EURAMET.EM-S39 – Final Report

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Participants

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Scope

Justervesenet (JV) has produced a set of Current Shunts to be used as Current Transfer Standards with nominal values ranging from 30 mA to 20 A. The Current Shunts were developed as part of the EMRP project "Power & Energy" in which one set of shunts would be made available for comparison between NMIs. The Shunts have been designed for operation together with 90 Ω planar multi-junction thermal converters, where a nominal current input will produce a voltage drop of about 1 V across the shunt.

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.

Travelling Standards

The traveling standards (see Figure 1) consist of 8 JV AC-DC current shunts with nominal operating current values of 30 mA (#1212043), 100 mA (#1212036), 300 mA (#1301008), 1 A (#1301009), 3 A (#1301001), 5 A (#1212023), 10 A (#1301022) and 20 A (#1301017). The shunts are produced at NOTE NORGE AS located at Kjeller, Norway, based on a design made by JV.

Figure 1: The current shunts viewed from the output side. The 20 A shunt has UHF input connector, while all the others have N connectors.

Measuring Conditions

- If the AC-DC difference of the connected thermal converters is *not* known, the contribution of the thermal converters must be eliminated by switching the positions of them and averaging the results.
- The results must *either* be averaged from measurements of the shunt in both "Lo" and "Hi" position, *or* if it is to be measured only in the "Lo" position, the asymmetry of the setup must be accounted for in the uncertainty budget.
- At least 1 hour should be allowed for stabilization after the first application of current, and sufficient delay time should be used between successive applications of alternating and direct current.
- Recommended ambient conditions are 23±1 °C and a relative humidity of 45±5 %.

Measurement Procedure

The AC-DC difference of each Shunt is measured at its nominal current and the following frequencies:

10 Hz, 20 Hz, 55 Hz, 110 Hz, 400 Hz, 1 kHz, 5 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz.

In addition the 5 A and 20 A Shunts were measured at 3 A and 10 A, respectively, by JV.

Results

The following tables are a summary of the results, stated in μA/A, with calculated uncertainties (k=2). At the start of the measurement, there was a slight misunderstanding between the participants, leading PTB to measure at 120 Hz instead of 110 Hz. The difference is expected to be small, and should be well covered by the uncertainty range of the results.

Results from PTB

Table 1: AC-DC difference (μA/A)

	30 mA	100 mA	300 mA	1 A	3 A	5 A	10 A	20 A
10 Hz	0.3	0.4	-0.4	1.6	-0.2	1	-2	-1
20 Hz	-0.3	-0.3	-1.2	-0.2	-0.1	1	0	-1
55 Hz	0.2	0.3	-0.7	0.3	0.1	2	1	0
120 Hz	0.0	0.4	-0.4	0.3	0.0	1	0	-1
400 Hz	-0.3	-0.4	-1.0	0.3	0.4	2	0	0
1 kHz	0.0	0.4	-0.6	-0.3	0.2	1	0	0
5 kHz	0.0	0.3	-0.8	0.1	-0.4	0	0	0
10 kHz	-0.7	-0.5	-0.5	-0.8	-0.8	0	0	0
20 kHz	-0.1	0.2	-2.5	-2.7	-1.7	-2	-6	-4
50 kHz	-1.4	0.9	-4.7	-4.7	-5	-7	-17	-12
100 kHz	-3.6	0.7	-7.0	-4	-7	-8	-18	-6

Table 2: Calculated uncertainties (μA/A, k=2)

	30 mA	100 mA	300 mA	1 A	3 A	5 A	10 A	20 A
10 Hz	3.4	3.4	4.4	4.4	5.2	11	20	22
20 Hz	3.4	3.4	4.4	4.4	5.2	11	20	22
55 Hz	1.8	1.8	2.4	2.6	3.6	11	20	22
120 Hz	1.8	1.8	2.4	2.4	3.6	11	20	22
400 Hz	1.8	1.8	2.4	2.6	3.6	11	20	22
1 kHz	2.0	2.0	2.4	2.4	3.6	11	20	22
5 kHz	1.9	1.9	2.4	2.6	3.6	11	20	22
10 kHz	1.7	1.7	2.4	2.4	3.6	11	20	22
20 kHz	1.9	1.9	3.6	3.6	5.6	11	26	30
50 kHz	2.4	2.4	5.4	5.6	8.0	12	38	44
100 kHz	4.2	4.2	5.4	8.8	15	24	70	86

Results from JV

Table 3: AC-DC difference (µA/A)

	30mA	30mA - Control	100mA	300mA	1A	3A	5A	10A	20A	20A - Control	20A @ 10A	5 A @ 3A
10 Hz	0.3	0.2	-0.5	-0.6	-0.7	-0.3	0	-1	0	1	1	0
20 Hz	0.1		0.3	0.2	-0.1	0.2	0.7	0.2	1		1	0.6
55 Hz	0.1	0.0	-0.2	-0.5	-0.8	-0.4	0.0	-0.2	0.2	0.1	0.0	0.0
110 Hz	0.0		-0.1	-0.4	-0.6	-0.4	0.0	-0.1	-0.1		0.1	-0.1
400 Hz	0.0	0.0	0.1	-0.1	-0.2	0.0	-0.6	0.0	-0.1	0.0	-0.2	-0.6
1 kHz	0.0	0.0	0.0	-0.1	-0.4	-0.2	0.1	0.1	0.4	0.2	0.2	0.0
5 kHz	-0.1		0.1	-0.3	-0.6	0.0	-0.4	0.4	0.5		0.4	-0.3
10 kHz	-0.2		0.1	-0.7	-0.6	-0.3	0.2	0.2	0.8		0.7	-0.1
20 kHz	-0.3	-0.4	0.5	-0.9	-0.3	-0.1	0.3	0.6	2.3	2.3	2.4	0.4
50 kHz	-0.8		1.2	-3.4	-1.8	-2.3	-2.4	-1.5	4.7		5	-2.8
100 kHz	-1.7	-2.2	2.2	-5.0	-2.1	-3.3	-5	-2	10	10	10	-6

Table 4: Calculated uncertainties (µA/A, k=2)

	30mA	100mA	300mA	1A	3A	5A	10A	20A	20A @ 10A	5 A @ 3A
10 Hz	5.3	6.1	7.5	8.6	10	10	11	12	12	10
20 Hz	4.4	4.9	6.0	6.9	8.2	8.4	9.2	10	10	8.4
55 Hz	3.4	3.7	4.5	5.1	6.4	6.6	7.2	7.9	8.2	6.6
110 Hz	3.4	3.7	4.5	5.1	6.4	6.6	7.2	7.9	8.2	6.6
400 Hz	3.3	3.5	4.3	4.9	6.2	6.4	7.0	7.6	7.9	6.4
1 kHz	3.3	3.4	4.2	4.8	6.1	6.3	6.9	7.6	7.8	6.3
5 kHz	3.4	3.4	4.2	4.9	6.2	6.4	6.9	7.6	8.2	6.4
10 kHz	3.4	3.5	4.3	4.9	6.2	6.3	7.0	7.6	8.2	6.3
20 kHz	3.4	3.5	4.3	4.9	6.2	6.7	7.2	8.0	9.0	6.7
50 kHz	3.5	3.7	4.5	5.0	6.4	7.4	8.0	9.3	11	7.4
100 kHz	3.8	4.0	4.9	5.5	7.6	10	11	13	15	10

Comparison of the results

From the tables above, the degree of equivalence E_n can be calculated as:

$$E_n = \frac{|\delta_{PTB} - \delta_{JV}|}{(u_{PTB}^2 + u_{JV}^2)},$$

where $\delta_{PTB/JV}$ is the reported AC/DC difference and $u_{PTB/JV}$ is the calculated uncertainty (k = 2). As can be seen from Figure 2, the E_n value is below 0.4 for all the measured points in the comparison.

Table 5: Degree of equivalence E$_n$

	30 mA	100 mA	300 mA	1 A	3 A	5 A	10 A	20 A
10 Hz	0.01	0.12	0.03	0.24	0.01	0.09	0.06	0.06
20 Hz	0.06	0.10	0.18	0.01	0.04	0.02	0.01	0.08
55 Hz	0.04	0.13	0.03	0.20	0.07	0.16	0.06	0.01
120 Hz	0.00	0.12	0.00	0.16	0.05	0.08	0.01	0.04
400 Hz	0.07	0.12	0.19	0.10	0.05	0.21	0.00	0.00
1 kHz	0.01	0.11	0.10	0.02	0.06	0.07	0.00	0.02
5 kHz	0.03	0.04	0.10	0.12	0.06	0.03	0.02	0.02
10 kHz	0.13	0.16	0.04	0.03	0.07	0.01	0.01	0.03
20 kHz	0.05	0.08	0.28	0.39	0.19	0.18	0.24	0.20
50 kHz	0.15	0.06	0.18	0.39	0.26	0.32	0.40	0.37
100 kHz	0.34	0.27	0.28	0.18	0.22	0.10	0.22	0.19
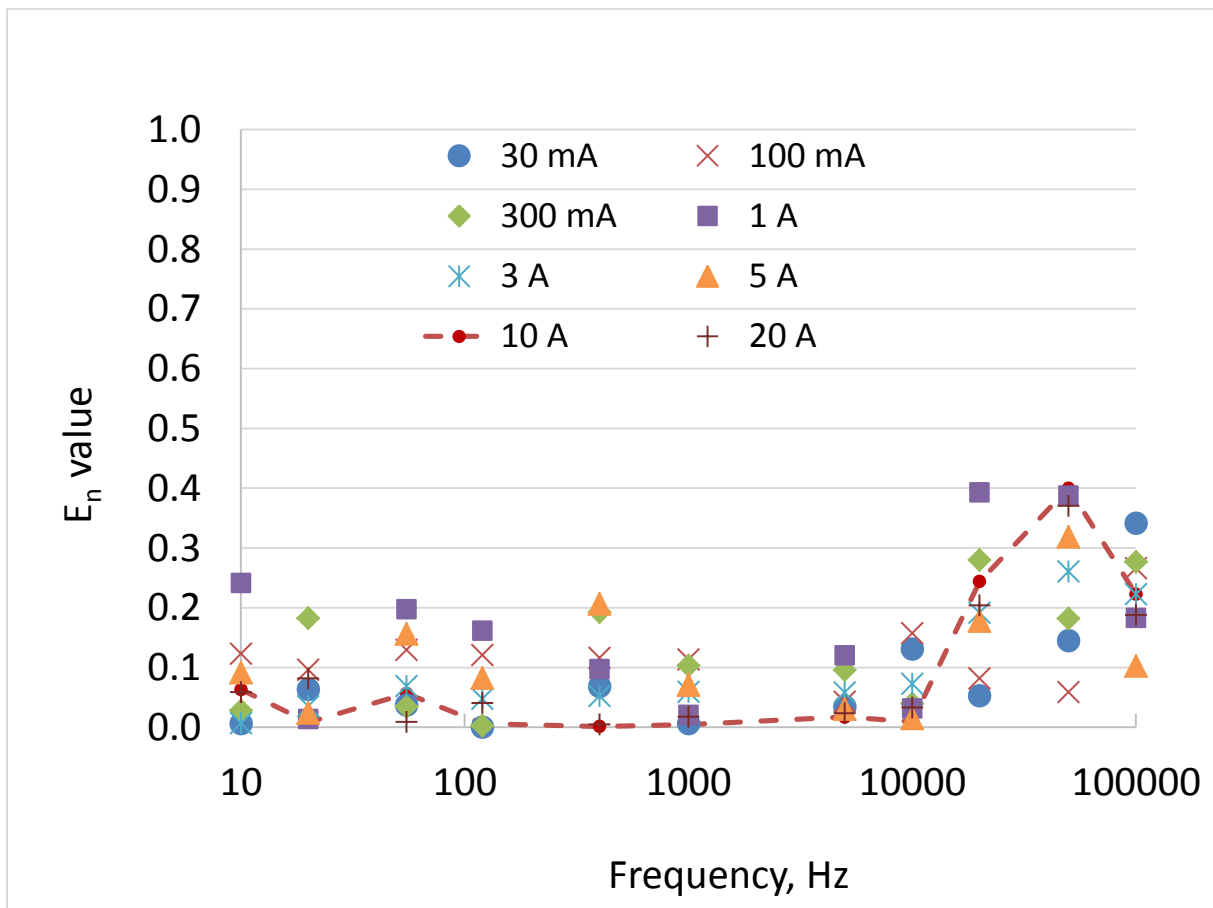
Figure 2: Degree of equivalence between the measurements in the comparison, from table 5.

The figures below, show detailed graphs of the results presented in tables 1-4.
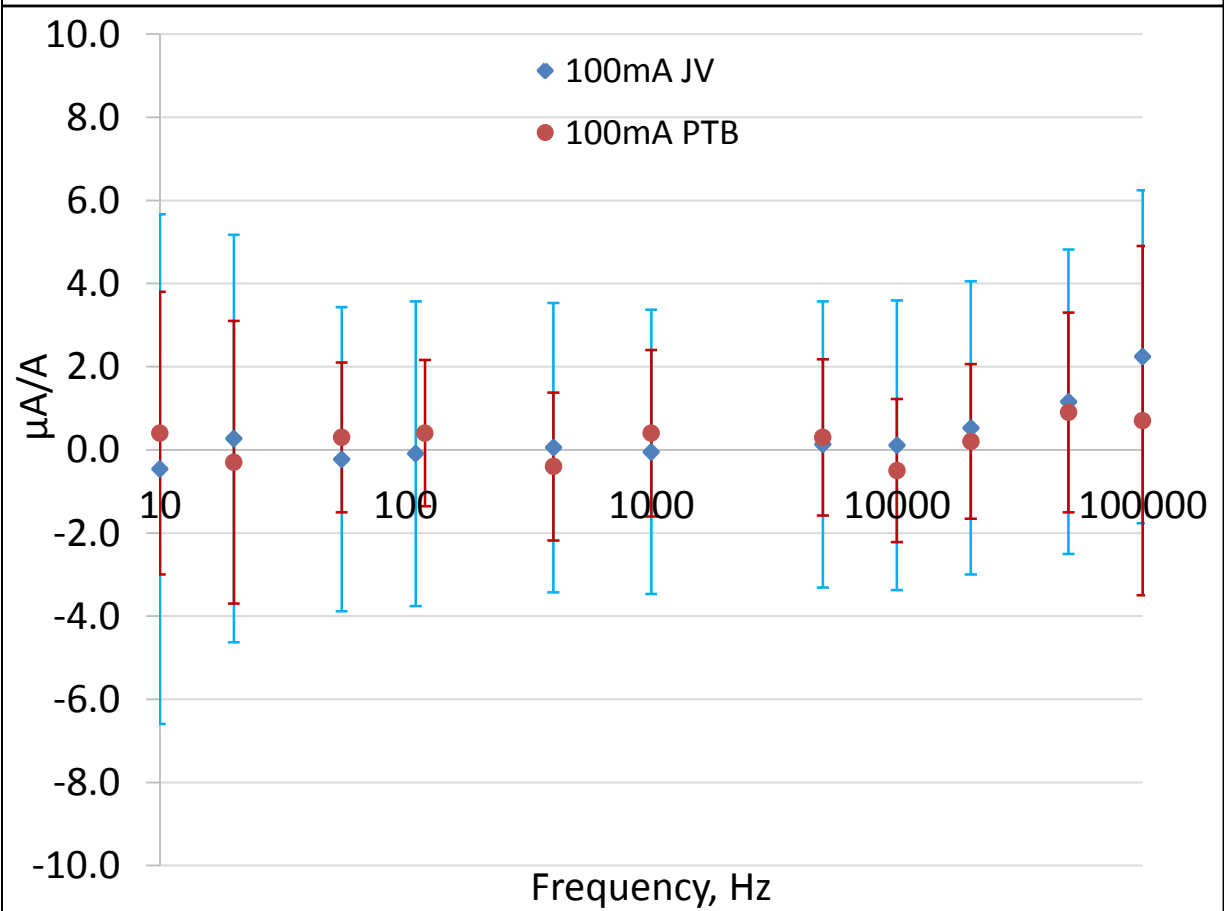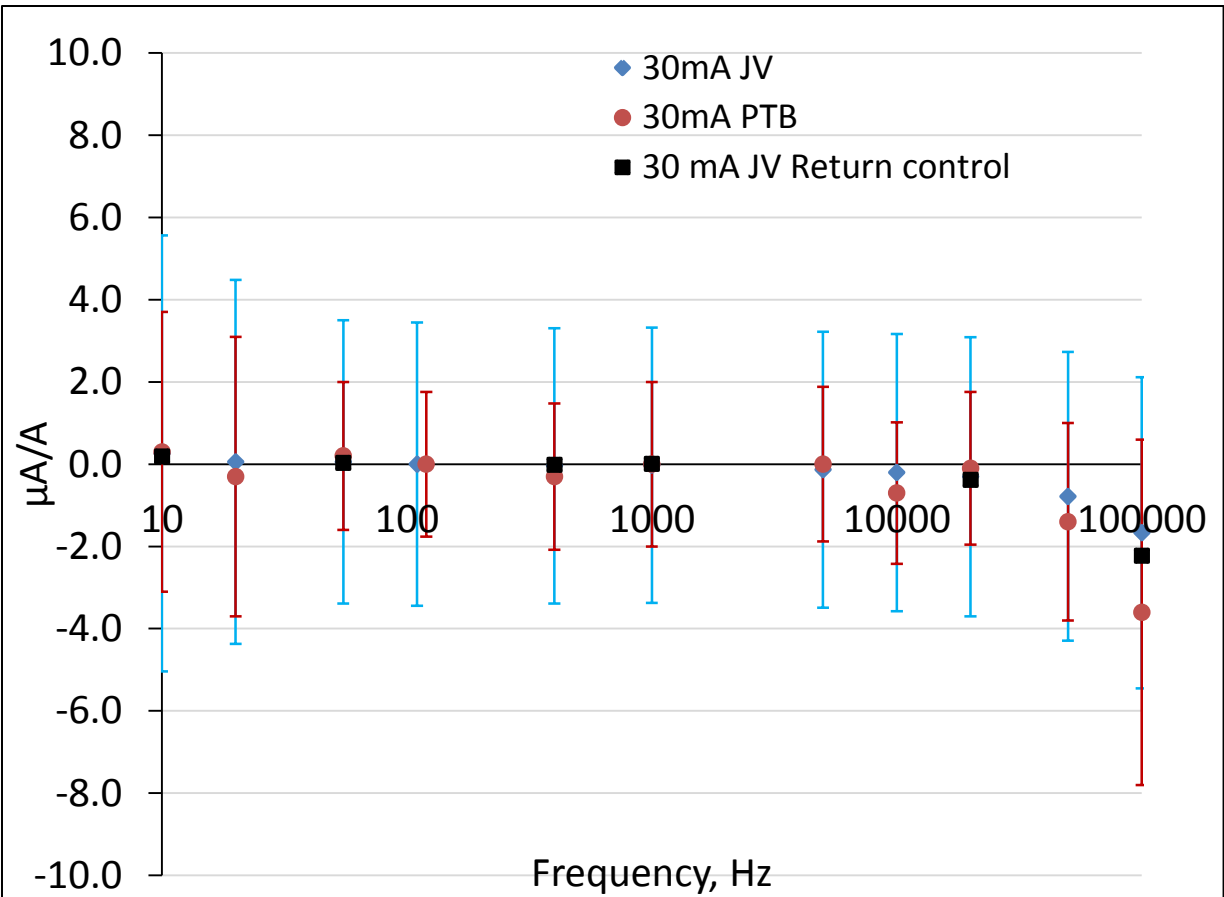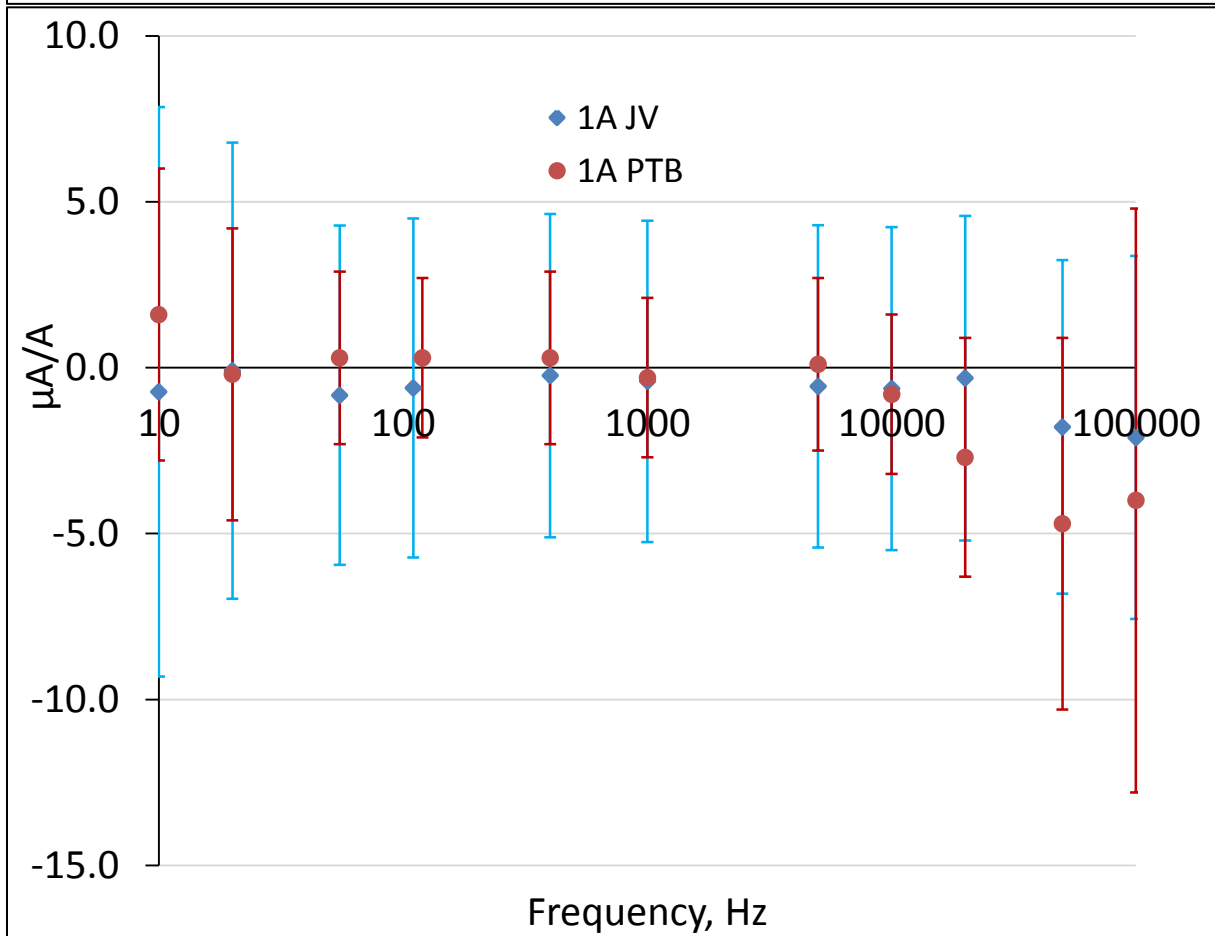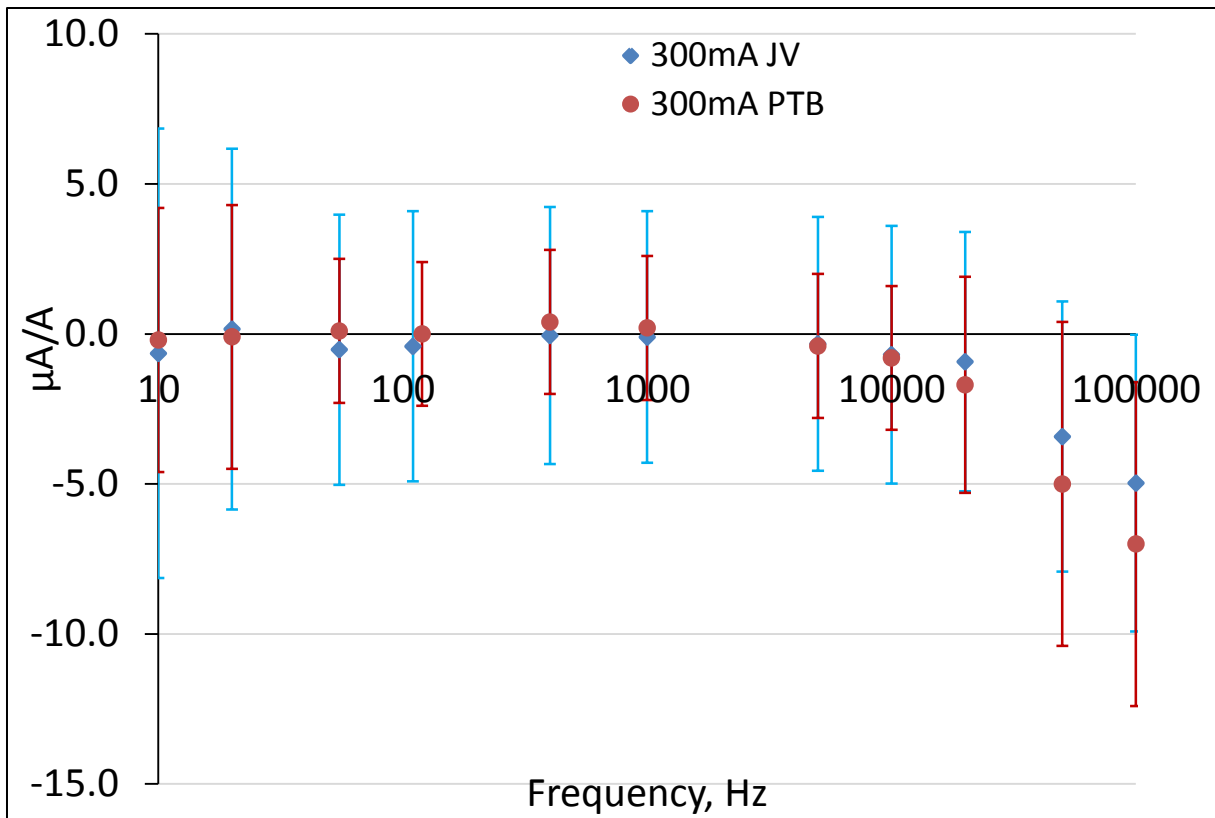
Summary of results and conclusion

The measurements were conducted according to plan, and no unexpected incidents were reported. Comparison of the results show that for frequencies below 10 kHz, the results are virtually the same. Above 10 kHz, 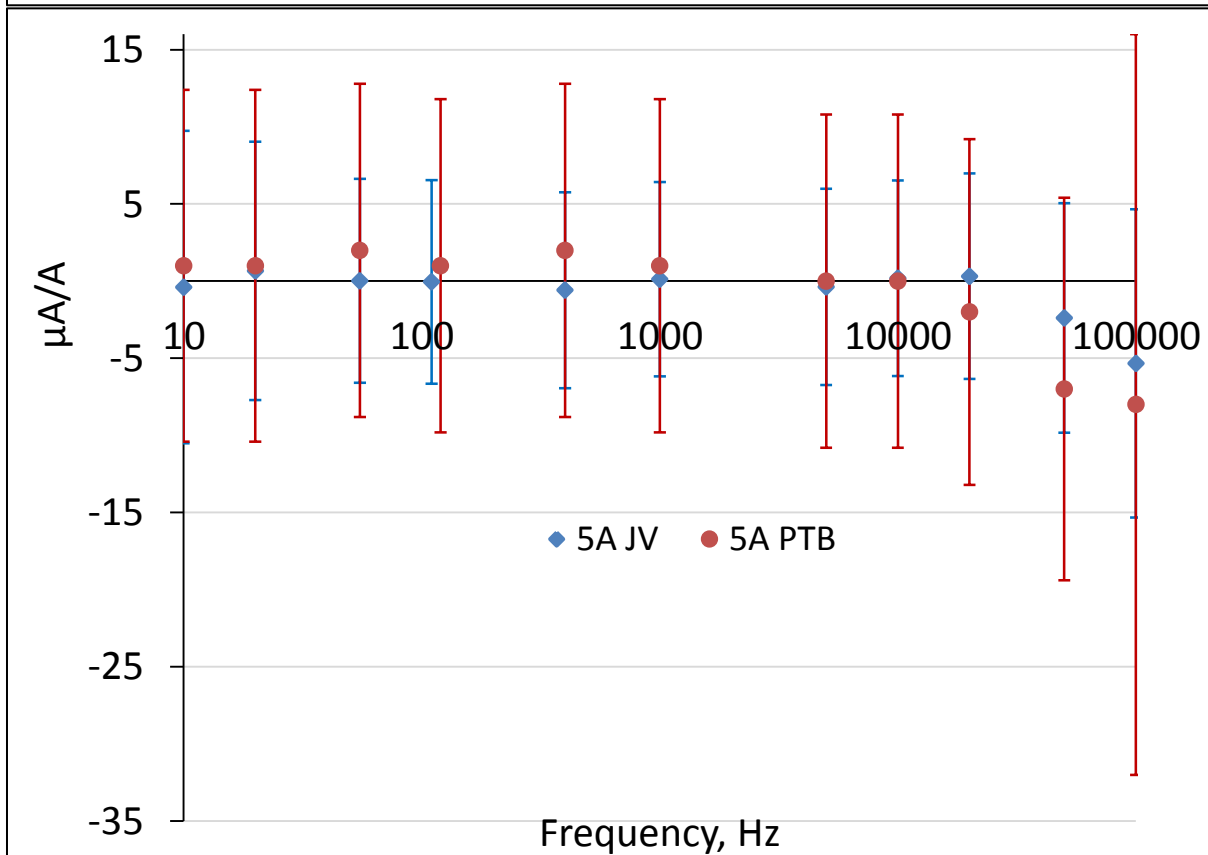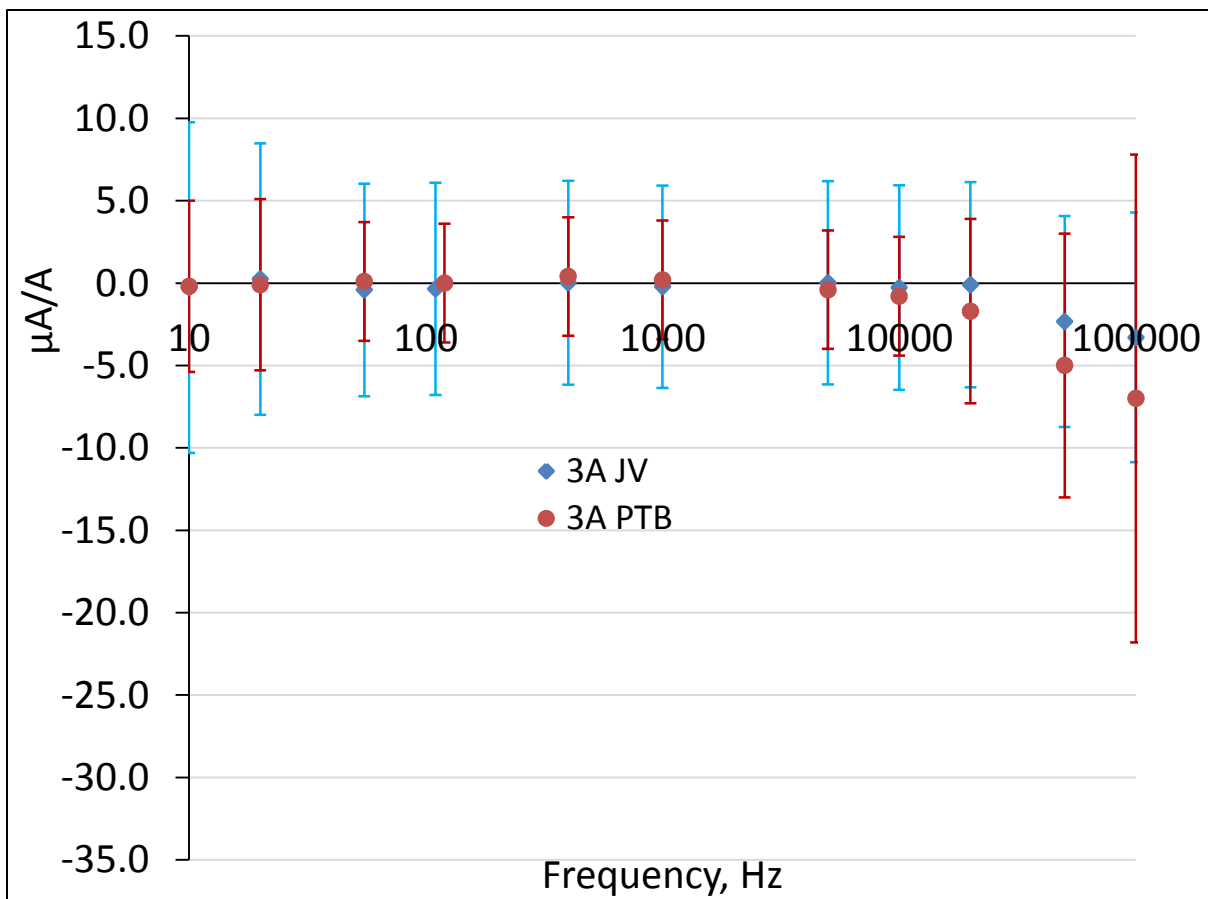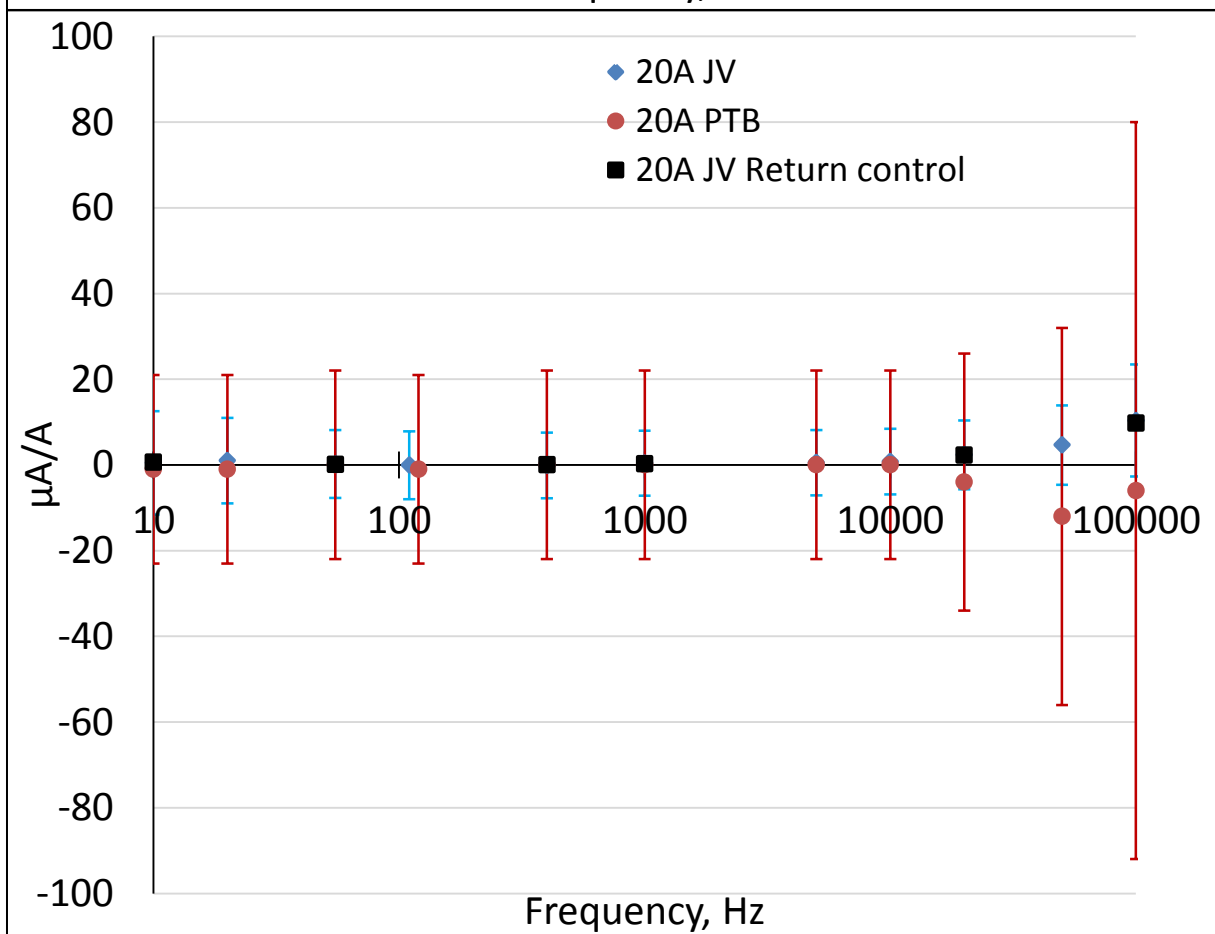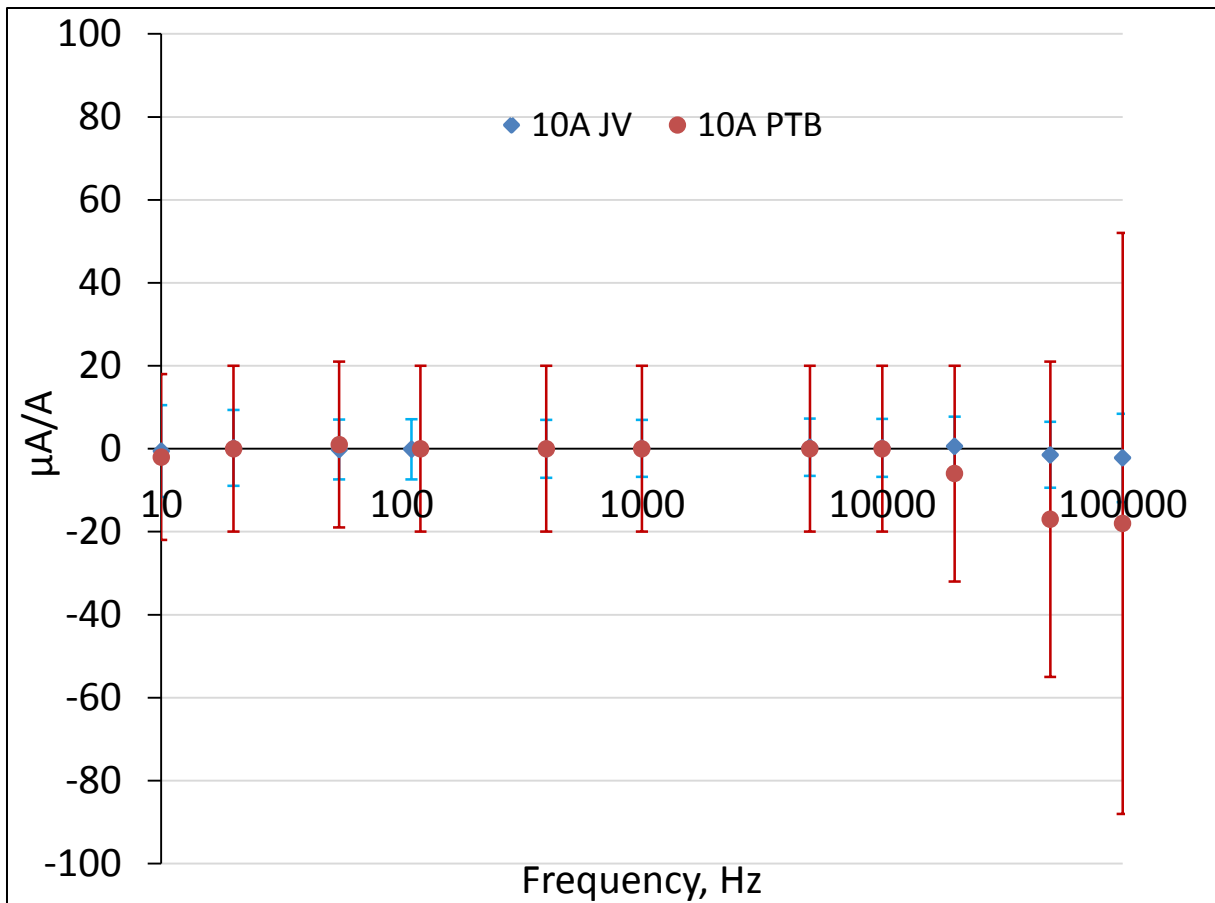it appears as if there is a systematic deviation between the two laboratories, which is most prominent for the two highest currents. The measurements from PTB, above 10 kHz, show an inductive behavior, relative to the JV measurements, which leads to a tendency for negative AC-DC difference. The fact that the deviation increases quite linearly with frequency, indicates that the deviation is due to a systematic difference between the laboratories. However, the results are well within the uncertainties from both laboratories for all points. A clear explanation for the deviation cannot be given at the present time, but plans are being made for a deeper investigation of this effect, which likely arises from the difference in choice of reference shunts[1] and/or the guarding[2] of the measurements equipment.

A control measurement was performed on two of the shunts (30 mA and 20 A) after return from PTB. Both shunts showed very small or no deviation from the first measured values.

In the appendix, reports from both participants are included, where a detailed description of the uncertainties are given.

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[1] Lind, K., Sorsdal, T., & Slinde, H. (2008). Design, modeling, and verification of high-performance AC–DC current shunts from inexpensive components. *Instrumentation and Measurement, IEEE Transactions on*, *57*(1), 176-181.

[2] Funck, T., & Klonz, M. (2007). Improved AC–DC current transfer step-up with new current shunts and potential driven guarding. *Instrumentation and Measurement, IEEE Transactions on*, *56*(2), 361-364.

Shunt measurements at PTB

For ac-dc current transfer, the following current transfer standards are used at PTB:

- From 20 mA to 300 mA shunt resistors made up from four to six parallel resistors mounted in a star configuration directly on a type N or GR 874 connector
- From 500 mA to 10 A commercially available shunts made by Holt
- Between 20 A and 100 A commercially available shunts made by Fluke

All shunts are of coaxial design to minimize inductive coupling and are designed to provide a nominal output voltage of 1 V or 0.8 V for nominal currents above 10 A. Each shunt is equipped with a 90 Ω planar multijunction thermal converter (PMJTC) as the actual transfer device. For the small currents the loading due to the parallel connection of the PMJTC was taken into account when designing the shunts resistance value.

A single quartz PMJTC with 117 Ω heater resistance operated between 20 mA and 40 mA is used to calibrate the standards rated from 20 mA to 100 mA in the first upward step. From here three step-up chains are made up: The first consisting only of the 200 mA standard, the second running from 300 mA via 1 A and 3 A to 10 A and the third chain consisting of the standards for 500 mA, 2.5 A, 5 A, and 20 A. Also 50 A and finally 100 A are in this chain.

The actual shunt comparison measurements were carried out as follows:

1. The shunt under calibration was equipped with a 90 Ω PMJTC, which was used as a voltage transfer standard and had been calibrated at 1 V before.
2. This shunt-PMJTC combination was calibrated with the usual ac-dc current transfer calibration procedure using the ac-dc transfer difference of the current transfer standard, δ_{S_I}, and the measured difference δ_D:
   $\delta_X = \delta_{S\_I} + \delta_D$
3. From the such measured ac-dc transfer difference of the shunt-PMJTC combination the ac-dc transfer difference of the PMJTC, δ_{S_U}, was subtracted to obtain the ac-dc transfer difference of the shunt alone:
   $\delta_{shunt} = \delta_{S\_I} + \delta_D - \delta_{S\_U}$

The measurements are traceable to the realization of ac-dc transfer difference at PTB.

To calculate the uncertainties of measurement, the following sources of uncertainties are considered:

- $u(\delta_{S\_I})$, the uncertainty of the current transfer standard used
- $u(\delta_D)$, the uncertainty of the difference measurement
- $u(\delta_M)$, the uncertainty due to different measurement stations
- $u(\delta_A)$, the uncertainty due to the standard deviation of the measurements
- $u(\delta_P)$, the uncertainty due to the power dependence
- $u(\delta_{LF})$, the uncertainty due to the low frequency ripple
- $u(\delta_{S\_U})$, the uncertainty of the voltage transfer standard used

So the full model equation makes up as:

$\delta_{shunt} = \delta_{S\_I} + \delta_D + \delta_M + \delta_A + \delta_P + \delta_{LF} - \delta_{S\_U}$

Since the model equation is a sum and all partial uncertainties are of normal distribution, a simple root of sum of squares can be used for evaluation of the uncertainties.

Dates and environmental conditions

Shunt	SN		Date	Temperature	Humidity
JV-30mA	#1212043	max	2014-01-03	23,5 °C	36,1 %
		min	2014-01-03	22,5 °C	34,5 %
JV-100mA	#1212036	max	2013-12-16	22,5 °C	35,1 %
		min	2013-12-13	22,0 °C	32,4 %
JV-300mA	#1301008	max	2013-12-17	22,8 °C	35,8 %
		min	2013-12-16	22,0 °C	34,0 %
JV-1A	#1301009	max	2014-01-02	23,2 °C	35,1 %
		min	2014-01-02	22,5 °C	33,2 %
JV-3A	#1301001	max	2014-01-06	22,8 °C	35,9 %
		min	2014-01-06	22,4 °C	30,8 %
JV-5A	#1212023	max	2014-01-07	22,5 °C	38,4 %
		min	2014-01-07	22,1 °C	36,1 %
JV-10A	#1301022	max	2014-01-08	22,8 °C	40,2 %
		min	2014-01-08	22,1 °C	37,2 %
JV-20A	#1301017	max	2014-01-09	22,9 °C	38,8 %
		min	2014-01-09	22,1 °C	36,8 %

JV-30mA #1212043	10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
$u(\delta_{S\_I})$	1,2	1,2	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,93	1,3
$u(\delta_D)$	0,05	0,16	0,25	0,14	0,14	0,52	0,28	0,05	0,13	0,02	0,06
$u(\delta_M)$	0,50	0,50	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,40	0,50
$u(\delta_A)$	0,28	0,24	0,12	0,12	0,20	0,08	0,26	0,06	0,33	0,31	0,08
$u(\delta_P)$	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
$u(\delta_{S\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
$u(\delta)$	1,7	1,7	0,90	0,88	0,89	1,0	0,94	0,86	0,93	1,2	2,1

JV-100mA #1212036	10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
$u(\delta_{S\_I})$	1,2	1,2	0,58	0,58	0,58	0,58	0,58	0,58	0,58	0,93	1,3
$u(\delta_D)$	0,12	0,09	0,45	0,07	0,23	0,01	0,15	0,16	0,06	0,05	0,24
$u(\delta_M)$	0,50	0,50	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,40	0,50
$u(\delta_A)$	0,19	0,46	0,11	0,23	0,38	0,46	0,27	0,11	0,15	0,12	0,12
$u(\delta_P)$	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
$u(\delta_{S\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
$u(\delta)$	1,7	1,8	0,98	0,89	0,97	0,98	0,91	0,88	0,87	1,2	2,1

JV-300mA #1301008	10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
$u(\delta_{S\_I})$	1,8	1,8	0,83	0,83	0,83	0,83	0,83	0,83	0,85	0,89	1,8
$u(\delta_D)$	0,25	0,28	0,35	0,08	0,21	0,19	0,18	0,23	0,10	0,22	0,06
$u(\delta_M)$	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	1,0
$u(\delta_A)$	0,18	0,20	0,16	0,16	0,18	0,22	0,15	0,14	0,18	0,15	0,19
$u(\delta_P)$	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	1,5	2,5	0,5
$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
$u(\delta_{S\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
$u(\delta)$	2,2	2,2	1,2	1,2	1,2	1,2	1,2	1,2	1,8	2,7	2,7

JV-1A	#1301009		10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
		$u(\delta_{s\_I})$	1,8	1,8	0,83	0,83	0,83	0,83	0,83	0,83	0,85	0,89	1,8
		$u(\delta_D)$	0,02	0,12	0,29	0,10	0,12	0,14	0,36	0,19	0,02	0,19	0,10
		$u(\delta_M)$	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	1,0
		$u(\delta_A)$	0,27	0,14	0,40	0,27	0,53	0,29	0,42	0,37	0,24	0,40	0,37
		$u(\delta_P)$	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	1,5	2,5	3,5
		$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
		$u(\delta_{s\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
		$u(\delta)$	**2,2**	**2,2**	**1,3**	**1,2**	**1,3**	**1,2**	**1,3**	**1,2**	**1,8**	**2,8**	**4,4**

JV-3A	#1301001		10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
		$u(\delta_{s\_I})$	2,3	2,3	1,6	1,6	1,6	1,6	1,6	1,6	2,3	3,0	5,1
		$u(\delta_D)$	0,22	0,04	0,01	0,03	0,04	0,08	0,07	0,16	0,28	0,04	0,14
		$u(\delta_M)$	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	0,30	1,0
		$u(\delta_A)$	0,23	0,11	0,23	0,09	0,13	0,12	0,26	0,25	0,08	0,16	0,15
		$u(\delta_P)$	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	1,5	2,5	5,0
		$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
		$u(\delta_{s\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
		$u(\delta)$	**2,6**	**2,6**	**1,8**	**1,8**	**1,8**	**1,8**	**1,8**	**1,8**	**2,8**	**4,0**	**7,4**

JV-5A	#1212023		10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
		$u(\delta_{s\_I})$	2,3	2,3	1,6	1,6	1,6	1,6	1,6	1,6	2,3	3,0	5,1
		$u(\delta_D)$	0,35	0,06	0,10	0,04	0,00	0,12	0,37	0,41	0,38	0,26	0,20
		$u(\delta_M)$	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0	3,0
		$u(\delta_A)$	0,29	0,32	0,29	0,28	0,47	0,34	0,29	0,50	0,36	0,32	0,27
		$u(\delta_P)$	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	10
		$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
		$u(\delta_{s\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
		$u(\delta)$	**5,7**	**5,7**	**5,4**	**5,4**	**5,4**	**5,4**	**5,4**	**5,4**	**5,6**	**6,2**	**12**

JV-10A	#1301022		10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
		$u(\delta_{s\_I})$	8,6	8,6	8,4	8,4	8,4	8,4	8,4	8,4	11	16	31
		$u(\delta_D)$	0,02	0,06	0,11	0,25	0,18	0,32	0,07	0,12	0,13	0,21	0,14
		$u(\delta_M)$	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,5	3,0
		$u(\delta_A)$	0,3	0,2	0,2	0,3	0,3	0,3	0,3	0,2	0,3	0,2	0,2
		$u(\delta_P)$	5,0	5,0	5,0	5,0	5,0	5,0	5,0	5,0	8,0	10	15
		$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
		$u(\delta_{s\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
		$u(\delta)$	10	10	9,8	9,8	9,8	9,8	9,8	9,8	13	19	35

JV-20A	#1301017		10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
		$u(\delta_{s\_I})$	8,6	8,6	8,4	8,4	8,4	8,4	8,4	8,4	11	16	31
		$u(\delta_D)$	0,01	0,03	0,01	0,25	0,27	0,31	0,53	0,21	0,45	0,16	0,35
		$u(\delta_M)$	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,5	3,0
		$u(\delta_A)$	0,1	0,2	0,2	0,2	0,1	0,1	0,2	0,1	0,2	0,2	0,1
		$u(\delta_P)$	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	10	15	30
		$u(\delta_{LF})$	0,50	0,50	0	0	0	0	0	0	0	0	0
		$u(\delta_{s\_U})$	1,0	1,0	0,55	0,55	0,55	0,55	0,55	0,55	0,55	0,55	1,6
		$u(\delta)$	11	11	11	11	11	11	11	11	15	22	43

Shunt	SN	I	f	10 Hz	20 Hz	55 Hz	120 Hz	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
JV-30mA	#1212043	30 mA	$\delta*10^6$	0,3	-0,3	0,2	0,0	-0,3	0,0	0,0	-0,7	-0,1	-1,4	-3,6
			$u*10^6$ (k=1)	1,7	1,7	0,90	0,88	0,89	1,0	0,94	0,86	0,93	1,2	2,1
JV-100mA	#1212036	100 mA	$\delta*10^6$	0,4	-0,3	0,3	0,4	-0,4	0,4	0,3	-0,5	0,2	0,9	0,7
			$u*10^6$ (k=1)	1,7	1,7	0,90	0,88	0,89	1,0	0,94	0,86	0,93	1,2	2,1
JV-300mA	#1301008	300 mA	$\delta*10^6$	-0,4	-1,2	-0,7	-0,4	-1,0	-0,6	-0,8	-0,5	-2,5	-4,7	-7,0
			$u*10^6$ (k=1)	2,2	2,2	1,2	1,2	1,2	1,2	1,2	1,2	1,8	2,7	2,7
JV-1A	#1301009	1 A	$\delta*10^6$	1,6	-0,2	0,3	0,3	0,3	-0,3	0,1	-0,8	-2,7	-4,7	-4
			$u*10^6$ (k=1)	2,2	2,2	1,3	1,2	1,3	1,2	1,3	1,2	1,8	2,8	4,4
JV-3A	#1301001	3 A	$\delta*10^6$	-0,2	-0,1	0,1	0,0	0,4	0,2	-0,4	-0,8	-1,7	-5	-7
			$u*10^6$ (k=1)	2,6	2,6	1,8	1,8	1,8	1,8	1,8	1,8	2,8	4,0	7,4
JV-5A	#1212023	5 A	$\delta*10^6$	1	1	2	1	2	1	0	0	-2	-7	-8
			$u*10^6$ (k=1)	5,7	5,7	5,4	5,4	5,4	5,4	5,4	5,4	5,6	6,2	12
JV-10A	#1301022	10 A	$\delta*10^6$	-2	0	1	0	0	0	0	0	-6	-17	-18
			$u*10^6$ (k=1)	10	10	10	10	10	10	10	10	13	19	35
JV-20A	#1301017	20 A	$\delta*10^6$	-1	-1	0	-1	0	0	0	0	-4	-12	-6
			$u*10^6$ (k=1)	11	11	11	11	11	11	11	11	15	22	43

Shunt calibration at JV

The current shunts have been calibrated with self-made current shunts[1] together with 90 Ω planar multi-junction thermal converters (TVC), where a nominal current input will produce a voltage drop of about 1 V across the shunt. Traceability of the reference shunts is accomplished by a step-up calibration from a 30 mA current shunt with computable AC-DC difference. The contribution of the TVC is eliminated by averaging the results from the two combination of TVC and shunt, while the reference shunt is in "high" position. Asymmetrical contribution of the setup is reduced by averaging the results of the TVC + shunt in both "high" and "low" position. In total, this procedure average the results of the two shunts and two TVC in four combinations.

Uncertainty in current step-up with shunts

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

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

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

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

All expectation values are 0, except from $\delta_{ref1,j}$ and $\delta_{KMRi,j}$. The total uncertainty at step N and frequency j can then be expressed as:

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

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.[2] 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 δ_{lin}. For the step-up of the reference shunts, the linearity of the shunts are also considered, and coveres in δ_{linS}. For direct comparison with a calibrated reference shunt with the same nominal value, and at nominal current, the contribution from the linearity is expected to be very small, and is not included in the uncertainty of the object, but included in the uncertainty of the reference.

$u(\delta_T)$ – *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.[3]

$u(\delta_{KMR})$ – *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[4] 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.

$u(\delta_{ind})$ – *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 $s_{i,j}$. In the measurements conducted in this comparison, standard deviations are typically in the range 0.1 - 0.3 ppm.

Date and environment

The shunts were calibrated during a time period from 22.06.2013-22.11.2013 and control measurements, as well as the full range of the 20 A were performed during the time period 06.06.2013-24.06.2014. During this time, the temperature was kept at 23 °C ± 1 °C with a relative humidity of 45% $\pm$ 5%.

Notes

[1]K. Lind, T. Sørsdal, and H. Slinde. "Design, modeling, and verification of high-performance AC–DC current shunts from inexpensive components."Instrumentation and Measurement, IEEE Transactions on 57.1 (2008): 176-181.

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

[3]Lind, K., 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.

[4]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.

Results

The following two tables are a summary of the results stated in μA/A with calculated uncertainties:

AC/DC difference in μA/A

	30mA	30mA*	100mA	300mA	1A	3A	5A	10A	20A	20A*	20A**	5 A***
10 Hz	0.3	0.2	-0.5	-0.6	-0.7	-0.3	0	-1	0	1	1	0
20 Hz	0.1		0.3	0.2	-0.1	0.2	0.7	0.2	1		1	0.6
55 Hz	0.1	0.0	-0.2	-0.5	-0.8	-0.4	0.0	-0.2	0.2	0.1	0.0	0.0
110 Hz	0.0		-0.1	-0.4	-0.6	-0.4	0.0	-0.1	-0.1		0.1	-0.1
400 Hz	0.0	0.0	0.1	-0.1	-0.2	0.0	-0.6	0.0	-0.1	0.0	-0.2	-0.6
1 kHz	0.0	0.0	0.0	-0.1	-0.4	-0.2	0.1	0.1	0.4	0.2	0.2	0.0
5 kHz	-0.1		0.1	-0.3	-0.6	0.0	-0.4	0.4	0.5		0.4	-0.3
10 kHz	-0.2		0.1	-0.7	-0.6	-0.3	0.2	0.2	0.8		0.7	-0.1
20 kHz	-0.3	-0.4	0.5	-0.9	-0.3	-0.1	0.3	0.6	2.3	2.3	2.4	0.4
50 kHz	-0.8		1.2	-3.4	-1.8	-2.3	-2.4	-1.5	4.7		5	-2.8
100 kHz	-1.7	-2.2	2.2	-5.0	-2.1	-3.3	-5	-2	10	10	10	-6

Calculated uncertainties in μA/A ($k = 2$)

	30mA	100mA	300mA	1A	3A	5A	10A	20A	20A**	5A***
10 Hz	5.3	6.1	7.5	8.6	10	10	11	12	12	10
20 Hz	4.4	4.9	6.0	6.9	8.2	8.4	9.2	10	10	8.4
55 Hz	3.4	3.7	4.5	5.1	6.4	6.6	7.2	7.9	8.2	6.6
110 Hz	3.4	3.7	4.5	5.1	6.4	6.6	7.2	7.9	8.2	6.6
400 Hz	3.3	3.5	4.3	4.9	6.2	6.4	7.0	7.6	7.9	6.4
1 kHz	3.3	3.4	4.2	4.8	6.1	6.3	6.9	7.6	7.8	6.3
5 kHz	3.4	3.4	4.2	4.9	6.2	6.4	6.9	7.6	8.2	6.4
10 kHz	3.4	3.5	4.3	4.9	6.2	6.3	7.0	7.6	8.2	6.3
20 kHz	3.4	3.5	4.3	4.9	6.2	6.7	7.2	8.0	9.0	6.7
50 kHz	3.5	3.7	4.5	5.0	6.4	7.4	8.0	9.3	11	7.5
100 kHz	3.8	4.0	4.9	5.5	7.6	10	11	13	15	10

*Return control measurements at JV.
**Measured current was 10 A.
***Measured current was 3 A.

Detailed uncertainties for each calibration

30 mA #1212043 - I = 30 mA

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.07	1.6	0.10	0.40	1.0	0.10	0.10	1.5	0.20	1.0	0.10	5.3
20 Hz	0.07	1.4	0.10	0.40	1.0	0.10	0.10	1.0	0.20	0.80	0.10	4.4
55 Hz	0.08	1.2	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	3.4
110 Hz	0.06	1.2	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	3.4
400 Hz	0.06	1.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.3
1 kHz	0.08	1.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.3
5 kHz	0.07	1.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.4
10 kHz	0.07	1.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.4
20 kHz	0.11	1.2	0.11	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.4
50 kHz	0.07	1.3	0.16	0.40	1.0	0.10	0.10	0.30	0.20	0.40	0.10	3.5
100 kHz	0.09	1.4	0.22	0.40	1.0	0.10	0.10	0.30	0.20	0.60	0.10	3.8

100 mA #1212036 - I = 100 mA

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.06	2.2	0.10	0.40	1.0	0.10	0.10	1.5	0.20	1.0	0.10	6.1
20 Hz	0.05	1.8	0.10	0.40	1.0	0.10	0.10	1.0	0.20	0.80	0.10	4.9
55 Hz	0.06	1.3	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	3.7
110 Hz	0.14	1.3	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	3.7
400 Hz	0.11	1.3	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.5
1 kHz	0.06	1.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.4
5 kHz	0.06	1.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.4
10 kHz	0.08	1.3	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.5
20 kHz	0.05	1.3	0.11	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	3.5
50 kHz	0.06	1.4	0.16	0.40	1.0	0.10	0.10	0.30	0.20	0.40	0.10	3.7
100 kHz	0.05	1.6	0.22	0.40	1.0	0.10	0.10	0.30	0.20	0.60	0.10	4.0

300 mA #1301008 - I = 300 mA

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.05	3.1	0.10	0.40	1.0	0.10	0.10	1.5	0.20	1.0	0.10	7.5
20 Hz	0.06	2.5	0.10	0.40	1.0	0.10	0.10	1.0	0.20	0.80	0.10	6.0
55 Hz	0.05	1.9	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	4.5
110 Hz	0.06	1.9	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	4.5
400 Hz	0.06	1.8	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.3
1 kHz	0.06	1.7	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.2
5 kHz	0.06	1.7	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.2
10 kHz	0.05	1.8	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.3
20 kHz	0.05	1.8	0.11	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.3
50 kHz	0.05	1.9	0.16	0.40	1.0	0.10	0.10	0.30	0.20	0.40	0.10	4.5
100 kHz	0.05	2.1	0.22	0.40	1.0	0.10	0.10	0.30	0.20	0.60	0.10	4.9

1 A #1301009 - I = 1 A

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.08	3.7	0.10	0.40	1.0	0.10	0.10	1.5	0.20	1.0	0.10	8.6
20 Hz	0.09	3.0	0.10	0.40	1.0	0.10	0.10	1.00	0.20	0.80	0.10	6.9
55 Hz	0.06	2.2	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	5.1
110 Hz	0.14	2.2	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	5.1
400 Hz	0.16	2.1	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.9
1 kHz	0.07	2.1	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.8
5 kHz	0.08	2.1	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.9
10 kHz	0.06	2.1	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.9
20 kHz	0.06	2.1	0.11	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	4.9
50 kHz	0.06	2.2	0.16	0.40	1.0	0.10	0.10	0.30	0.20	0.40	0.10	5.0
100 kHz	0.07	2.4	0.22	0.40	1.0	0.10	0.10	0.30	0.20	0.60	0.10	5.5

3 A #1301001 - I = 3 A

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.19	4.5	0.10	0.40	1.0	0.10	0.10	1.5	0.20	1.0	0.10	10
20 Hz	0.18	3.8	0.10	0.40	1.0	0.10	0.10	1.0	0.20	0.80	0.10	8.2
55 Hz	0.19	3.0	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	6.4
110 Hz	0.08	3.0	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	6.4
400 Hz	0.10	2.9	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.2
1 kHz	0.19	2.8	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.1
5 kHz	0.24	2.8	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.2
10 kHz	0.20	2.9	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.2
20 kHz	0.19	2.9	0.11	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.2
50 kHz	0.18	3.0	0.16	0.40	1.0	0.10	0.10	0.30	0.20	0.40	0.10	6.4
100 kHz	0.18	3.6	0.22	0.40	1.0	0.10	0.10	0.30	0.20	0.60	0.10	7.6

5 A #1212023 - I = 3 A

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{linS})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.38	4.6	0.10	0.40	1.0	0.10	0.10	1.0	1.5	0.20	1.0	0.10	10
20 Hz	0.39	3.8	0.10	0.40	1.0	0.10	0.10	1.0	1.0	0.20	0.80	0.10	8.4
55 Hz	0.41	3.0	0.10	0.40	1.0	0.10	0.10	1.0	0.50	0.20	0.30	0.10	6.6
110 Hz	0.17	3.0	0.10	0.40	1.0	0.10	0.10	1.0	0.50	0.20	0.30	0.10	6.6
400 Hz	0.15	2.9	0.10	0.40	1.0	0.10	0.10	1.0	0.30	0.20	0.30	0.10	6.4
1 kHz	0.48	2.9	0.10	0.40	1.0	0.10	0.10	1.0	0.30	0.20	0.30	0.10	6.4
5 kHz	0.45	2.9	0.10	0.40	1.0	0.10	0.10	1.5	0.30	0.20	0.30	0.10	6.4
10 kHz	0.46	2.9	0.10	0.40	1.0	0.10	0.10	1.5	0.30	0.20	0.30	0.10	6.4
20 kHz	0.45	3.1	0.11	0.40	1.0	0.10	0.10	1.5	0.30	0.20	0.30	0.10	6.7
50 kHz	0.48	3.5	0.16	0.40	1.0	0.10	0.10	2.0	0.30	0.20	0.40	0.10	7.5
100 kHz	0.45	4.8	0.22	0.40	1.0	0.10	0.10	2.0	0.30	0.20	0.60	0.10	10

5 A #1212023 - I = 5 A

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.12	4.6	0.10	0.40	1.0	0.10	0.10	1.5	0.20	1.0	0.10	10
20 Hz	0.12	3.8	0.10	0.40	1.0	0.10	0.10	1.0	0.20	0.80	0.10	8.4
55 Hz	0.12	3.0	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	6.6
110 Hz	0.11	3.0	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	6.6
400 Hz	0.13	2.9	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.4
1 kHz	0.12	2.9	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.3
5 kHz	0.12	2.9	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.4
10 kHz	0.15	2.9	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.3
20 kHz	0.12	3.1	0.11	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.7
50 kHz	0.11	3.5	0.16	0.40	1.0	0.10	0.10	0.30	0.20	0.40	0.10	7.4
100 kHz	0.12	4.8	0.22	0.40	1.0	0.10	0.10	0.30	0.20	0.60	0.10	10

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10 A #1301022 - I = 10 A

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.21	5.1	0.10	0.40	1.0	0.10	0.10	1.5	0.20	1.0	0.10	11
20 Hz	0.19	4.2	0.10	0.40	1.0	0.10	0.10	1.0	0.20	0.80	0.10	9.2
55 Hz	0.18	3.4	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	7.2
110 Hz	0.32	3.4	0.10	0.40	1.0	0.10	0.10	0.50	0.20	0.30	0.10	7.2
400 Hz	0.31	3.3	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	7.0
1 kHz	0.17	3.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.9
5 kHz	0.17	3.2	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	6.9
10 kHz	0.16	3.3	0.10	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	7.0
20 kHz	0.21	3.4	0.11	0.40	1.0	0.10	0.10	0.30	0.20	0.30	0.10	7.2
50 kHz	0.23	3.8	0.16	0.40	1.0	0.10	0.10	0.30	0.20	0.40	0.10	8.0
100 kHz	0.30	5.2	0.22	0.40	1.0	0.10	0.10	0.30	0.20	0.60	0.10	11

20 A #1301017 - I = 20 A

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.24	5.6	0.10	0.4	1.0	0.1	0.1	1.5	0.2	1.0	0.1	12
20 Hz	0.28	4.7	0.10	0.4	1.0	0.1	0.1	1.0	0.2	0.8	0.1	10
55 Hz	0.25	3.7	0.10	0.4	1.0	0.1	0.1	0.5	0.2	0.3	0.1	7.9
110 Hz	0.25	3.7	0.10	0.4	1.0	0.1	0.1	0.5	0.2	0.3	0.1	7.9
400 Hz	0.25	3.6	0.10	0.4	1.0	0.1	0.1	0.3	0.2	0.3	0.1	7.6
1 kHz	0.27	3.6	0.10	0.4	1.0	0.1	0.1	0.3	0.2	0.3	0.1	7.6
5 kHz	0.27	3.6	0.10	0.4	1.0	0.1	0.1	0.3	0.2	0.3	0.1	7.6
10 kHz	0.24	3.6	0.10	0.4	1.0	0.1	0.1	0.3	0.2	0.3	0.1	7.6
20 kHz	0.22	3.8	0.11	0.4	1.0	0.1	0.1	0.3	0.2	0.3	0.1	8.0
50 kHz	0.25	4.5	0.16	0.4	1.0	0.1	0.1	0.3	0.2	0.4	0.1	9.3
100 kHz	0.24	6.4	0.22	0.4	1.0	0.1	0.1	0.3	0.2	0.6	0.1	13

20 A #1301017 - I = 10 A

	s	$u(\delta_{ref})$	$u(\delta_T)$	$u(\delta_{sf})$	$u(\delta_{DMMnoise})$	$u(\delta_{CMRR})$	$u(\delta_{KMR})$	$u(\delta_{linS})$	$u(\delta_{lin})$	$u(\delta_{dist})$	$u(\delta_x)$	$u(\delta_{ind})$	$u(\delta)(k=2)$
10 Hz	0.21	5.6	0.10	0.4	1.0	0.1	0.1	1.0	1.5	0.2	1.0	0.1	12
20 Hz	0.22	4.7	0.10	0.4	1.0	0.1	0.1	1.0	1.0	0.2	0.8	0.1	10
55 Hz	0.25	3.7	0.10	0.4	1.0	0.1	0.1	1.0	0.5	0.2	0.3	0.1	8.2
110 Hz	0.20	3.7	0.10	0.4	1.0	0.1	0.1	1.0	0.5	0.2	0.3	0.1	8.2
400 Hz	0.16	3.6	0.10	0.4	1.0	0.1	0.1	1.0	0.3	0.2	0.3	0.1	7.9
1 kHz	0.28	3.6	0.10	0.4	1.0	0.1	0.1	1.0	0.3	0.2	0.3	0.1	7.8
5 kHz	0.21	3.6	0.10	0.4	1.0	0.1	0.1	1.5	0.3	0.2	0.3	0.1	8.2
10 kHz	0.25	3.6	0.10	0.4	1.0	0.1	0.1	1.5	0.3	0.2	0.3	0.1	8.2
20 kHz	0.27	3.8	0.11	0.4	1.0	0.1	0.1	2.0	0.3	0.2	0.3	0.1	9.0
50 kHz	0.26	4.5	0.16	0.4	1.0	0.1	0.1	3.0	0.3	0.2	0.4	0.1	11
100 kHz	0.20	6.4	0.22	0.4	1.0	0.1	0.1	3.5	0.3	0.2	0.6	0.1	15