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Comparison of a Thermal AC Voltage Standard in the 1–30-MHz Frequency Range

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Comparison of a Thermal AC Voltage Standard in the 1 MHz to 30 MHz Frequency Range

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Abstract - **The paper presents results of a comparison of a travelling AC voltage standard, which was a fused-silica NIST planar multijunction thin-film thermal converter (PMJTC). The AC-DC voltage transfer difference of the standard was measured at 2 V and selected frequencies from 1 MHz to 30 MHz against primary thermal AC voltage standards at SUT, INRiM, RISE and Trescal.**

Index Terms - measurement standards, thermal converter, AC-DC transfer, AC-DC transfer difference, key comparison

I. INTRODUCTION

The reproduction of AC voltage in the 1 MHz - 30 MHz frequency range is realized by means of the AC-DC voltage transfer standards based on thermal voltage converters (TVC). The interlaboratory comparisons of standard TVCs are of utmost importance for the evaluation of their accuracy, detection of systematic errors and providing compatibility of worldwide alternating voltage measurements in the 1 MHz - 30 MHz frequency range.

The article refers to the trilateral comparison presented in [1], but its content has been substantially extended. Among others it presents results obtained after the fourth participant - INRiM - had joined the comparison.

II. REASONS FOR THE NEW COMPARISON

The new comparison was performed because of the following reasons:

1. The former comparison at frequencies up to 100 MHz was performed between NRC, VSL, PTB and NIST in 2001 [2], i.e. 17 years ago. The preceding comparisons were performed between 15 participating laboratories in 1999 [3] and 5 laboratories in 1993 [4].

2. The AC-DC transfer difference of the SUT primary AC voltage standards was recently determined in the 1 MHz – 30 MHz frequency range [5], [6]. The estimated uncertainty of these standards is comparable to the best AC voltage standards available in this frequency range.

III. TRAVELING STANDARD

The traveling standard was a type 6002A PMJTC, designed and manufactured by NIST [7]. The nominal input voltage of this TVC is $U_N = 3$ V and the nominal resistance of the heater is 600 Ω. This TVC uses a fused silica substrate of lower relative permittivity than silicon which leads to less capacitive coupling between heater and thermocouples and improves the high-frequency performance. However, due to a thicker membrane the sensitivity of the NIST 6002A PMJTC is lower than the sensitivity of a PTB/IPHT PMJTC [8]. The output voltage of 6002A at nominal input voltage is approximately 20 mV, while the output voltage of the PTB/IPHT PMJTC is 5 times higher.

The original 6002 TVC was slightly modified at SUT: the original output connector was replaced with a UHF-Twin connector and the shell of the N-type input connector was internally connected with the LO pin of the output UHF-Twin connector. To reduce the coupling between the heater wires and the output, the wires between the PMJTC output and the UHF-Twin connector were twisted together. Additionally, the output of the PMJTC was internally shunted with a 2.2 µF ceramic surface-mount capacitor. The latter is a well-known method used to reduce the effect on the ac-dc difference due to capacitive coupling between PMJTC heater and thermocouples. This effect is substantial for PTB/IPHT PMJTCs, but for 6002A PMJTC this effect is negligibly small, which was proven by performing multiple AC-DC measurements with and without this capacitor.

The stability of the AC-DC transfer difference of the travelling standard was confirmed by comparison with another SUT AC voltage standard both before and after the comparison. Measurements were performed in December 2016 and January 2018 in the frequency range 1 MHz to 10 MHz. The AC-DC transfer differences measured in 2018 were within ±3 µV/V of the values measured in 2016.

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IV. PARTICIPANTS

The comparison was performed between SUT, Poland, INRiM, Italy, RISE, Sweden and Trescal, Denmark. The traveling standard was provided by SUT. A short description of the primary AC voltage standards, AC-DC comparators and uncertainty analysis for each participant is presented below:

A. Silesian University of Technology (Poland)

The primary SUT AC voltage standard is based on two calculable coaxial TVCs described in [9], [5]. In the 10 kHz - 30 MHz frequency range their AC-DC transfer differences as well as their uncertainties were calculated using a complex mathematical model [6]. A self-made Fast Reversed DC Source (FRDC) was used to determine the AC-DC transfer difference between 40 Hz and 10 kHz [8], [10]-[13]. At lower frequencies (10... 40) Hz a method similar to the one presented in [14] was applied. The AC-DC measurements were made using the SUT automated two-channel AC-DC comparator shown in Fig.1 [15]. The AC-DC transfer difference was measured relative to DC voltage at all frequencies.

The uncertainty budget for the measurement of the traveling standard against SUT reference standard is presented in Table I. The table presents also the combined standard uncertainty and the expanded uncertainty. The uncertainty budget in Table I includes the influence of the reference standard, noise and nonlinearity of the DC nanovoltmeters, the influence of the T-connector and connector impedances and leakages and dispersion of measurements, expressed as the standard deviation. The standard deviation shown in Table I was calculated from 12 consecutive measurements. The noise and nonlinearity of DC nanovoltmeters were calculated based on the documentation for the used instruments (Keithley 2182A). The uncertainty introduced by the measurement set-up is caused by different leakages, including leakage between heaters and thermocouples of both compared TVCs. This uncertainty component was determined experimentally after performing a number of AC-DC comparisons using TVCs of different construction.
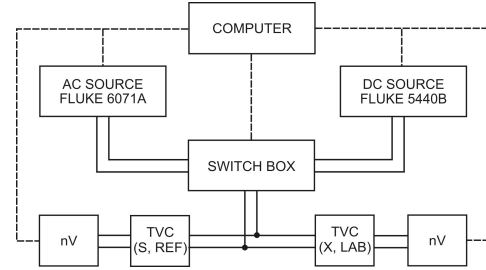

Fig.1: Measurement set-up at SUT for frequencies from 1 MHz to 30 MHz.

The influence of T-connector on the AC-DC transfer difference measurement results was determined experimentally as well. The two TVCs were compared against each other a couple of times using the same T-connector, but both TVCs were disconnected and connected again after each comparison. The obtained results showed an influence of the variable contact resistance between the N-type TVC input connectors and N-type connector. The stability of the contact resistance of the input connector of the T-connector has been additionally verified by performing a similar experiment using three different T- connectors from the same manufacturer, which were used in SUTs laboratory for different periods of time. One of these T-connectors was brand new, the second had been used a few times only.

The third T-connector has currently been used in the AC-DC comparator for approximately half of year. The observed deviations between the measurements results using these different T-connectors was also used to estimate their influence on the uncertainty of the AC-DC comparator. Additionally, several experiments with an additional type N female to male adapter mounted between the TVC and T-adapter were conducted. The results of these experiments and results of the performed theoretical calculation (influence of length of N-type connector and T-connector) were used to estimate the uncertainty of AC-DC comparator introduced by the N-type connector and T-connector.

All the above measurements were performed at an electromagnetically shielded chamber with stabilized temperature (21.5±0.5)°C and a relative air humidity (30±10)%.

TABLE I
UNCERTAINTY OF THE AC-DC VOLTAGE TRANSFER DIFFERENCE MEASUREMENTS AT SUT

Contribution to total uncertainty (µV/V)	Standard uncertainty (µV/V) at $U = 2$ V and at frequency:						
	1 MHz	2 MHz	5 MHz	7 MHz	10 MHz	20 MHz	30 MHz
Reference standard	1	2	5	11	17	60	130
Standard deviation for 12 measurements	1	1	1	1	1	1	2
Measurement setup and bead leakages	1.5	2.5	5	7	10	20	25
T-connector and input connectors	0.2	0.7	1.5	3	5	17	37
Nanovoltmeters	2	2	2	2	2	2	2
Combined standard uncertainty:	3	5	8	11	19	63	132
Expanded uncertainty, $k = 2$ (95%):	**6**	**8**	**16**	**28**	**40**	**132**	**274**

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B. *Istituto Nazionale di Ricerca Metrologica - INRiM (Italy)*

At Istituto Nazionale di Ricerca Metrologica of Italy (INRIM) the national standard for AC-DC voltage transfer is maintained at the lowest level of uncertainty from 10 Hz to 1 MHz by a group of thermal converters composed of thin-film MJTCs, calculable 3D-MJTCs and a calculable HF-SJTC. For frequencies from 1 MHz to 30 MHz a group of three calculable RF-SJTCs converters [8] is used as reference standard. The rated input voltage of the RF-SJTCs is 4 V, their nominal heater resistance is about 800 Ω and the output voltage is 7 mV.

The measurement setup employed for comparisons beyond 1 MHz is a two-channel fully automated system based on a DC calibrator and an arbitrary waveform source (RF-DAC) having 14-bit vertical resolution, update frequency up to 2 GS/s, stable output voltage and harmonic distortion below -40 dBc up to 30 MHz. An RF-coaxial switch, equipped exclusively with N-connectors and capable of operating at low voltages, as well as two synchronized low noise and high precision digital nanovoltmeters suitable for direct reading of electromotive forces of thermal converters complete the measurement setup. For routine high precision comparisons in the range from 10 Hz to 1 MHz and voltages up to 1 kV, some modules of the measuring system are swapped. In particular, the RF-DAC source and the RF-coaxial switch are replaced with an AC calibrator and a standard coaxial switch suitable for withstanding high voltages. A T-connector was used to connect in parallel the input of the TVCs under comparison. The AC-DC difference of the thermal converters under test was determined using the midplane of the T-connector as reference plane.

All the measurements were performed at an environmental temperature of (23.0±0.5)°C and a relative air humidity of (48±5)%. A simplified schematic of the automatic AC-DC measuring system is reported in Fig. 2.

A single AC-DC transfer pattern is composed of a sequence of alternating and direct current voltages, $V_{AC}-V_{DCN}-V_{AC}-V_{DCP}-V_{AC}$. It is performed after an initial warm-up time of about 60 min has been elapsed, followed by the experimental determination of the sensitivity of both TVCs under comparison. Moreover, both amplitudes of V_{DCN} and V_{AC}

voltages are usually aligned as close as possible the amplitude of V_{DCP} using an automatic convergence procedure. This allows us to reduce the stabilization time within the AC-DC transfer sequence, which ranges typically from 30 s to 60 s, thus ensuring very low changes of electromotive-forces of both thermal converters during the whole measurement time. The aperture time useful for the recording of electromotive forces of thermal converters under comparison is set to about 30 s. Table II. reports the uncertainty budget for the measurement of the SUT traveling standard against a group of HF-SJTCs used for this comparison. As can be seen, the largest contributions from 7 MHz to 30 MHz derive from: i) the reference standard, $u(\delta_{Ref})$, which also includes the relative deviation between the measured and calculated ac-dc difference; ii) the deviation from different determination,
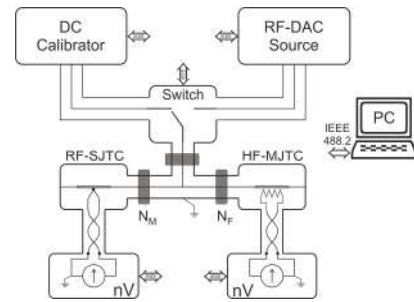

Fig. 2. Automatic AC-DC measurement set-up employed at INRIM. The AC-DC switch break off the inner and outer conductors of the coaxial cables used to connect the DC calibrator and the RF source to the input of the voltage T-connector.

using three different RF-SJTCs; iii) T-connector and bead leakages, $u(\delta_{TC})$, which has been determined experimentally. In particular, it was found that about half of such a contribution depends on the way in which the T-connector is realized and if further N-adapters, e.g. male-male or male-female, are added between the T-connector and the input of one of the TVCs. Further mitigations are planned to be performed in order to reduce this contribution.

TABLE II
UNCERTAINTY OF THE AC-DC VOLTAGE TRANSFER DIFFERENCE MEASUREMENTS AT INRiM

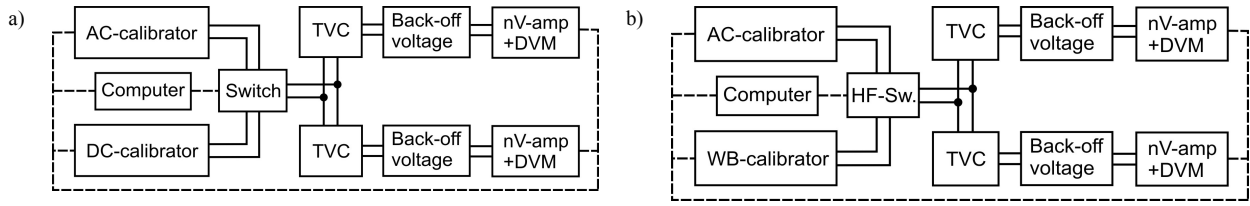| Contribution to total uncertainty (µV/V)	Standard uncertainty (µV/V) at U = 2 V and at frequency:							
	1 kHz	1 MHz	2 MHz	5 MHz	7 MHz	10 MHz	20 MHz	30 MHz
Reference standard, $u(\delta_{Ref})$	0.7	10	13	16	19	24	44	93
Standard deviation of the mean of 20 measurements, $u(\delta_A)$	0.3	0.5	0.5	0.5	0.7	0.7	0.8	1
Repeated measurements, $u(\delta_R)$	0.3	0.6	0.6	0.6	0.8	1.5	1.5	3
Deviation from different determination, $u(\delta_D)$	0.5	2	2	5	15	25	40	65
Measurement setup, $u(\delta_M)$	0.5	1	1	1	1	1	3	6
T-connector and bead leakages, $u(\delta_{TC})$	0.3	1	3	10	20	30	40	80
Combined standard uncertainty:	1	11	14	20	32	46	72	140
Expanded uncertainty, $k = 2$ (95%):	**2**	**21**	**28**	**39**	**63**	**92**	**144**	**280**

Fig.3. Measurement set-up at RISE: a) for frequencies from 10 Hz to 1 MHz, b) for frequencies above 1MHz.

C. RISE (Sweden)

RISE Research Institutes of Sweden is the National Metrology Institute of Sweden. The AC-DC voltage transfer difference at the primary level is maintained by a group of 3D-MJTCs manufactured by PTB [16] and calculable HF SJTC (HF-TVCs) manufactured by VSL [17]. At medium frequencies around 1 kHz we have made a realization using a fast-reversed DC source (FRDC) [12]. Around 1 kHz the AC-DC voltage transfer difference of a 3D-MJTC depends mainly on the Peltier and Thomson effects [16]. At frequencies higher than 1 kHz the AC-AC$_{1\,kHz}$ voltage transfer difference is based on the VSL modeling of HF-TVCs [17].

The travelling standard is calibrated in two steps. The AC-DC difference is measured at 1 kHz and the AC-AC$_{1\,kHz}$ difference is measured at higher frequencies. Adding the two differences gives the AC-DC difference of the travelling standard. The comparisons of the travelling standard and the standards of RISE are made using an automated two-channel measuring system (Fig. 3) configured for measuring AC-DC difference or AC-AC difference with reference to 1 kHz. The two transfer standards to be compared are connected in parallel using type N T-connector. The AC-DC difference and the AC-AC difference of the travelling standard are measured with the center of the T-connector as the reference plane. The low terminal of the transfer standards output connector is connected to the low terminal of the T-connector (for the travelling standard its internal connection is used only), which is the common ground point. When measuring AC-DC difference, the AC- and DC-calibrators are connected to the T-connector and the transfer standards via a fast switch (and a coaxial choke not shown in the Fig. 3). After warm-up of the TVCs the measurement starts by determining the scale factors of the two transfer standards by measuring the change in output voltage for a known change in input voltage at 1 kHz (approximately equal to DC). Then the RMS-value of the AC-voltage is adjusted to within $\pm 1 \cdot 10^{-4}$ of the DC-voltage. AC- and DC-voltage is applied consecutively and the differences between the output voltages of the transfer standards and the back-off voltages are amplified with very linear nanovolt amplifiers and measured by digital voltmeters (DVMs). The AC-DC transfer difference is determined according to (1) but with *nE* for the test and reference TVC replaced by the measured scale factors.

The measurement of AC-AC$_{1kHz}$ difference at 1 MHz and higher frequencies is quite similar to what is described above. But the high frequency (HF) voltage is generated with a WB-calibrator and the switching is made with a HF-switch. Also, a resistor is connected in parallel with the two TVCs near the T-connector to make the load approximately 50 Ω.

The measurements are made in a laboratory with ambient temperature $(23\pm1)^{o}$C and relative humidity (40 ± 10)%. The TVCs are kept in a chamber to minimize drift and temperature changes.

The uncertainty of the measured AC-DC transfer difference of the travelling standard and its uncertainty contributions are presented in Table III. The uncertainty of the reference at high frequencies is based on the calibration of a HF-TVC at VSL and the long-term stability is estimated on the agreement between calculated and measured differences of our two HF-TVCs. The uncertainty of the indicated value is the standard deviation of the mean of 14 measurements. Uncertainty of the indicated values due to instability of the input voltages is minimized by simultaneous triggering of the DVMs.

The main sources of uncertainty in the measurement set-up is the uncertainty in the measured scale factors, non-linear drift of the back-off sources and TVCs and non-linearity of the nV-amplifiers. The influence of the scale factors increases at higher frequencies as the measured AC-AC difference between the test and reference TVC increase. Uncertainty in the measured values due to linear drift in the output voltages and the back-off voltages are minimized by using a symmetric measuring sequence: AC$_{1kHz}$, AC, AC$_{1kHz}$ and DC$^-$, AC, DC$^+$.

The uncertainties from the following contributions in the measurement set-up are or are made negligible: reversal errors of TVCs, non-pure spectra of AC- and DC-sources, non-symmetric switching times, common mode currents, leakage in switch and frequency deviation.

During the measurements two type N T-connectors are used. The travelling standard has a type N female input connector but the two transfer standards used by RISE have different input connectors. The 3D-MJTC has type N female and the HF-TVC has type N male. The T-connector used for the AC-DC difference measurement has two type N male output connectors. At 1 kHz the uncertainty due to the T-connector is negligible. The T-connector used for the AC-AC difference measurement has one male and one female type N output connector. The uncertainty of this T-connector is estimated from measurements of the change in AC-AC difference when a type N adapter female to male is added between the T-connector and one of the TVCs. The maximum uncertainty contribution of the T-connector from the reference plane to its output connector is estimated to the change in AC-AC difference corresponding to ± 1 mm. The uncertainty of the reference 3D-MJTC at 1 kHz is based on the FRDC measurement and the uncertainty of the measured AC-DC difference at 1 kHz is due to the measurement set-up and repeatability.

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TABLE III
UNCERTAINTY OF THE AC-DC VOLTAGE TRANSFER DIFFERENCE MEASUREMENTS AT RISE

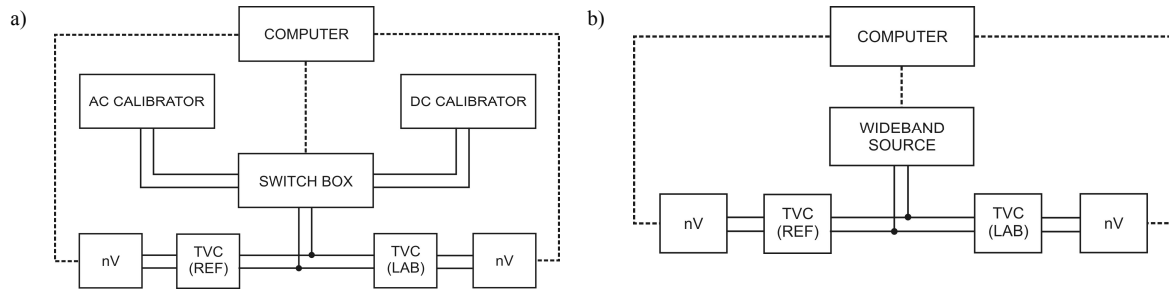| Contribution to total uncertainty (μV/V)	Standard uncertainty (μV/V) at U = 2 V and at frequency:							
	1 kHz	1 MHz	2 MHz	5 MHz	7 MHz	10 MHz	20 MHz	30 MHz
Reference standard AC-AC$_{1kHz}$ difference		5	10	12	15	15	40	90
Long term stability reference standard		2	2	4	7	10	20	65
Indicated AC-AC$_{1kHz}$ difference		2	2	2	2	2	2	2
Measurement set-up		2	3	3	5	5	10	20
T-connector		0,1	0,5	1	2	4	15	35
Reference standard AC-DC difference at 1 kHz	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Comparison AC-DC difference at 1 kHz	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Combined standard uncertainty:	0.7	6.2	11	13,5	17.5	20	50	120
Expanded uncertainty, k = 2 (95%):	**1.4**	**13**	**22**	**27**	**35**	**40**	**100**	**240**

Fig. 4. Measurement set-up at Trescal: a) for frequencies from 10 Hz to 1 MHz, b) for frequencies above 1 MHz.

D. TRESCAL (Denmark)

The Danish National Standard for AC voltage and AC-DC voltage transfer difference is realized and maintained at TRESCAL. Three PTB type 3D-MJTCs [16], [18] are used for AC-DC voltage transfer difference measurements up to 1 MHz. A schematic diagram of the two-channel set-up for measurements from 10 Hz to 1 MHz used at Trescal is shown in Fig. 4a. DC voltage of both polarities and AC voltage is applied alternately to both thermal converters by use of an automated switch box in a predetermined sequence, AC, DC+, AC, DC–, AC. For measurements at frequencies above 1 MHz two VSL type SJTCs [17] and one NIST type 6002 MJTC [7] are used. Measurements at frequencies above 1 MHz are carried out relative to 1 kHz by use of a fully automated two-channel set-up, including an AC voltage source and two high-resolution DMMs. A switch box is not used in this set-up. Instead the AC voltage source is switched internally between 1 kHz and the desired high frequency ranging from 1 MHz to 30 MHz. In this case the measurement sequence becomes AC, AC$_{1 kHz}$, AC, AC$_{1 kHz}$, AC. The measured AC-AC$_{1 kHz}$ transfer difference is subsequently corrected by the measured AC-DC transfer difference at 1 kHz to obtain the resulting AC-DC transfer difference at the frequencies from 2 MHz to 30 MHz. A schematic diagram of the set-up is shown in Fig. 4b. All instruments are computer controlled via GPIB. The environmental conditions during the measurements are kept at (23±1)°C and (45±15)% RH. The measurement procedure for AC-DC transfer measurements is described in section V. A new graphical feature has been added to the software for the automated measurement process, providing an indication of the drift of the measured AC-DC transfer difference during the measurements. The power coefficients n of the thermal converters are determined by use of a versatile automated program dedicated to this task. For the measured AC-DC transfer difference of the travelling standard δ_{lab} the resulting measurement uncertainties are compiled in Table IV. Standard uncertainties at the each frequency are estimated for a number of influence parameters. The standard uncertainties of the reference standards used at 1 kHz and 1 MHz is estimated with contributions due to capacitance, inductance and dielectric loss of the heater and leads and skin effect. A fast reversed DC (FRDC) source has been used to determine the thermoelectric effects of the converters. The standard uncertainties of the reference standards used from 2 MHz to 30 MHz are the calibration uncertainties given by VSL. The standard deviation is determined from at least 12 repeated measurements at each frequency and calculated as the standard deviation of the mean. The influence of the measured power coefficients relies on its determination (±0,005), and depends on the measured AC-DC transfer difference.

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TABLE IV
UNCERTAINTY OF THE AC-DC VOLTAGE TRANSFER DIFFERENCE MEASUREMENTS AT TRESCAL

Contribution to total uncertainty (µV/V)	Standard uncertainty (µV/V) at U = 2 V and at frequency:							
	1 kHz	1 MHz	2 MHz	5 MHz	7 MHz	10 MHz	20 MHz	30 MHz
Reference standard	0.3	13	15	15	15	15	40	90
Standard deviation	0.5	1	3	3	4	4	5	5
Power coefficients	0.01	0.3	0.5	0.6	0.7	1	3	6
Linearity, nV-meters	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Noise & thermal voltage, nV-meters	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Resolution, nV-meters	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
T-connector	0.01	5	7	10	15	20	30	50
Different reference standards	1	5	8	15	20	30	45	70
1 kHz reference (above 1 MHz)			1.5	1.5	1.5	1.5	1.5	1.5
Combined standard uncertainty:	1.5	15	19	24	30	40	68	125
Expanded uncertainty, k = 2 (95%):	**3**	**30**	**38**	**48**	**60**	**80**	**136**	**250**

The uncertainty components corresponding to nanovoltmeters have been estimated based on its specification: 7½-digit resolution, noise typically from 1.5 nV to 10 nV and result of measurements using Josephson DC voltage system: linearity typically from 1 nV to 5 nV for a 50 µV/V interval around the measured output voltage. Due to skin effect and transmission line effects a variation in length of the two arms from the centre of the T-connector, which is the reference plane of the measurements, will influence the measured AC-DC transfer difference. Furthermore these frequency dependent effects vary for different T-connectors. Experiments with different T-connectors and different N-type male-female adapters inserted on one side of the T-connector lead to estimated standard uncertainties of 5 µV/V at 1 MHz, increasing to 50 µV/V at 30 MHz. The different result obtained with the three different reference standards, which have slightly different impedance characteristics, is also considered as an uncertainty component. Further influence parameters such as frequency accuracy (100 µHz/Hz), harmonic distortion (below 0.5%), time constants and temperature coefficients of the thermal converters are considered to be negligible.

V. RESULT OF COMPARISON

The AC-DC transfer difference of the traveling standard δ_{lab} is determined from the measured output voltages E of the reference standard (ref) and the traveling standard (lab) at DC voltage and AC voltage and the AC-DC transfer difference of the reference standard δ_{ref} by the expression:

$$\delta_{\text{lab}} = \frac{E_{\text{ref,AC}} - E_{\text{ref,DC}}}{n_{\text{ref}} E_{\text{ref,DC}}} - \frac{E_{\text{lab,AC}} - E_{\text{lab,DC}}}{n_{\text{lab}} E_{\text{lab,DC}}} + \delta_{\text{ref}} \quad (1)$$

where n_{ref} and n_{lab} are the power coefficients of the reference and travelling standards respectively, taking the nonlinear input relation $E = kV^n$ of a thermal voltage standard into account, were E and V is output and input voltage of the standard, respectively. Eq. (1) was also used to determine the AC-AC$_{\text{1kHz}}$ difference at RiSE.

The power coefficients were determined by the approximate relation $n = \Delta E / \Delta V \cdot V / E$ with ΔE denoting a small change in output voltage corresponding to a small change ΔV in input voltage. Typically the power coefficients were measured by all participants at DC voltage by varying the nominal voltage V by an amount ΔV, typically ±50 µV/V, and measuring the change in output voltage ΔE. In order to compensate for the thermoelectric effects of the heater elements it is necessary to apply DC voltage of both polarities. Therefore the terms $E_{\text{ref,DC}}$ and $E_{\text{lab,DC}}$ in (1) are average $E_{\text{DC}} = (E_{\text{DC+}} + E_{\text{DC-}})/2$. Following a warm-up time of at least 30 minutes AC and DC voltage is applied to the thermal converters in the sequence V_{AC} - $V_{\text{DC+}}$ - V_{AC} - $V_{\text{DC-}}$ - V_{AC} in order to compensate for a linear drift of the thermal converters. Typically a 30 - 90 s stabilization period is chosen after each switching operation before averaging 5 output voltage readings taken in 5 s intervals of both nanovoltmeters. At each frequency the result δ_{lab} is finally calculated as the mean value of at least 12 repeated runs of the measurement sequence.

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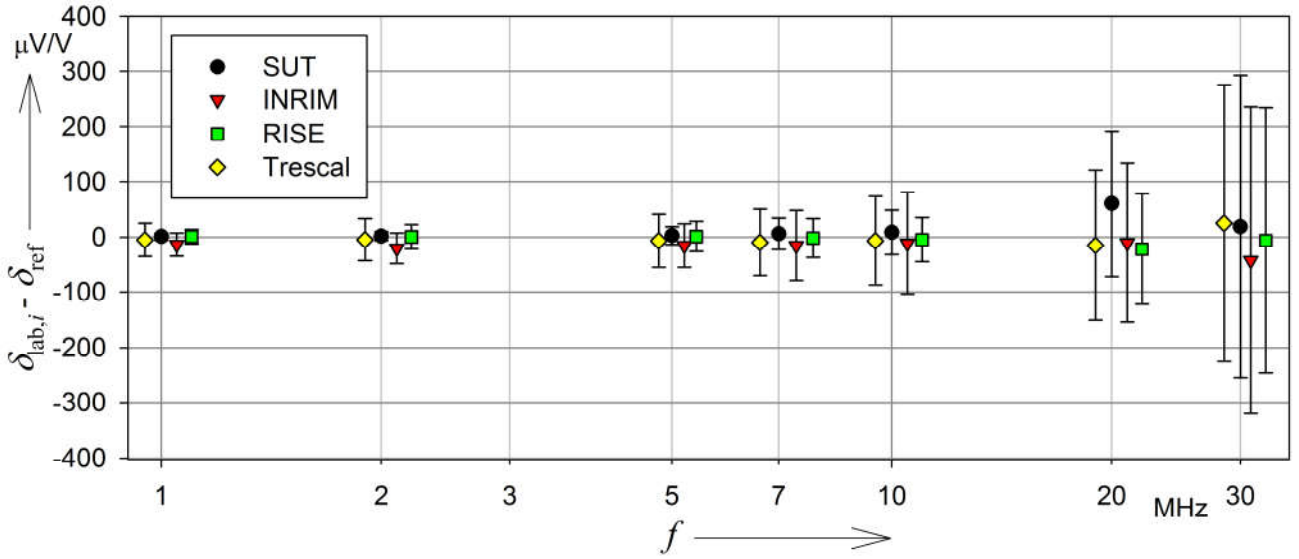Actual identifier: IEEE_TIM-20-00854_rev.2

Fig. 5. Result of the comparison presented as the deviation between the participants results and the reference value. Bars represent expanded uncertainty (k=2).

Each participant measured the AC-DC transfer difference $\delta_{\text{lab},i}$ of the travelling AC voltage standard for selected frequencies. For each frequency, the deviation $\Delta(\delta) = \delta_{\text{lab},i} - \delta_{\text{ref}}$ was calculated, where:

$$\delta_{\text{ref}} = \sum \frac{\delta_{\text{lab}i}}{u^2(\delta_{\text{lab}i})} u^2(\delta_{\text{ref}}). \qquad (2)$$

is the comparison reference value calculated as the weighted average [19] and $\delta_{\text{lab}i}$ and $u(\delta_{\text{lab}i})$ are the AC-DC transfer differences and their uncertainties, respectively, measured by the i-th participant. The standard uncertainty of the reference value u(delta ref) is determined by:

$$\frac{1}{u^2(\delta_{\text{ref}})} = \sum \frac{1}{u^2(\delta_{\text{lab}i})} . \qquad (3)$$

The result of the comparison is shown in Fig. 5.

The AC-DC transfer differences measured by the new participant (INRiM) has further consolidated the comparison result previously reported by the other three laboratories [1], within the level of uncertainty declared by each participant.

VI. CONCLUSION

The results obtained within the comparison of AC voltage standards at SUT, INRiM, RISE and Trescal show good consistency in the 1 MHz - 30 MHz frequency range and remain within the uncertainties declared by these institutions. It was also shown that due to stability of its AC-DC transfer difference the fused-silica based PMJTC is well suited to be used as a traveling standard.

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