Improved AC-DC Current Transfer Standards from 10 mA to 100 A

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Abstract

Recent developments resulted in new planar multijunction thermal converters on quartz substrate (QPMJTC), which are now used as the basic calculable ac-dc current transfer standards with very small uncertainties. To reduce the contribution of the measurement set-up to the uncertainty budget, potential driven guarding has been implemented.

With new current shunts from the National Metrology Institute of Norway, Justervesenet (JV) and a new transconductance amplifier the frequency range of the ac-dc current transfer has been increased up to 1 MHz and 1 A.

The current level dependence of the ac-dc difference of the current shunts is the predominant uncertainty contribution in the step-up procedure starting from 40 mA to higher currents. With the newly developed high current micropotentiometers the current level dependence of the Justervesenet shunts has been measured to be negligibly small up to 10 A.

A newly designed single-stage current transformer for up to 100 A and 100 kHz with the ratio of 100 to 1 allows to evaluate the current level dependences of the ac-dc difference of current shunts from 30 A to 100 A.

Introduction

Ac-dc current transfer is used to link the calibration of ac current measurement instruments to the SI unit of current, which is defined at dc. The quantity to be measured is the ac-dc current transfer difference δ_i, defined as

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

where

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

I_{dc} is the dc current which when reversed produces the same mean output indication as the ac current.

Reversing the dc current and taking the mean is important, since due to various dc offsets and thermoelectric effects almost always a dc reversal difference occurs. It is defined as the relative difference of the magnitudes of the positive and the negative dc current required to obtain the same output indication.

In ac-dc current transfer measurements often two ac-dc transfer devices such as thermal converters are compared, so that the difference of the ac-dc transfer differences of a standard and a device under test is determined. The uncertainties given for these measurements are the combination of the uncertainty of the measurement and of the uncertainty of the ac-dc transfer difference of the standard.

1. Quartz PMJTC

The use of a quartz substrate improves the high-frequency behavior of PMJTCs so that the ac-dc voltage and current transfer differences become calculable [1]. This has motivated PTB to use the QPMJTCs as the new basis for ac-dc current transfer standards at currents from 10 mA to 40 mA and at frequencies from 10 kHz to 1 MHz.

To calculate the ac-dc current transfer differences of the Quartz-PMJTC, a model of the input impedance $\underline{Z}$ of the PMJTC was developed. This model includes the contribution of ac-dc differences arising from:

A. the change of the real part of the impedance $\underline{Z}$ of the heater with frequency (δ_{i1}) and
B. the impedances of the various leads from the input connector to the bond pads of the chip (δ_{i2}).

To predict the frequency behavior of the heater, it is modeled as a lossy transmission line of ten elements. The bifilar heater is split into two halves to calculate the capacitances C_1 between the halves and C_2 from the heater to the thermocouples as well as the heater inductance L_H. The basic element of the transmission line is shown in Figure 1.

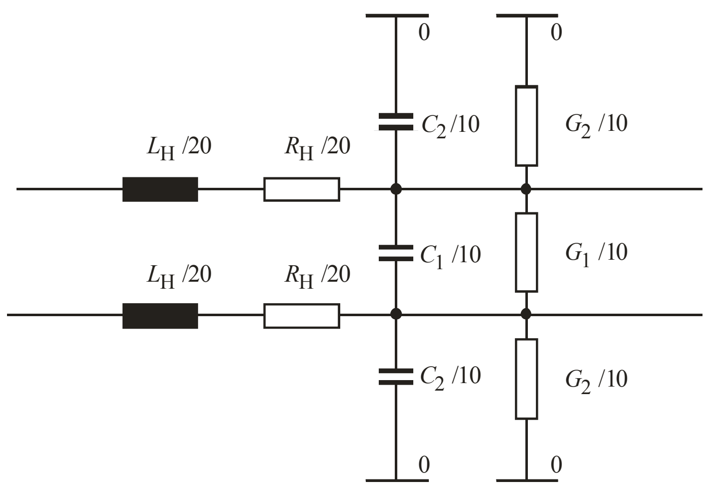

Figure 1. Basic element of the transmission line modeling the heater/thermocouples system of the Quartz PMJTC (C_1 = 0.1 pF, C_2 = 0.3 pF, L_H = 3 nH, R_H = heater resistance, G_1 = 0.8 nS and G_2 = 1.8 nS at 100 kHz).

All simulations were performed from 100 kHz to 1 MHz. The ac-dc current transfer difference was calculated from the equation

$$\delta_{\mathrm{i1}} = \sqrt{\frac{R_{\mathrm{H}}}{\mathrm{Re}\{\underline{Z}\}}} - 1 \tag{1}$$

where $\mathrm{Re}\{\underline{Z}\}$ denotes the real part of the input impedance $\underline{Z}$ and R_{H} the dc resistance of the input circuit.

For the calculation of the ac-dc current transfer difference due to the impedance of the leads to the bond pads of the chip (δ_{i2}) a lumped parameter model of the heater and the leads was used. The schematic of the model used is shown in Figure 2.

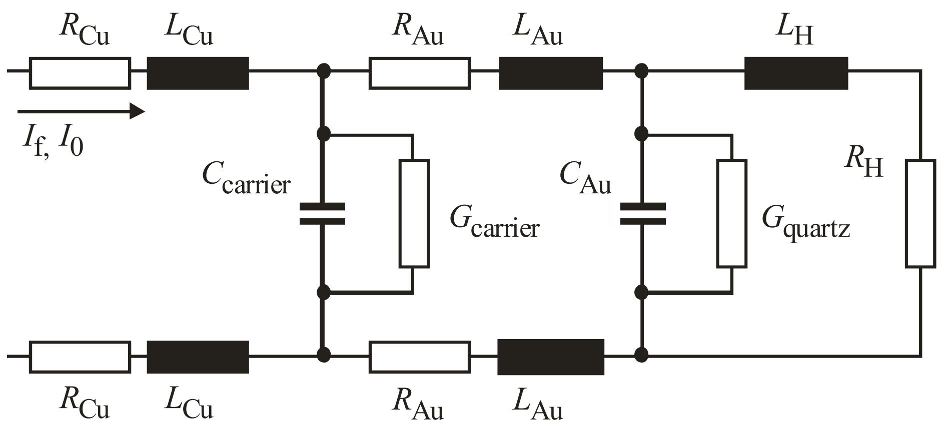

Figure 2. Lumped parameter model with the capacitance $C_{\mathrm{carrier}} = 0.7$ pF between the soldering pads on the carrier and the Cu-leads to the carrier, Au-leads to the bond pads with the capacitance $C_{\mathrm{Au}} = 0.07$ pF, dielectric losses in the carrier ($\tan\delta = 1\cdot10^{-3}$), dielectric losses in quartz ($\tan\delta = 8\cdot10^{-4}$), $R_{\mathrm{Cu}} = 1$ mΩ, $R_{\mathrm{Au}} = 5$ mΩ, and the inductance of both $L_{\mathrm{Cu}} = 1$ nH and $L_{\mathrm{Au}} = 5$ nH.

The ac-dc transfer difference δ_{i2} was calculated for 100 kHz to 1 MHz from the equation

$$\delta_{\mathrm{i2}} = \frac{|\underline{Z}_2 \cdot (\underline{Z}_3 + \underline{Z}_4)|}{|\underline{Z}_3 \cdot (2 \cdot \underline{Z}_1 + \underline{Z}_2)|} - 1 \tag{2}$$

with the impedances

$$\underline{Z}_1 = (R_{\mathrm{Cu}} + \mathrm{j}\omega \cdot L_{\mathrm{Cu}})$$
$$\underline{Z}_2 = (G_{\mathrm{carrier}} + \mathrm{j}\omega \cdot C_{\mathrm{carrier}})^{-1}$$
$$\underline{Z}_3 = (G_{\mathrm{quartz}} + \mathrm{j}\omega \cdot C_{\mathrm{Au}})^{-1}$$
$$\underline{Z}_4 = (R_{\mathrm{H}} + \mathrm{j}\omega \cdot 2 \cdot L_{\mathrm{H}})$$

Figure 3 shows the calculated sum $\delta_{\mathrm{i}} = \delta_{\mathrm{i1}} + \delta_{\mathrm{i2}}$ of the ac-dc current transfer differences.

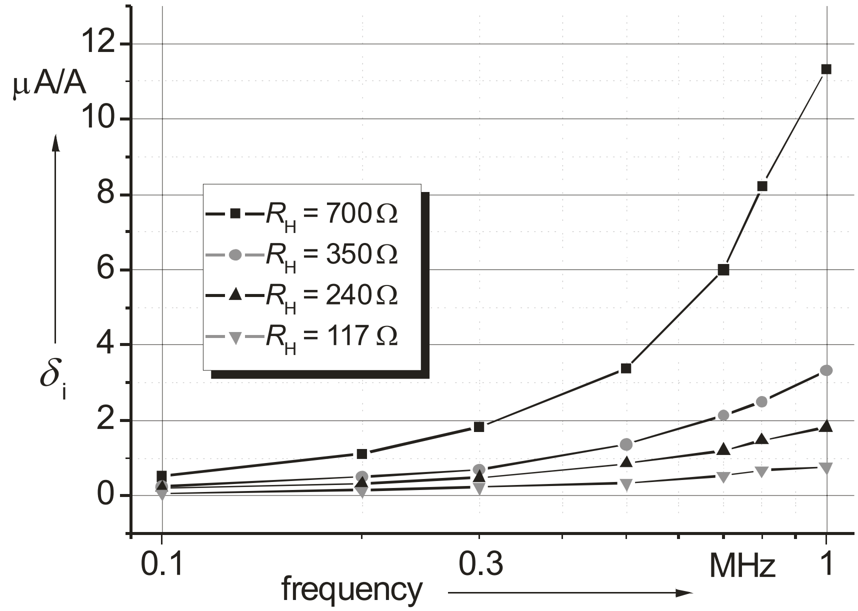

Figure 3. Sum $\delta_i = \delta_{i1} + \delta_{i2}$ of the calculated ac-dc current transfer differences for different heater resistances.

It is obvious, that with a small heater resistance of about 100 Ω very small ac-dc current transfer differences below 1 µA/A can be obtained at frequencies up to 1 MHz. To validate the model of the Quartz-PMJTC used for the simulation, measured and calculated ac-dc transfer differences between two PMJTCs with different heater resistances were compared. For the measurement, two PMJTCs were put closely together in the same housing and connected in series by short and thin wires. Figure 4 shows the measured and calculated ac-dc current transfer differences:

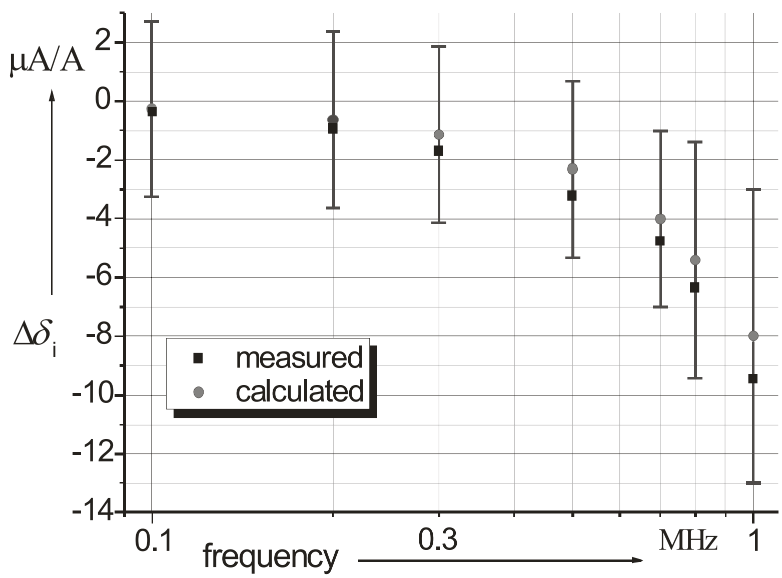

Figure 4. Measured and calculated differences $\Delta\delta_i$ between two Quartz-PMJTCs with heater resistances of 117 Ω and 700 Ω with standard uncertainty bars for 100 kHz to 1 MHz.

An estimation of the uncertainty u of the calculated ac-dc transfer difference is obtained by investigating the contributions of the different parameters in the model. Both mentioned transfer differences δ_{i1} and δ_{i2} are written as a function of the different parameters such as capacitances, resistances and conductances. By our experience, the manufacturing process of the QPMJTCs leads to parameter scatter of less than 20%. Also the estimation or measurement of the impedances has an uncertainty of several percent. Therefore the different model parameters are varied by 20% one after the other in the simulation. The related variance is obtained by squaring the differences in the results.

Figure 5 shows the estimated standard uncertainty u of a Quartz-PMJTC with a heater resistance of 117 Ω for frequencies from 100 kHz to 1 MHz.

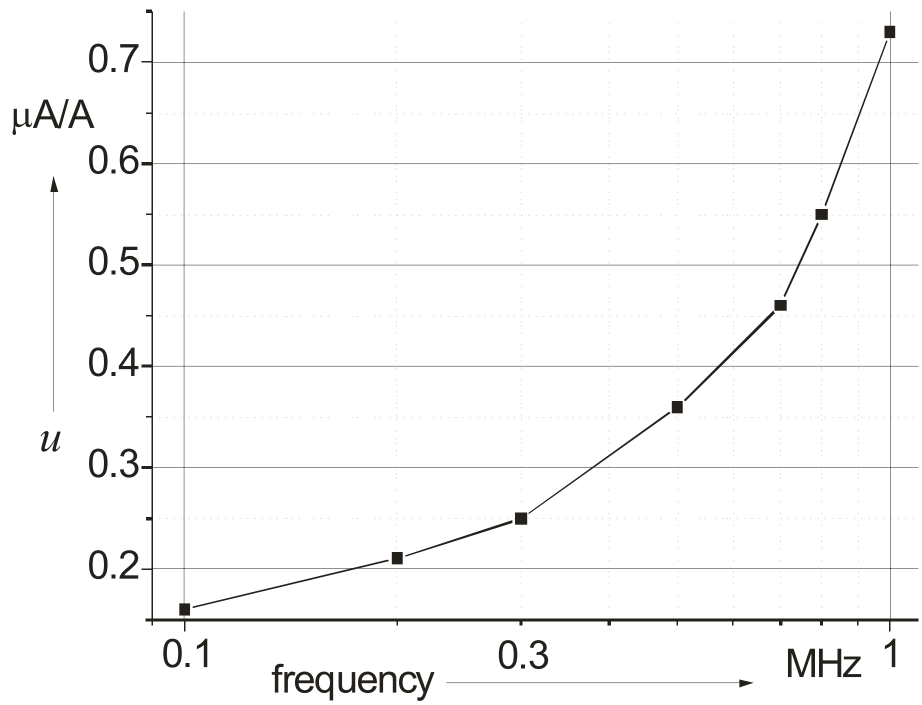

Figure 5. Estimated standard uncertainty u of the ac-dc current transfer difference of a Quartz-PMJTC with a heater resistance of 117 Ω for frequencies from 100 kHz to 1 MHz.

2. Measurement set-up for ac-dc current transfer difference measurements

For the measurements of the ac-dc current transfer differences, the two PMJTCs to be compared are connected in series. Since the driving current source has to be grounded, one PMJTC has to be operated floating. This means, that the voltage developed at the other, grounded PMJTC appears as common mode voltage to the floating PMJTC. To minimize current leakage, the PMJTCs are connected in series symmetrically with minimal capacitances (2.6 pF) using a special T-piece made from N-panel connectors as shown in figure 6.

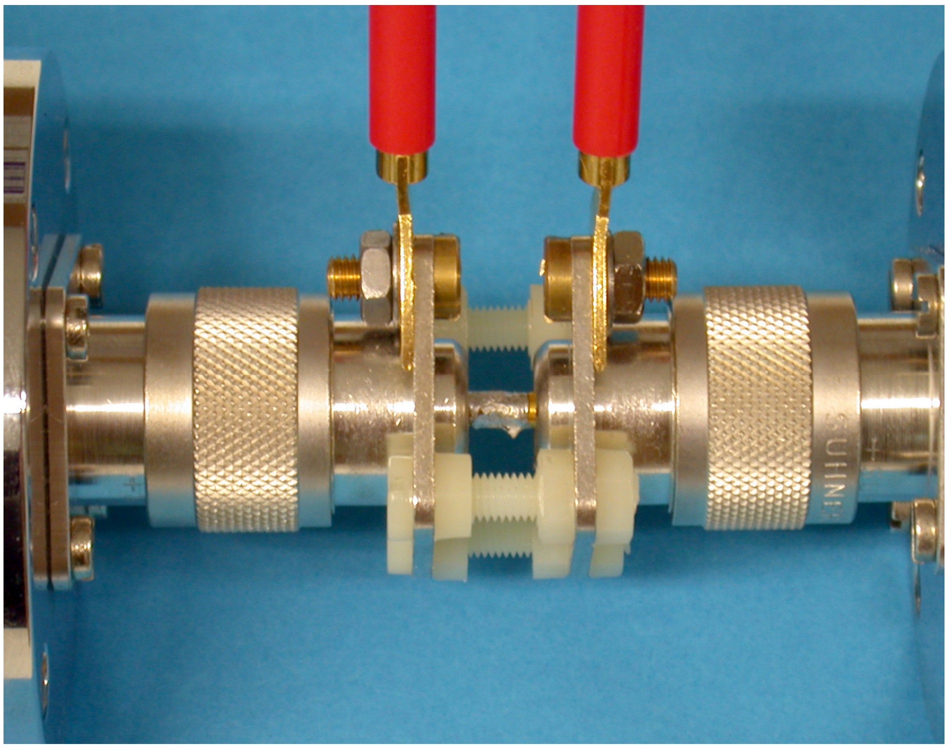

Figure 6. Symmetrical series connection of two current transfer standards with minimal capacitances.

PMJTCs exhibit a stray capacitance between their heater and the thermocouples. At higher frequencies a significant current flows through this capacitance and through the thermocouples. Connecting a capacitor of about 2 µF across the thermocouple terminals greatly reduces the ac ripple on the output voltage of the thermocouples (which can disturb the dc nanovoltmeter). Furthermore, if the ac potential of the thermocouples changes with respect to the heater potential, also the stray current changes. This introduces a frequency dependent error. Therefore in the measurement set-up one terminal of the thermocouples as well as the shield of the thermocouple cable has to be connected to low-terminal of the heater, which in turn is connected to the housing of the PMJTC.

This is done by connecting the floating PMJTC “upside-down” using the symmetrical Tee-connection and by providing a guard potential derived from the current source’s “Hi” terminal to the nanovoltmeter´s guard box. The nanovoltmeter of course has to be operated floating, too, as shown in figure 7. The whole setup is very symmetrical so that there is no difference to the normal grounded operation for the PMJTC operated floating.

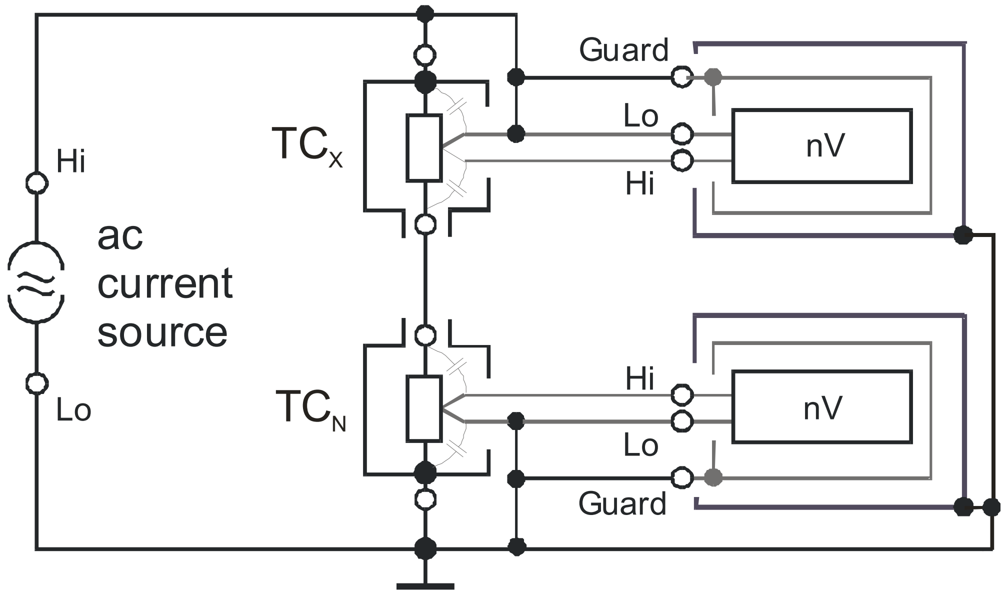

Figure 7. Ac-dc current transfer difference comparison setup for PMJTCs using potential driven guards.

3. Step-up chain to build an ac-dc current transfer difference scale

Quartz PMJTCs can be used as ac-dc current transfer difference standards for current levels from some mA up to about 40 mA. For higher currents shunts are used to transfer the current to a voltage, which in turn is measured by a PMJTC. In combination with shunts PMJTCs on silicon substrate are more suitable, because they offer better sensitivity and a larger dynamic range. So the number of steps in the step-up chain can be smaller. The calculable ac-dc transfer difference of the quartz PMJTC is no longer an advantage, since the shunt contributes to the ac-dc current transfer difference, too.

At PTB, five types of shunts are used to build up the current scale. All shunts are designed coaxially to minimize inductive coupling.

1. For currents up to 300 mA, shunts made up from four to six parallel resistors mounted in a star configuration directly on an N type connector are built up.
2. From 500 mA to 5 A commercially available shunts made by Holt are used.
3. For 10 A and 20 A Fluke type A40A shunts can be used.
4. Two sets of Justervesenet design shunts from 30 mA up to 10 A have recently have been put into operation.
5. Currents between 30 A and 100 A can be measured using a set of four EL-9800 shunts (NIST design).

Figure 8 and figure 9 show the newly designed Justervesenet shunts [3]. The cross sectional drawing in figure 8 demonstrates the small area covered by the current path, while on the photo in figure 9 the large number of resistors used for current equalization is visible as silver colored solder dots.

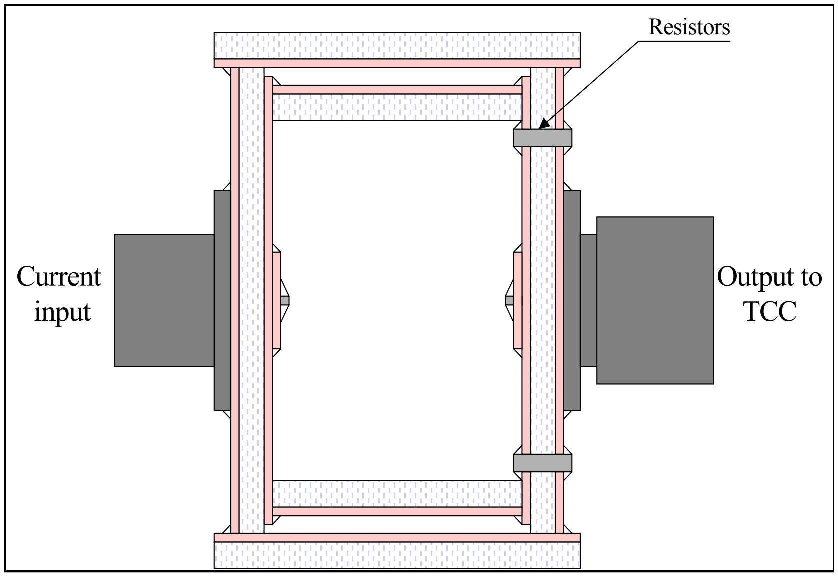

Figure 8. Cross sectional drawing of the Justervesenet shunts.

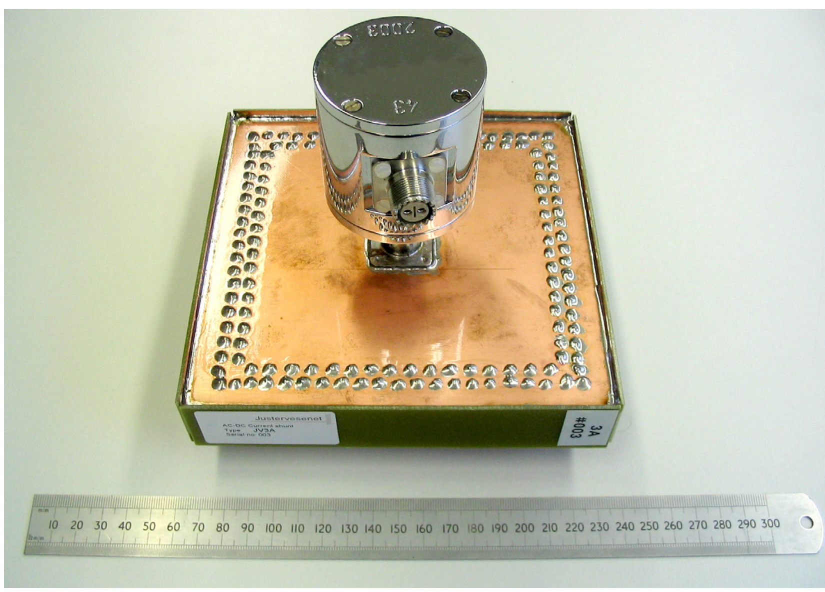

Figure 9. Photograph of a Justervesenet shunt with attached PMJTC.

Three different step-up chains up to 5 A are shown in table I, all starting from the calculable Quartz-PMJTC at 20 mA or 30 mA. Chains A and B use shunts as described under 1. and 2., whereas chain C is entirely made up from JV shunts. The application of differently constructed shunts and different current steps gives the opportunity to estimate the current level dependence in the step-up, in which the shunts are calibrated at lower than rated current, but are used at rated current.

Table I. Step-up chains used at PTB.

step \ chain	A	B	C
0 (start)	20 mA	30 mA	30 mA
1	50 mA	100 mA	100 mA
2	100 mA	500 mA	300 mA
3	200 mA	1 A	1 A
4	500 mA	5 A	3 A
5	1 A		5 A
6	2 A		
7	5 A		

Different transfer standards calibrated using the step-up chains with differently constructed shunts have been compared at 5 A. The differences found at 100 kHz were less than 5 µA/A. At 1 A and 1 MHz the differences were less than 10 µA/A. This is an indication, that the level dependence had been estimated too high in the former uncertainty analysis. To further investigate the level dependence, an experimental step-up using all the standards only at half their rated current was performed. The results support the lower current level dependence values used in the new uncertainty budget.

Another approach is to use as the standard a shunt designed for much higher current, so that virtually no heating and no current dependence occurs. Because the output voltage becomes very small now, an amplifier is used in front of the PMJTC. This amplifier in turn can be calibrated using micropotentiometers [4].

4. Special developments to extend the frequency and current range

Commercially available instruments and standards suit only a part of the needs for ac-dc current transfer measurements. Some devices have to be individually characterized to reduce their measurement uncertainties below the manufacturer's specifications. In many cases there are no suitable instruments on the market and special own developments are necessary.

4.1 Transconductance amplifier

Commercially available voltage calibrators, which are normally used for ac-dc transfer, can deliver only currents up to 50 mA at 1 MHz. The common high current amplifiers or transconductance amplifiers are limited in their operating frequency to about 100 kHz, or, if higher frequencies are possible, the dc stability and offset drift are poor.

Therefore a transconductance amplifier was designed to deliver currents of up to 1 A at frequencies from dc to 1 MHz. The main design goals were low dc reversal difference and low dc offset combined with low distortion and high bandwidth. This led to a feedback design as shown in Figure 10: A power amplifier drives the current through a shunt and through the grounded load. The voltage drop across the shunt is converted to a ground referred signal by a differential amplifier. This current-signal is compared to the also ground referred input voltage and the power amplifier is servo-controlled accordingly. To obtain various current ranges, the shunt can easily be exchanged because it is plugged on externally.

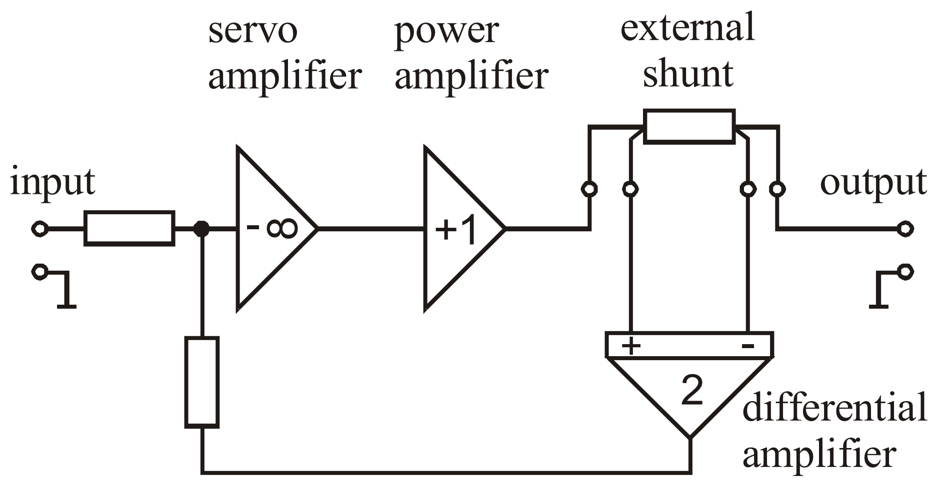

Figure 10. Schematic diagram of the transconductance amplifier for 1 A at 1 MHz.

4.2 Current transformer

In the step-up procedure the level dependence of the ac-dc difference of the EL-9800 high current shunts is the predominant contribution in the uncertainty budget especially at high frequencies. A single-stage current transformer for up to 100 A and 100 kHz with the ratio of 100 to 1 has been developed in collaboration of PTB and NIM, China. The single-stage current transformer was designed to have a coaxial input with a high current, high frequency (LC type) connector. Figure 11 shows the construction of the current transformer. It is directly mounted to the LC type connector (1). A brass bolt (3) across the window of the ferroalloy core (2) acts as the one turn primary winding. The one-layer 100-turn (with 0.6 mm wire diameter) secondary winding covers the entire core and is connected to an N type output connector (4).

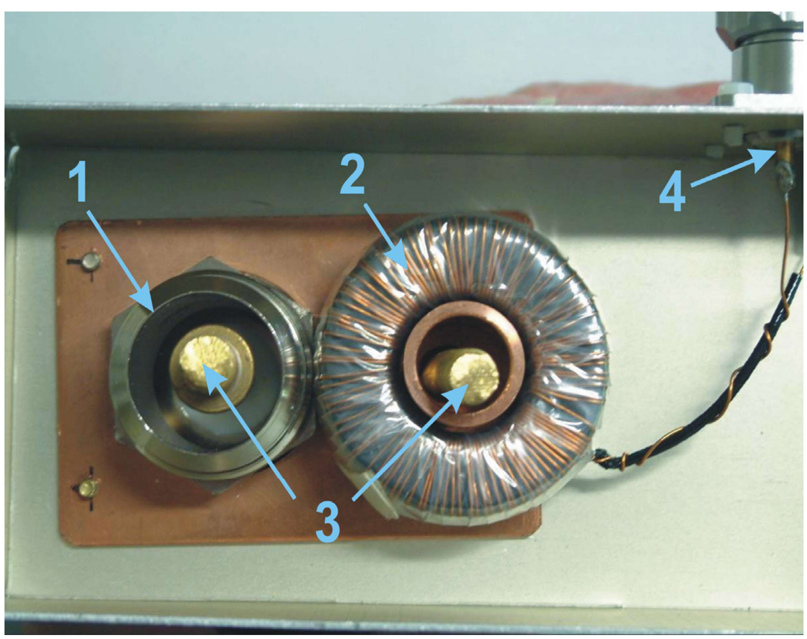

Figure 11. Current transformer construction (current link removed).

The ratio error of a single-stage current transformer can be divided into the magnetic error γ_M and capacitive error γ_C. Only γ_M is level dependent, because the permeability μ_r increases with the current level. The current level dependence of the current transformer can be determined with measurements at low current levels. The measurement uncertainty is small enough to contribute only negligibly to the uncertainty of the current level dependence of the shunt to be investigated.

The measurement set-up is shown in Figure 12. The high current shunt, R_X, is connected to the voltmeter V_X to measure its voltage drop. R_X is connected in series with the primary winding of the current transformer CT and both are fed with currents of different frequencies by the current source I_{ac}. The burden of the current transformer is the 1 Ω shunt R_N, the voltage drop of which is measured by the voltmeter V_N. A high current dc standard resistor was used as the reference to calibrate the dc value of R_X at different current levels.

Using this setup, the level dependence of the ac-dc current transfer difference of the EL9800 high current shunts is under investigation at current levels from 30 A to 100 A and at frequencies from 5 kHz to 100 kHz.

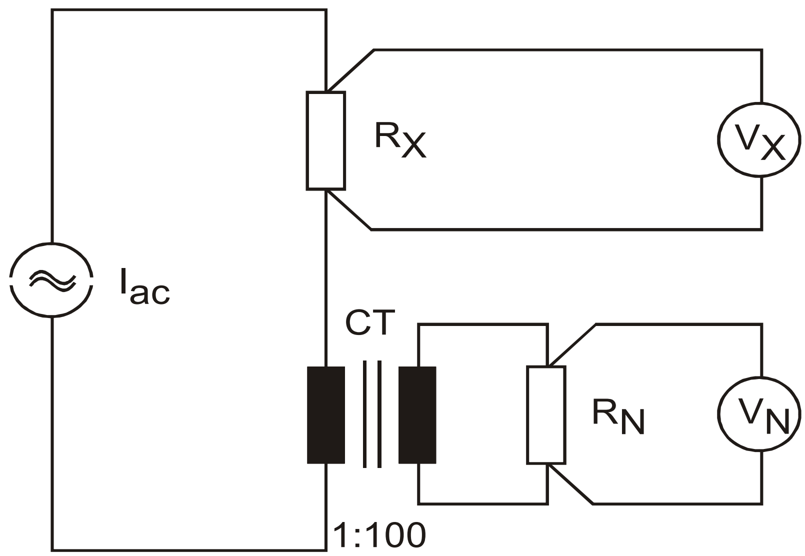

Figure 12. Measurement set-up to determine the current level dependence of high current shunts.

5. Uncertainty analysis

One dominating part in the former uncertainty budget [2] was the contribution due to different potentials between heater and thermocouples for the two PMJTCs in series. Using potential driven guards, this part is now negligibly small. The second dominating part was the contribution due to the current level dependence which is now decreased dramatically.
The new uncertainty budget in table II and table III contains the following influence quantities:

$u(\delta_{QPMJTC})$	Uncertainty of Quartz PMJTC
$u(\delta_{Step-1})$	Uncertainty of the previous step
$u(\delta_A)$	Standard deviation of the mean of 12 measurements.
$u(\delta_C)$	Uncertainty contributed by the measurement set-up.
u_{LEV}	Uncertainty contributed by the current level dependence of the shunt.
u_{LF}	Uncertainty of the low frequency transfer difference of the PMJTC.

Table II. Uncertainty budget for the step-up to 5 A.

Influence quantity	Standard uncertainty u in µA/A at the frequencies in kHz 0.010	1	10	100	500	1.000
30 mA (calculable Quartz PMJTC)						
$\boldsymbol{u(\delta_{Chip})}$	0.3	0.0	0.0	0.0	0.1	0.2
$\boldsymbol{u(\delta_{Connector})}$	0.0	0.0	0.0	0.1	0.4	0.7
$\boldsymbol{u(\delta_S)}$	0.30	0.00	0.00	0.10	0.41	0.73
$\boldsymbol{U(\delta_S)}$	**1**	**1**	**1**	**1**	**1**	**2**
100 mA (PMJTC + JV100mA vs. Quartz PMJTC)						
$u(\delta_{QPMJTC})$	0.3	0.0	0.0	0.1	0.4	0.7
$u(\delta_A)$	0.4	0.2	0.2	0.2	0.3	0.5
$u(\delta_C)$	0.2	0.2	0.2	0.2	0.2	0.3
u_{LEV}	0.1	0.1	0.1	0.1	0.2	0.3
u_{LF}	0.4	0.0	0.0	0.0	0.0	0.0
$u(\delta_{100mA})$	0.68	0.30	0.30	0.32	0.58	0.98
$\boldsymbol{U(\delta_{100mA})}$	**2**	**2**	**2**	**2**	**2**	**5**
300 mA (PMJTC + JV300mA vs. PMJTC + JV100mA)						
$u(\delta_{Step-1})$	0.7	0.3	0.3	0.3	0.6	1.0
$u(\delta_A)$	0.4	0.2	0.2	0.2	0.3	0.5
$u(\delta_C)$	0.2	0.2	0.2	0.2	0.2	0.3
u_{LEV}	0.3	0.1	0.3	0.5	0.7	1.0
u_{LF}	0.4	0.0	0.0	0.0	0.0	0.0
$u(\delta_{300mA})$	0.95	0.42	0.51	0.66	0.98	1.5
$\boldsymbol{U(\delta_{300mA})}$	**2**	**2**	**2**	**2**	**3**	**5**
1 A (PMJTC + JV1A vs. PMJTC + JV300mA)						
$u(\delta_{Step-1})$	1.0	0.4	0.5	0.7	1.0	1.5
$u(\delta_A)$	0.4	0.2	0.2	0.2	0.3	0.5
$u(\delta_C)$	0.2	0.2	0.2	0.2	0.2	0.3
u_{LEV}	1.0	1.0	1.0	1.5	2.0	3.0
u_{LF}	0.4	0.0	0.0	0.0	0.0	0.0
$u(\delta_{51A})$	1.5	1.1	1.2	1.7	2.3	3.4
$\boldsymbol{U(\delta_{1A})}$	**4**	**3**	**3**	**4**	**6**	**10**
5 A (PMJTC + JV5A vs. PMJTC + JV1A)						
$u(\delta_{Step-1})$	1.5	1.1	1.2	1.7		
$u(\delta_A)$	0.4	0.2	0.2	0.2		
$u(\delta_C)$	0.2	0.2	0.2	0.2		
u_{LEV}	1.0	1.0	1.5	3.5		
u_{LF}	0.4	0.0	0.0	0.0		
$u(\delta_{5A})$	1.9	1.5	1.9	3.9		
$\boldsymbol{U(\delta_{5A})}$	**4**	**4**	**4**	**8**		

The expanded uncertainties U are rounded up to reasonable values, assuring $k \geq 2$.

Table III. Uncertainty budget for the step-up from 10 A.

Influence quantity	Standard uncertainty u in μA/A at the frequencies in kHz			
	0.010	**1**	**10**	**100**
10 A (PMJTC + JV10A vs. PMJTC + JV5A)				
$u(\delta_{Step-1})$	1.9	1.5	1.9	3.9
$u(\delta_A)$	0.4	0.2	0.2	0.4
$u(\delta_C)$	0.2	0.2	0.2	0.2
u_{LEV}	5.0	5.0	5.0	10.0
u_{LF}	0.4	0.0	0.0	0.0
$u(\delta_{10A})$	5.4	5.2	5.4	11
$\boldsymbol{U(\delta_{10A})}$	**12**	**12**	**12**	**25**
20 A (PMJTC + Fluke20A vs. PMJTC + JV10A)				
$u(\delta_{Step-1})$	5.4	5.2	5.4	25.3
$u(\delta_A)$	0.4	0.2	0.2	0.4
$u(\delta_C)$	0.2	0.2	0.2	0.2
u_{LEV}	10.0	10.0	15.0	30.0
u_{LF}	0.4	0.0	0.0	0.0
$u(\delta_{20A})$	11	11	16	39
$\boldsymbol{U(\delta_{20A})}$	**25**	**25**	**35**	**80**
50 A (PMJTC + EL-9850 vs. PMJTC + EL-9830)				
$u(\delta_{Step-1})$	11.4	11.3	15.9	39.3
$u(\delta_A)$	0.4	0.2	0.2	0.4
$u(\delta_C)$	0.2	0.2	0.2	0.2
u_{LEV}	10	10	20	40
u_{LF}	0.4	0.0	0.0	0.0
$u(\delta_{50A})$	15	15	26	56
$\boldsymbol{U(\delta_{50A})}$	**30**	**30**	**60**	**120**
100 A (PMJTC + EL-9880 vs. PMJTC + EL-9850)				
$u(\delta_{Step-1})$	15.2	15.1	25.6	56.0
$u(\delta_A)$	0.4	0.2	0.2	0.4
$u(\delta_C)$	0.2	0.2	0.2	0.2
u_{LEV}	10	10	30	50
u_{LF}	0.4	0.0	0.0	0.0
$u(\delta_{100A})$	18	18	39	75
$\boldsymbol{U(\delta_{100A})}$	**40**	**40**	**80**	**150**

The expanded uncertainties U are rounded up to reasonable values, assuring $k \geq 2$.

6. Conclusion

The application of a PMJTC on quartz substrate as calculable transfer standard significantly reduces the measurement uncertainty of ac-dc current transfer difference and ac current calibrations. Improvements of the measurement set-up for comparing current transfer standards by applying potential driven guarding and the use of several different step-up chains allowed to reduce the measurement uncertainty of the step-up to higher currents up to 100 A. For example, the expanded measurement uncertainty for 5 A at 100 kHz could be reduced by a factor of more than seven from former 60 μA/A to now 8 μA/A.

Using a newly designed transconductance amplifier, the frequency range of the current transfer measurements could be extended to 1 MHz for currents up to 1 A. To investigate the current level dependence of high current shunts, a transformer based method was developed.

7. References

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