	0,2	0,2	A	normal
Unc. of ref. shunt from cerfiticate	12,0	12,0	12,0	12,0	12,0	15,0	25,0	B	normal
Unc. of PMJTC from cerfiticate	6,0	4,0	4,0	4,0	4,0	4,0	6,0	B	normal
Resolution on ref DMM	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Resolution on UUT DMM	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Long term stability of ref. current shunt	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Level dependence of thermal converter	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular
Reproducibility of measurement	1,0	1,0	1,0	1,0	1,0	1,0	1,0	B	rectangular

Standard uncertainty:	6,8	6,4	6,4	6,4	6,4	7,8	12,9
Expanded Uncertainty:	13,6	12,8	12,8	12,8	12,8	15,7	25,8
Coverage factor *k*:	2	2	2	2	2	2	2