RMO Supplementary Comparison EURAMET.EM-S46
High voltage comparison of DC ratio

FINAL REPORT

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1. Introduction

Metrology area, branch	Electricity and Magnetism, High Voltage and Current
Description	High DC voltage ratio up to 200 kV
Time of measurement	2022-03-07 – 2022-03-25
Measurand(s)	DC voltage ratio
Parameter(s)	Nominal ratio: 20000 : 1 Voltage: up to 200 kV
Transfer device(s)	Star comparison, all references in one lab at the same time.
Comparison type	Supplementary comparison
Consultative Committee	CCEM (Consultative Committee for Electricity and Magnetism)
Related regional metrology organizations	EURAMET

2. Participants and organisation of the comparison

2.1 Co-ordinator and members of the support group

The pilot laboratory for the comparison was RISE (Sweden).

Co-ordinator:	Alf-Peter Elg +46 10 516 5518 alf.elg@ri.se
Support group:	Jari Hällström jari.hallstrom@vtt.fi
	Gert Rietveld grietveld@vsl.nl

2.2 List of participants

Acronym	Institute	Country	Status	Contact
RISE	Research Institutes of Sweden AB	Sweden	NMI	Dr. Alf-Peter Elg alf.elg@ri.se
VTT MIKES	Technical Research Centre of Finland Ltd	Finland	NMI	Dr. Jari Hällström jari.hallstrom@vtt.fi
PTB	Physikalisch-Technische Bundesanstalt	Germany	NMI	Dr. Johann Meisner johann.meisner@ptb.de
TUBITAK	TÜBITAK Ulusal Metroloji Enstitüsü	Turkey	NMI	Dr. Ahmet Merev ahmet.merev@tubitak.gov.tr
VSL	VSL National Metrology Institute (VSL)	Netherlands	NMI	Dr. Ernest Houtzager ehoutzager@vsl.nl

2.3 Organisation and comparison schedule

All dividers were sent to pilot laboratory for comparison. Participants defined the scale factor (ratio) of their divider using existing home laboratory procedures before sending the divider for comparison measurements at RISE. Each participant repeated their home calibration after the divider was returned after comparison. Comparison measurements were performed in February/March 2022 at RISE according to the schedule shown below.

Action	**Start**	**Finish**
Arrival of dividers to RISE	20.01.2022	22.02.2022
Temperature stabilization (7 days)	14.01.2022	01.03.2022
2 GΩ measurements (EURAMET.EM-S47)	21.01.2022	01.03.2022
200 kV scale factor measurements	7.03.2022	11.03.2022
Departure of dividers from RISE	21.03.2022	06.04.2022

2.4 Unexpected incidents

None.

3. The standards and measurement instructions

3.1 Description of the standards

The standards listed in Table 1 were identical 200 kV divider modules [4] shown in Figure 1. The dividers were built in 2013 as part of EU funded *Metrology for High Voltage Direct Current* (HVDC) project [6].

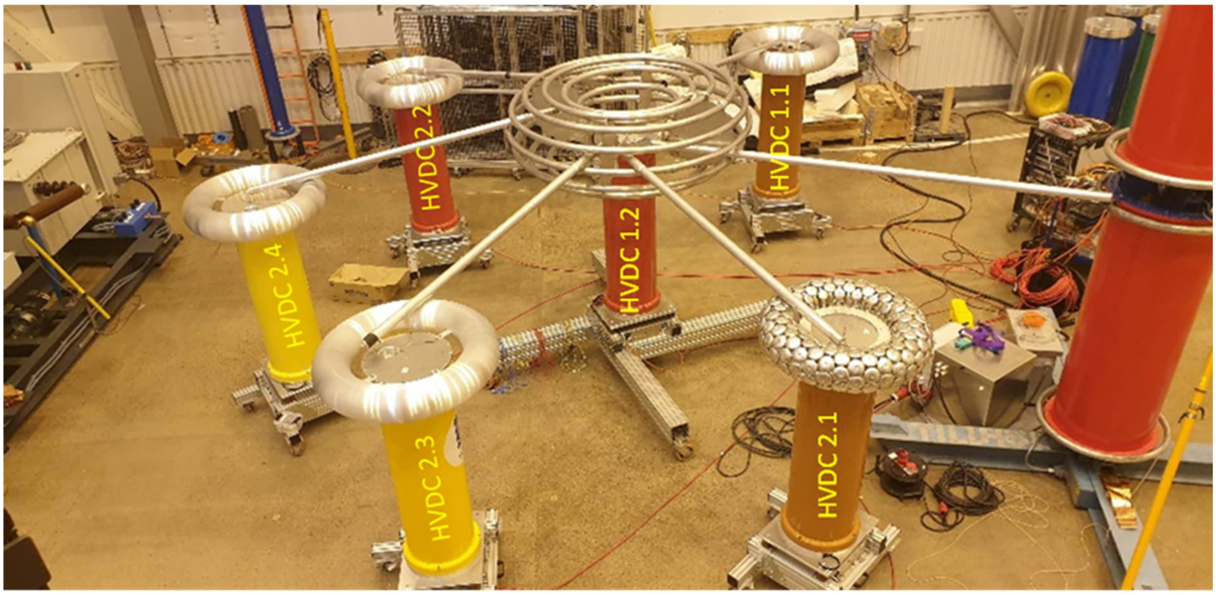


Figure 1 The five high voltage dividers to be compared (HVDC1.1, HVDC2.1, HVDC2.2, HVDC2.3, and HVDC2.4) were set around a sixth transfer divider used as central divider (HVDC1.2) in substitution method.

Table 1 Identifications of the dividers’ high and low voltage arms

	RISE	**PTB**	**TUBITAK**	**VSL**	**VTT**	**Reference for substitution method**
HV arm	HVDC1.1	HVDC2.1	HVDC2.2	HVDC2.3	HVDC2.4	HVDC1.2
LV arm	LV6	LV1	LV2	LV3	LV4	LV5

The outer diameter of a HV module is 480 mm, it is 1500 mm high, and it weighs 150 kg. A schematic of the internal structure of the HV module and the LV arm is shown in Figure 2. The components are enclosed in an SF_6 filled fiberglass tube. The top endplate houses a gas valve, pressure gauge and a feed-through for the reference divider signal. The bottom plate has a mating feed-through, so that the modules can be directly stacked and mounted on top of each other.

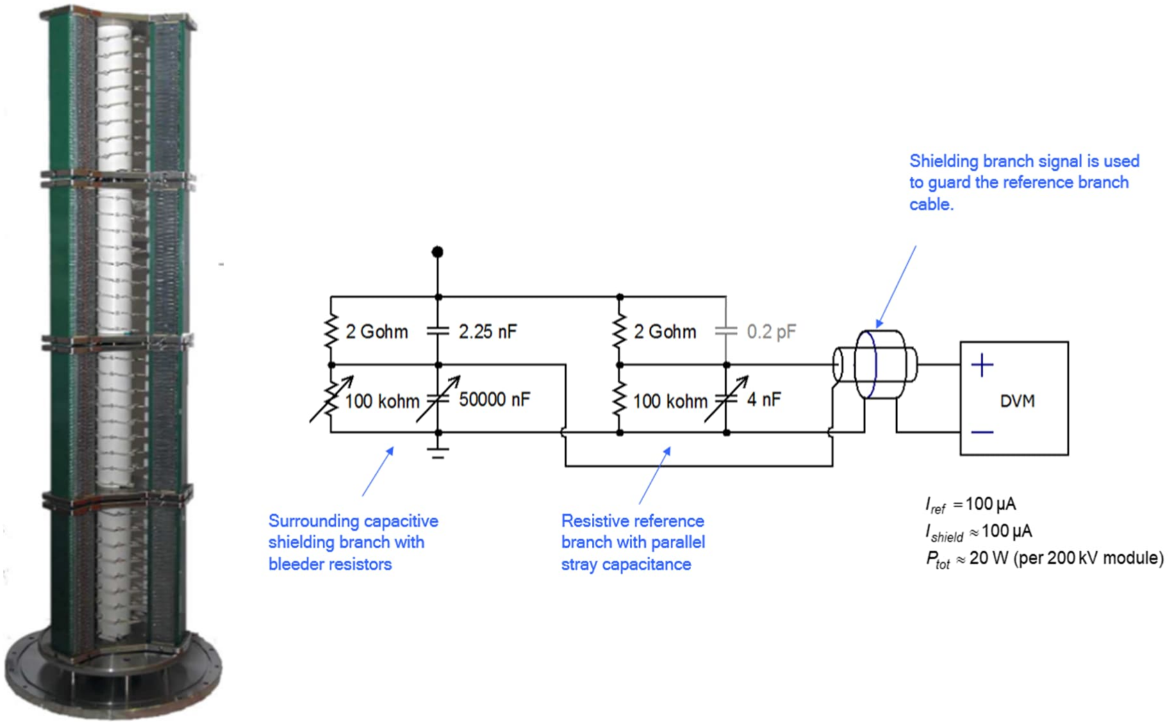


Figure 2 Left: Internal structure of the divider high voltage arm.
Resistive branch resistors on the white center support,
shielding branch capacitors inside the three green supports around it.
Right: The adjustments are used to optimise the AC behaviour, when needed.

3.2 Quantities to be measured and measurement conditions

The DC ratio of the divider, with nominal value of 20000. Recommended ambient temperature was (22.4 ± 0.5) °C.

3.3 Measurement instructions

Measurement instructions are provided in the Technical Protocol (Annex C). The standards were acclimatized for at least 7 days in the laboratory before commencement of measurements.

3.4 Deviations from the protocol

No adjustments of the protocol were necessary.

4. Scale factor values measured by the participants

Each participant calibrated the scale factor (ratio) of their divider before sending it the coordinator, and again when it returned to the participant after the comparison. The scale factor values, ambient temperature and calibration voltage level (1 kV, 10 kV or 50 kV) are shown in Table 2 together with respective uncertainties. The table also shows the applied temperature, power and voltage corrections, and interpolation of the scale factor to the date of the comparison measurement at RISE on 2022-03-10.

Comparison of these scale factors with scale factors based on resistance calibrations at RISE is shown in Annex A.

4.1.1 Temperature correction

The participants performed their own before and after calibrations on different ambient temperatures The temperature coefficients of the design were used to normalize the results to 22.4 °C.

Temperature dependence of the resistors in the HV arm of all dividers used in this comparison is (1.1 ± 0.2) µΩ/Ω/K according to [3].

Temperature dependence of the resistors in the LV arms dividers used in this comparison is from -0.27 to +0.73 ± 0.17 µΩ/Ω/K, according to VTT MIKES calibration during the manufacture of the dividers in 2013.

Respective temperature coefficients, corrections and their application are shown in Table 2.

4.1.2 Power correction

The participants performed their own before and after calibrations on different voltages. The known self heating effect of the design is 5 °C when the nominal voltage, 200 kV, is applied for a longer period. This power relationship is quadratic, and the respective corrections and their application is shown in Table 2.

4.1.3 Voltage correction

The participants performed their own before and after calibrations on different voltages. Voltage coefficient of the resistors in the HV arm of all dividers used in this comparison is (10 ± 4) µΩ/Ω/kV according to [3]. More recent estimate is (10.4 ± 0.6) µΩ/Ω/kV, based on re-evaluation of results of publication [5]. For the complete divider this leads to (-0.05 ± 0.04) µV/V/kV, when the voltage coefficient of the LV arm is ignored. The respective corrections and their application are shown in Table 2.

Table 2 Scale factor results reported by the participants together with applied temperature, power and voltage corrections, and interpolation to normalize the calibration results to 1 kV, 22.4 ºC and for 2022-03-10. All uncertainties *k*=2.

Lab	RISE	PTB	TUBITAK	VSL	VTT
HV arm	HVDC1.1	HVDC2.1	HVDC2.2	HVDC2.3	HVDC2.4
LV arm	LV6	LV1	LV2	LV3	LV4
HV arm TC [μΩ/Ω/K] [1]	1.1	1.1	1.1	1.1	1.1
LV arm TC [μΩ/Ω/K] [2]	0.73	0.34	-0.27	0.54	0.2

[1] E. Houtzager et al., “Selection and characterization of resistors for a HVDC reference divider”, CPEM 2012

[2] VTT calibration certificate M-13E092, 2013-10-23

Each lab before

	Certificate	I10369-K08	N/A	2021.01619	3353083.01, 3353083.02B	M-20E178
Results from certificates	Date	2022-01-27	2021-08-18	2021-08-22	2022-01-03	2022-02-07
	SF	19995.362	19996.045	19994.725	19999.347	20000.71
	Unc. [ppm]	6	1.1	3.6	10	2
	U [kV]	1	50	1	1	10
	T [°C]	23	22	23	22	21
	Unc. (*T*) [°C]	±1	±1	±1	±1	±2
Corrections to 1 kV and 22.4 °C	Temp corr. [μV/V] [3]	-0.2	0.3	-0.8	0.2	1.3
	Power corr. [μV/V] [4]	0.0	-0.3	0.0	0.0	0.0
	Volt corr. [μV/V] [5]	0.0	2.5	0.0	0.0	0.5
	Total corr. [μV/V]	-0.2	2.5	-0.8	0.2	1.7
	@ 1 kV, 22.4 °C	19995.36	19996.09	19994.71	19999.35	20000.74

Each lab after

	Certificate	I10723-K19	N/A	2022.01374	3353122.01, 3353122.02B	M-23E100
Results from certificates	Date	2023-02-07	2022-08-17	2022-09-17	2022-04-25	2023-04-12
	SF	19995.363	19996.052	19994.635	19999.365	20000.78
	Unc. [ppm]	6	1.1	3.7	10	3
	U [kV]	1	50	1	1	10
	T [°C]	23	22	23	22.4	21
	Unc. (*T*) [°C]	±1	±1	±1	±0.1	±2
Corrections to 1 kV and 22.4 °C	Temp corr. [μV/V] [3]	-0.2	0.3	-0.8	0.0	1.3
	Power corr. [μV/V] [4]	0.0	-0.3	0.0	0.0	0.0
	Volt corr. [μV/V] [5]	0.0	2.5	0.0	0.0	0.5
	Total corr. [μV/V]	-0.2	2.5	-0.8	0.0	1.7
	@ 1 kV, 22.4 °C	19995.36	19996.10	19994.62	19999.36	20000.81
	Unc.(corr.) [μV/V]	0.01	0.52	0.01	0.01	0.10

[3] See HV and LV arm temperature coefficients above

[4] Quadratic, 5 μV/V @ 200 kV

[5] (-0.05 ± 0.04) μV/V/kV [E. Houtzager et al., “Selection and characterization of resistors for a HVDC reference divider”, CPEM 2012]

Interpolation for

	Lab	RISE	PTB	TUBITAK	VSL	VTT
2022-03-10	SF	19995.36	19996.10	19994.66	19999.36	20000.75
	Unc. (SF) [μV/V]	6.0	1.4	3.7	10.0	3.0

5. Measurements at star lab, RISE

The five dividers listed in Table 1 were connected in a star formation according to Figure 1.

The outputs from all systems were connected via a scanner type National Instruments 34972A equipped with two boards type 34908A multiplexers (40 ch each). One board multiplexed the signals from the precision arms of the five dividers under test, and the other board the shield signals. The input to the two scanners were connected via a breakout box with BNC connectors. Four 3458A multimeters were used:

1. The precision arm reference divider (REF)
2. The precision arm from devices under test, multiplexed
3. The shield arm from devices under test, multiplexed
4. Dummy one providing trigger for the three above

A LabVIEW program controlled the scanner and performed single trigger measurements on the three 3458A above for each divider in turn,

1. HVDC2.1 (DUT, 2 signals) & HVDC1.2 (REF),
2. HVDC2.2 (DUT, 2 signals) & HVDC1.2 (REF),

etc.

N. HVDC1.5 (DUT, 2 signals) & HVDC1.2 (REF)

The loop of measurements was repeated on both polarities for 100 samples.

This process was repeated for 5 voltage levels according to Table 3.

Table 3 Comparison voltage levels and identification of RISE voltage sources

Voltage level	Voltage source
±1 kV	FUG HCP 350-65000
±10 kV	FUG HCP 350-65000
±50 kV	FUG HCP 350-65000
±100 kV	Hipotronics 300 kV module with Chroma 62150H-1000S AC source
±200 kV	Hipotronics 300 kV module with Chroma 62150H-1000S AC source

6. Measurement results and uncertainty

All participants provided their results with the associated uncertainty budget. The uncertainties were reported using coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95 %. The uncertainty of the measurement was to be estimated according to the BIPM Guide to the expression of Uncertainty in Measurement [2].

Uncertainty budgets for each participant are provided in Annex B.

Divider scale factors and their uncertainties estimated for the time of measurements at RISE in March 2022 are listed in Table 2. Type A component (based on the standard deviation of each comparison) is quadratically added to it to get the uncertainty of each comparison. The deviations from HVDC1.2, related type A uncertainty components and comparison uncertainties are shown in Table 4.

Table 4 Deviations from the stable reference (e), type A contributions based on the standard deviation of comparison results (U), and the comparison uncertainties (Ue).

Scale factors	Lab	RISE	PTB	TUBITAK	VSL	VTT
Scalefactor, 2022-03-10	SF	19995.36	19996.10	19994.66	19999.36	20000.75
SF uncertainty	U(SF) [µV/V]	6.0	1.4	3.7	10.0	3.0
1 kV comparison						
Diff. from HVDC1.2 reading	*e* [µV/V]	4.7	9.5	16.1	4.4	8.9
Type A, *k*=2	*U* [µV/V]	1.9	1.5	2.3	2.3	2.2
Comparison uncertainty, k=2	*Ue* [µV/V]	6.3	2.1	4.4	10.3	3.7
10 kV comparison						
Diff. from HVDC1.2 reading	*e* [µV/V]	5.8	9.1	18.3	6.5	8.8
Type A, *k*=2	*U* [µV/V]	0.2	0.2	0.4	0.2	0.2
Comparison uncertainty, k=2	*Ue* [µV/V]	6.0	1.5	3.7	10.0	3.0
50 kV comparison						
Diff. from HVDC1.2 reading	*e* [µV/V]	5.6	9.0	17.8	6.1	8.6
Type A, *k*=2	*U* [µV/V]	0.1	0.1	0.1	0.2	0.1
Comparison uncertainty, k=2	*Ue* [µV/V]	6.0	1.5	3.7	10.0	3.0
100 kV comparison						
Diff. from HVDC1.2 reading	*e* [µV/V]	4.7	8.8	16.1	4.4	8.9
Type A, *k*=2	*U* [µV/V]	5.5	5.8	5.9	5.6	5.7
Comparison uncertainty, k=2	*Ue* [µV/V]	8.2	5.9	7.0	11.5	6.4
200 kV comparison						
Diff. from HVDC1.2 reading	*e* [µV/V]	5.7	8.6	17.8	4.4	7.0
Type A, *k*=2	*U* [µV/V]	4.2	4.0	4.1	4.0	4.1
Comparison uncertainty, k=2	*Ue* [µV/V]	7.3	4.2	5.5	10.8	5.1

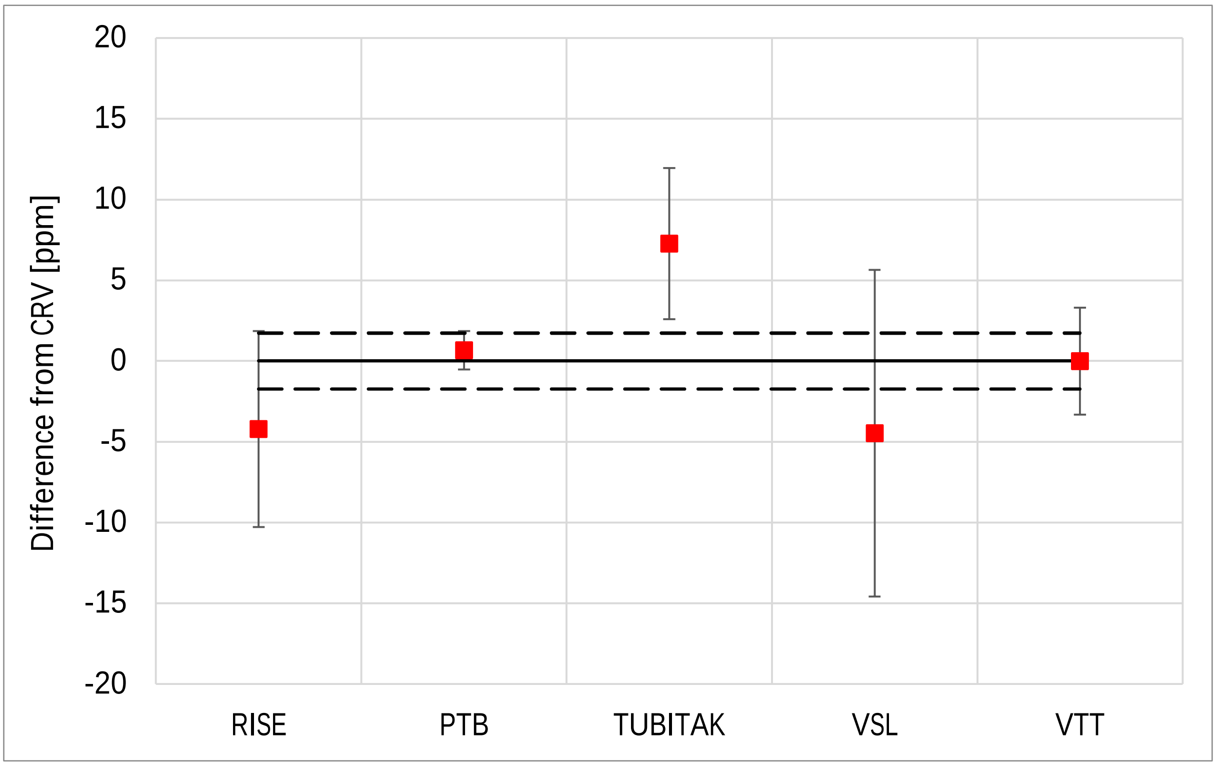
6.1 1 kV comparison results at RISE

The 1 kV comparison at RISE was performed using substitution method as described in clause 4. The scale factors from Table 2 were used for each divider in the analysis. The result of the 1 kV comparison together with the analysis of the results is shown in Table 5. The CRV is given as deviation from the stable reference (HVDC1.2) scale factor. The CRV and its expanded uncertainty (*k*=2) are calculated as described in clause 6.3.

Table 5 Comparison results and CRV, 1 kV

1 kV	RISE	PTB	TUBITAK	VSL	VTT
e_i [ppm]	4.7	9.5	16.1	4.4	8.9
$U(e_i)$ [ppm]	6.3	2.1	4.4	10.3	3.7
$e_i - y$ [ppm]	-4.2	0.7	7.3	-4.5	-0.01
$U(\Delta e_i)$ [ppm]	6.1	1.2	4.7	10.1	3.3
$\lvert E_n \rvert$	0.7	0.6	1.6	0.4	0.00
Exclude			1		

CRV [ppm]	8.9
U(CRV) [ppm]	1.7
Pr	40 %



6.2 Voltage linearity comparison at RISE

The linearity comparison was performed using substitution method as described in clause 4. The scale factors from Table 2 were used for each divider. The result of the linearity comparison together with the analysis of the results is shown in Table 6 to Table 9. The CRVs and their expanded uncertainties (k=2) are calculated as described in clause 6.3.

All dividers used in the comparison were identical, and they have a known voltage dependence of (-0.05 ± 0.04) µV/V/kV [4], which should be considered when using any these dividers.

Table 6 Comparison results and CRV, 10 kV

10 kV	RISE	PTB	TUBITAK	VSL	VTT
e_i [ppm]	5.8	9.1	18.3	6.5	8.8
$U(e_i)$ [ppm]	6.0	1.5	3.7	10.0	3.0
$e_i - y$ [ppm]	-3.1	0.3	9.5	-2.3	-0.09
$U(\Delta e_i)$ [ppm]	5.9	0.7	4.0	9.9	2.8
$\|E_n\|$	0.5	0.4	2.4	0.2	0.03
Exclude			1		

CRV [ppm]	8.8
U(CRV) [ppm]	1.3
Pr	71 %

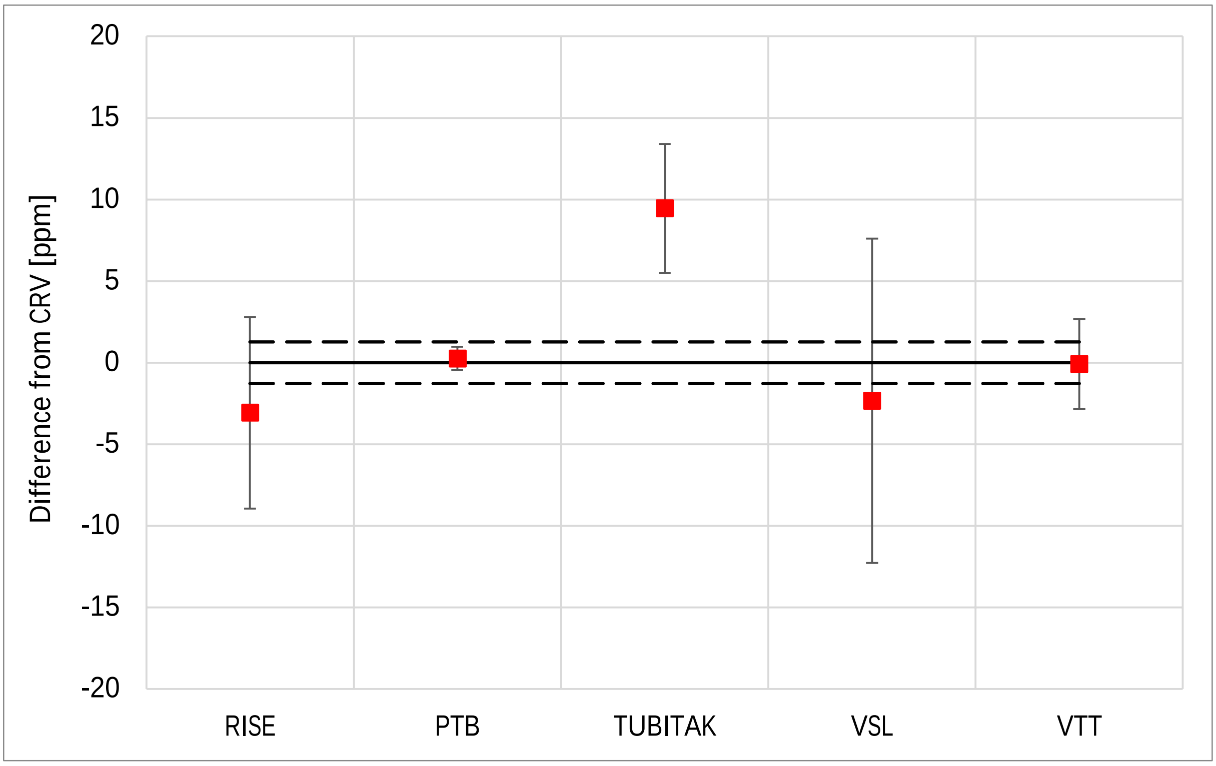


Table 7 Comparison results and CRV, 50 kV

50 kV	RISE	PTB	TUBITAK	VSL	VTT
e_i [ppm]	5.6	9.0	17.8	6.1	8.6
$U(e_i)$ [ppm]	6.0	1.5	3.7	10.0	3.0
$e_i - y$ [ppm]	-3.1	0.3	9.0	-2.6	-0.10
$U(\Delta e_i)$ [ppm]	5.9	0.7	3.9	9.9	2.8
$\|E_n\|$	0.5	0.4	2.3	0.3	0.04
Exclude			1		

CRV [ppm]	8.7
U(CRV) [ppm]	1.3
Pr	69 %

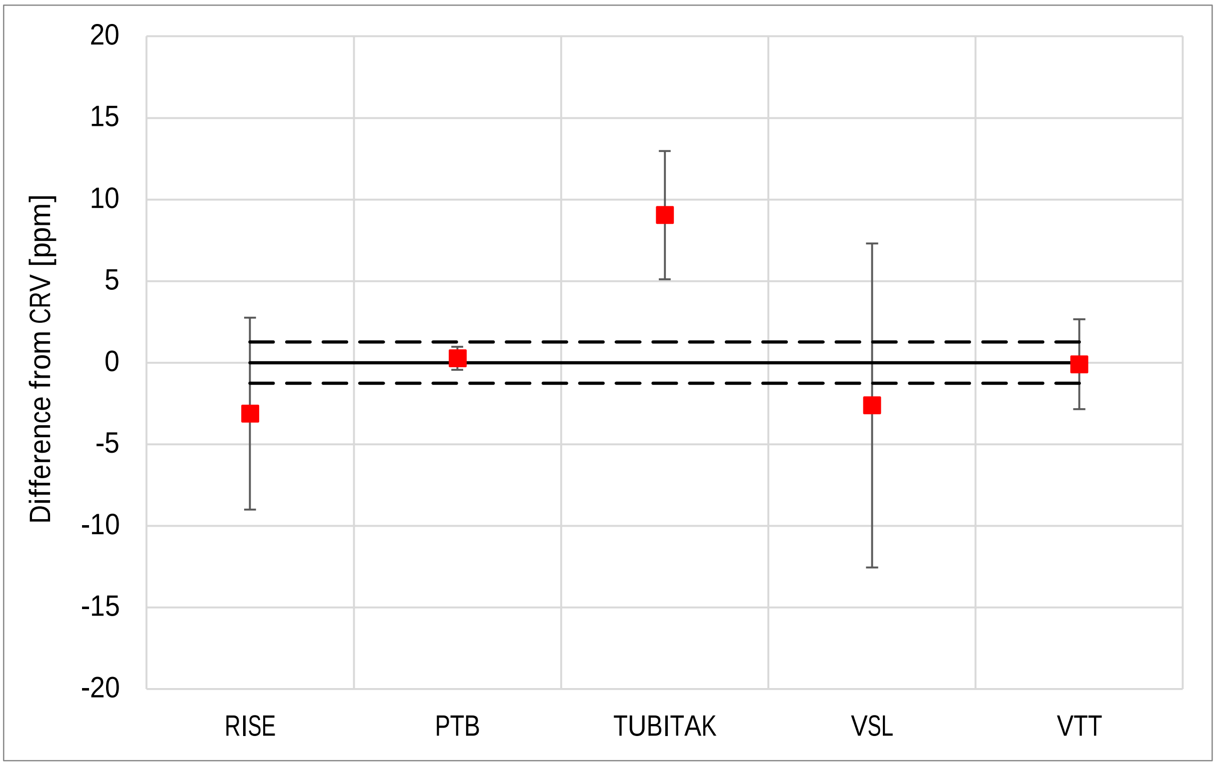


Table 8 Comparison results and CRV, 100 kV

100 kV	RISE	PTB	TUBITAK	VSL	VTT
e_i [ppm]	4.7	8.8	16.1	4.4	8.9
$U(e_\mathrm{i})$ [ppm]	8.2	5.9	7.0	11.5	6.4
$e_\mathrm{i} - y$ [ppm]	-4.7	-0.6	6.7	-5.0	-0.5
$U(\Delta e_\mathrm{i})$ [ppm]	7.5	5.0	6.2	11.0	5.6
$\lvert E_\mathrm{n} \rvert$	0.6	0.11	1.1	0.5	0.10
Exclude					

CRV [ppm]	9.4
U(CRV) [ppm]	3.2
Pr	21 %

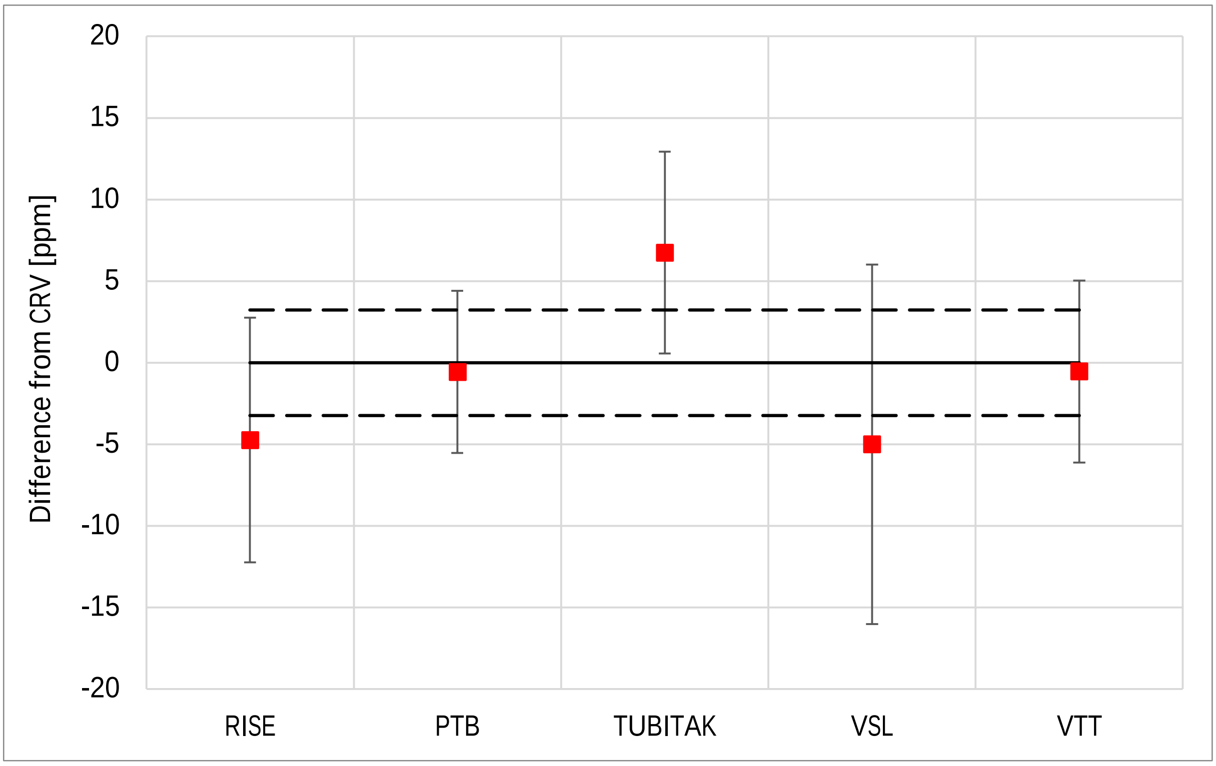
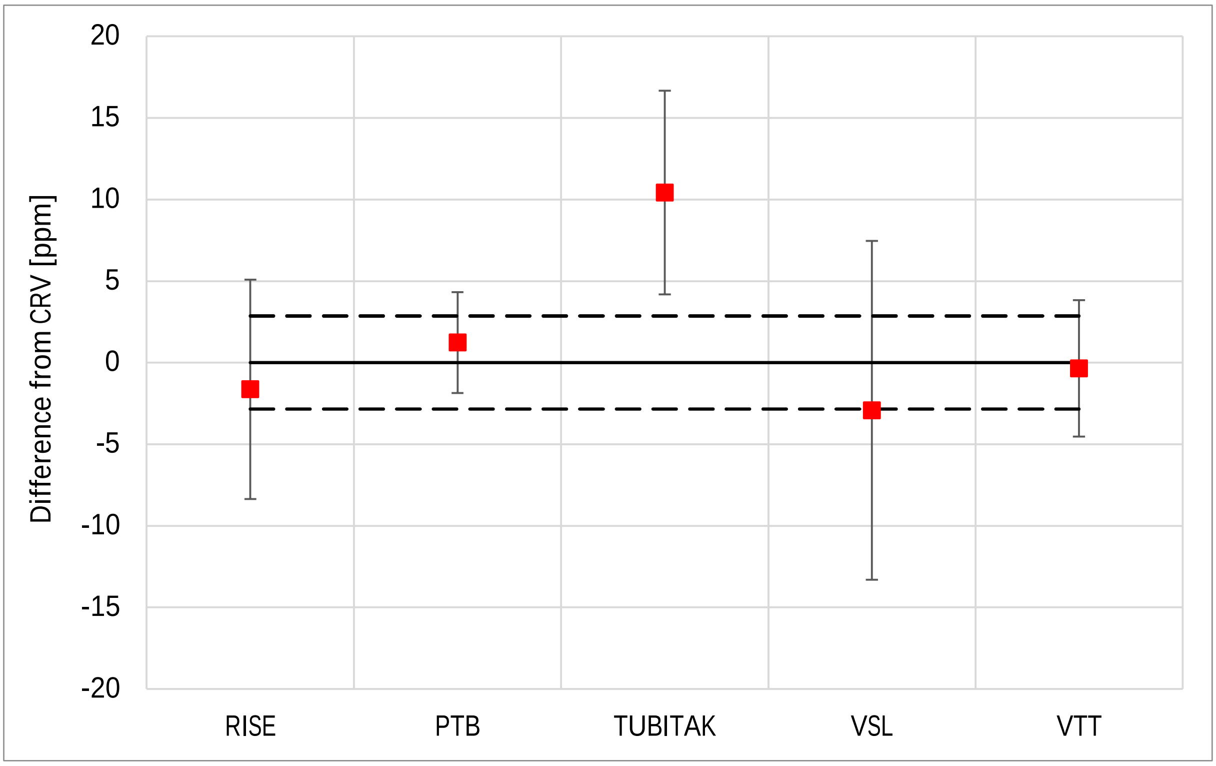


Table 9 Comparison results and CRV, 200 kV

200 kV	RISE	PTB	TUBITAK	VSL	VTT
e_i [ppm]	5.7	8.6	17.8	4.4	7.0
$U(e_i)$ [ppm]	7.3	4.2	5.5	10.8	5.1
$e_i - y$ [ppm]	-1.6	1.2	10.4	-2.9	-0.4
$U(\Delta e_i)$ [ppm]	6.7	3.1	6.2	10.4	4.2
$\lvert E_n \rvert$	0.2	0.4	1.7	0.3	0.08
Exclude			1		

CRV [ppm]	7.4
U(CRV) [ppm]	2.9
Pr	84 %



6.3 Calculation of CRVs

Analysis of comparison results is performed following the guidelines presented in [1].

The comparison reference value, CRV, is calculated separately for each voltage level. The CRV is considered as an estimation of the measurand according to the measurements provided by the participating laboratories.

This estimation, *y*, is determined as a weighted mean of the provided results where the weights are the inverse values of the squares of the associated standard uncertainties. However, that cannot be applied in case where some of the measurements are not consistent with the others.

The procedure is implemented in four steps:

1) Determination of the comparison reference value CRV (*y*), using the inverse values of the squares of the uncertainties as the weights:

$$y = \frac{\sum_{i=1}^{N} x_i\, u^{-2}(e_i)}{\sum_{i=1}^{N} u^{-2}(e_i)} \; .$$

2) Calculation of standard uncertainty of CRV, *u(y)*:

$$u(y) \;=\; \frac{1}{\sqrt{\sum_{i=1}^{N} u^{-2}(e_i)}} \, .$$

3) Consistency of results

   A χ^2 test is applied to carry out an overall consistency check of the results obtained (i.e., if all results can be regarded as belonging to the same statistical ensemble). For each measured parameter, the observed chi-squared value χ^2_{obs} is determined as:

$$\chi^2_{\text{obs}} = \sum_{i=1}^{N} \frac{(e_i - y)^2}{u^2(e_i)} \; .$$

   The number of degrees of freedom is $\nu = N - 1$, for *N* results.

   The consistency check is considered failed if

$$\Pr\{\ \chi^2(\nu) > \chi^2_{obs}\ \} < 5\ \%,$$

   where Pr denotes “probability of”.

   If the χ^2 test fails, then the laboratory with the largest $|d_i|$ value (see below for definition) is excluded from the determination of the CRV and the consistency check repeated. The process is then repeated as needed.

4) Exclusion of incompatible results

   Compatibility index, d_i, is defined as the ratio between the difference from the reference value and the standard uncertainty:

$$d_i = \frac{\Delta e_i}{u(\Delta e_i)} = \frac{e_i - y}{\sqrt{u^2(e_i) - u^2(y)}} \; .$$

The compatibility index $|d_i|$ describes the deviation from the CRV in relation to the calculated standard uncertainty of the deviation.

The standard uncertainties of the differences corresponding to those laboratories whose results have not been considered in the reference value calculation are obtained applying the following expression:

$$u^2\left(\Delta e_i\right)=u^2(e_i)+u^2(y),$$

since now the values are not correlated.

5) Compatibility of each laboratory with the estimate of CRV

In each case, the degree of equivalence (DoE) of laboratory *i* with the CRV is determined as the pair of values for the deviation from the CRV and the uncertainty of this deviation [Δe_i, $U(\Delta e_i)$] according to the expressions:

$$E_n=\frac{\Delta e_i}{U\left(\Delta e_i\right)},$$

$$\Delta e_\mathrm{i}=e_i-y \quad \text{and} \quad U\left(\Delta e_i\right)=2\cdot u\left(\Delta e_i\right),$$

where $u(\Delta e_i)$ is obtained applying the following expression:

$$u^2\left(\Delta e_i\right)=u^2(e_i)-u^2(y).$$

Note 1: The factor 2 in expression (1) above indicates a coverage factor of 95 % corresponding to a Gaussian distribution function.

Note 2: Expression (2) establishes a difference of two variances as consequence of the mutual dependence (or correlation) between x_i and *CRV*.

7. Conclusions

Different methods were used for the 20000:1 high DC voltage ratio (scale factor) calibration up to 200 kV by the participating laboratories. The traceability was based either on calibration of divider resistance values at 1 kV, or on voltage-ratio based devices used at 1 kV, 10 kV or 50 kV. Voltage-ratio based devices were traceable either to a Josephson voltage standard or to a self-calibrating ratio standard. After removal of one outlier, the expanded uncertainty (k=2) of the reference value at 1 kV was $1.7\cdot10^{-6}$, increasing up to $3.2\cdot10^{-6}$ on higher voltages. Comparison on voltages above 1 kV was based on the low voltage calibration, and on the previously determined voltage coefficient of the divider design.

8. References

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[3] E. Houtzager, G. Rietveld, J. Hällström, A. -P. Elg and J. H. N. van der Beek, "Selection and characterization of resistors for a HVDC reference divider," *2012 Conference on Precision electromagnetic Measurements*, Washington, DC, USA, 2012, pp. 197-198, doi: 10.1109/CPEM.2012.6250869.

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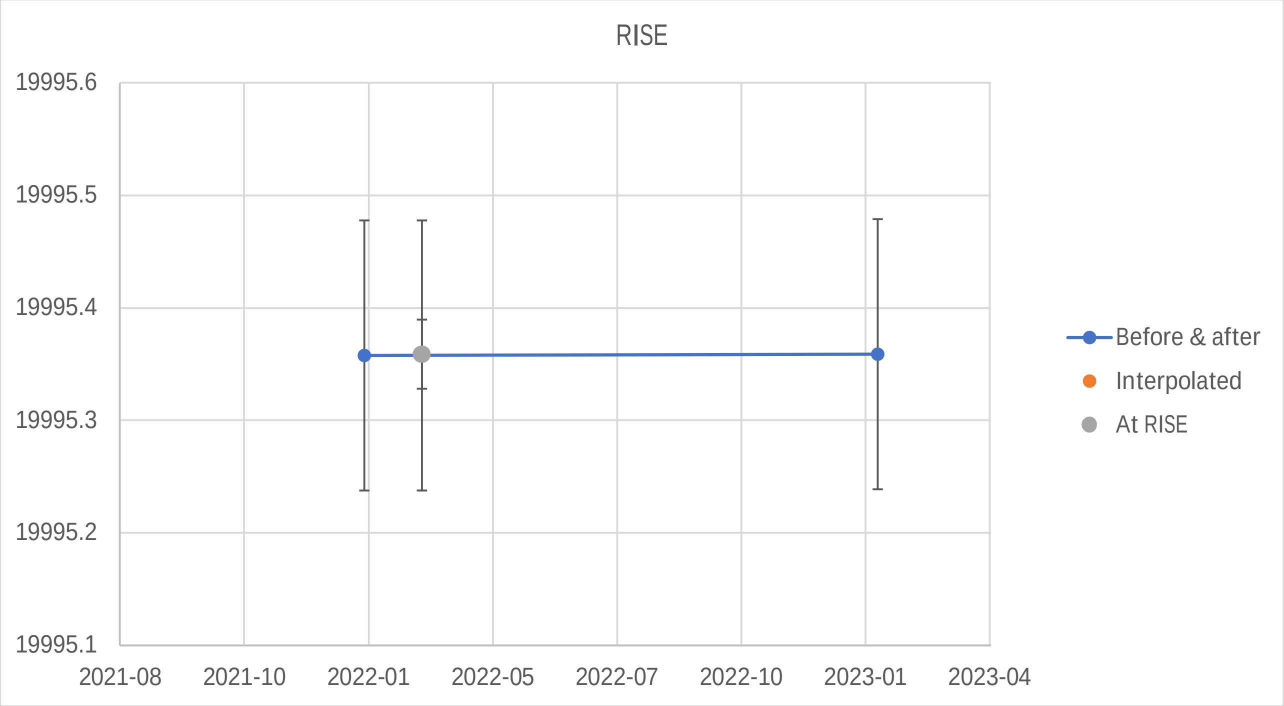
Annex A Comparison with RISE scale factor calibration

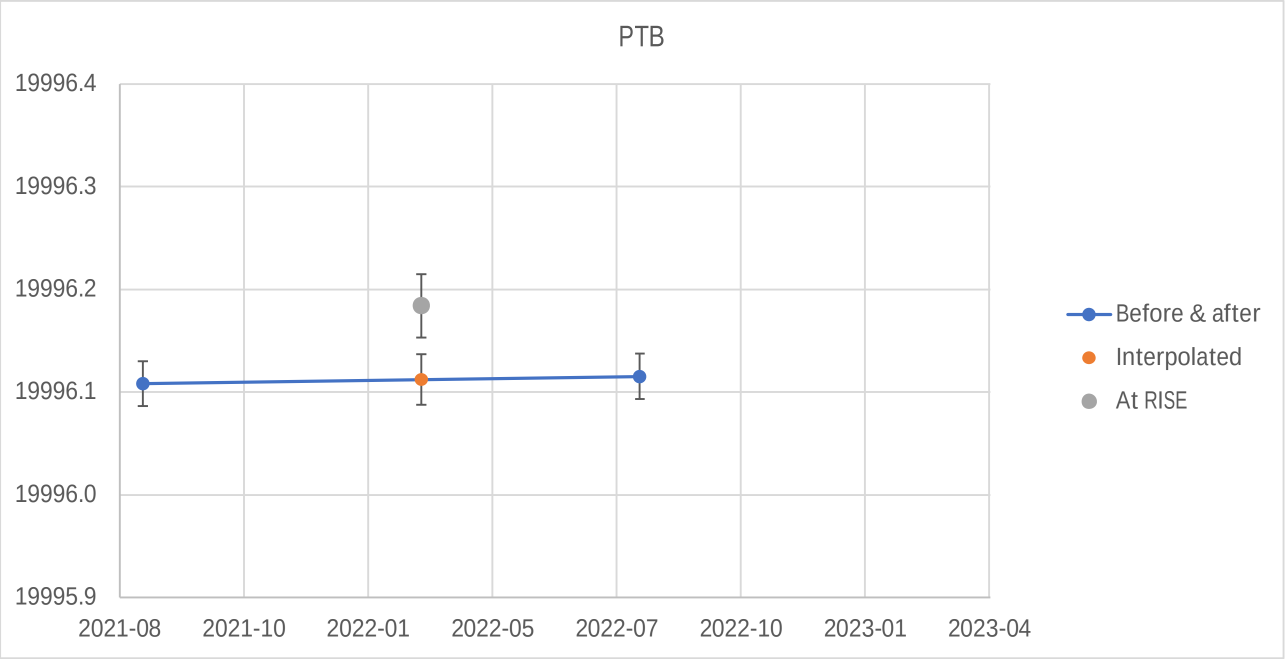
Table A-1 shows the summary scale factor calibrations by the participants and RISE. Each lab used their own method for their before and after values see Table 2). RISE calibrations are based on the measurement of the high and low voltage arm resistances in RISE resistance calibration laboratory during the comparison.

Table A-1 Comparison between scale factor calibrations by the participants and RISE.

Participants' calibrations	Lab	RISE	PTB	TUBITAK	VSL	VTT
Interpolated	SF	19995.36	19996.11	19994.66	19999.36	20000.75
for 2022-03-10	Unc. (SF) [µV/V]	6.0	1.2	3.7	10.0	3.0
RISE calibration, @ 1 kV, 22.4 °C						
Resistance	Certificate	I10369-K08	P105803-K01	P105803-K02	P105803-K03	P105803-K04
calibration	Date	2022-01-25	2022-02-12	2022-02-17	2022-02-24	2022-02-23
at RISE on	Rhv [GΩ]	2.039423	2.039464	2.039368	2.039829	2.039955
2022-02	Rlv [kΩ]	101.99992	101.99776	101.99937	101.99968	101.99868
	SF	19995.36	19996.18	19994.93	19999.39	20000.82
	Unc. (SF) [µV/V]]	1.54	1.54	1.54	1.54	1.54
Difference from RISE value						
Diff. from RISE	e [µV/V]	-0.1	-3.6	-13.2	-1.3	-3.4
Uncertainty	Unc. (e) [µV/V]	6.2	2.0	4.0	10.1	3.4

The graphs below show the before and after measurements by the participants (blue dots), the value interpolated for 2022-03 (orange dot) and the value measured at RISE in January/February 2022 (grey dot). One division on vertical scale corresponds to about 5 µV/V.




PTB
19996.4
19996.3
19996.2
19996.1
19996.0
19995.9
2021-08
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2022-01
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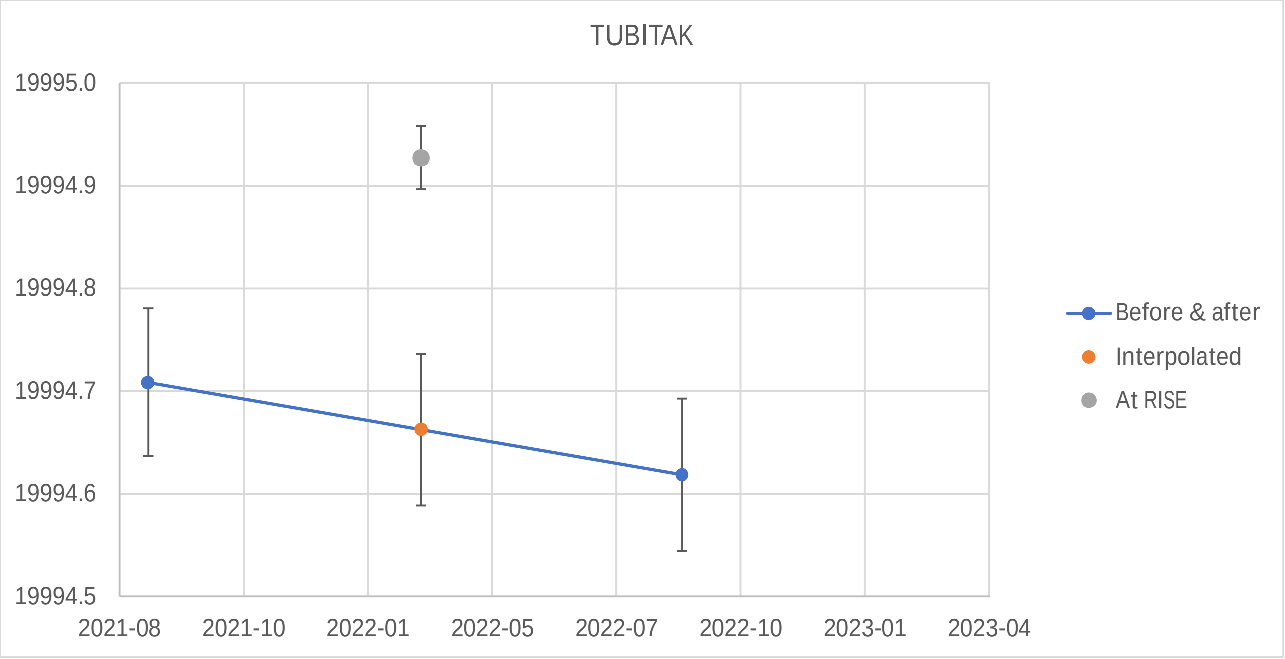
2022-07
2022-10
2023-01
2023-04
Before & after
Interpolated
At RISE


TUBITAK
19995.0
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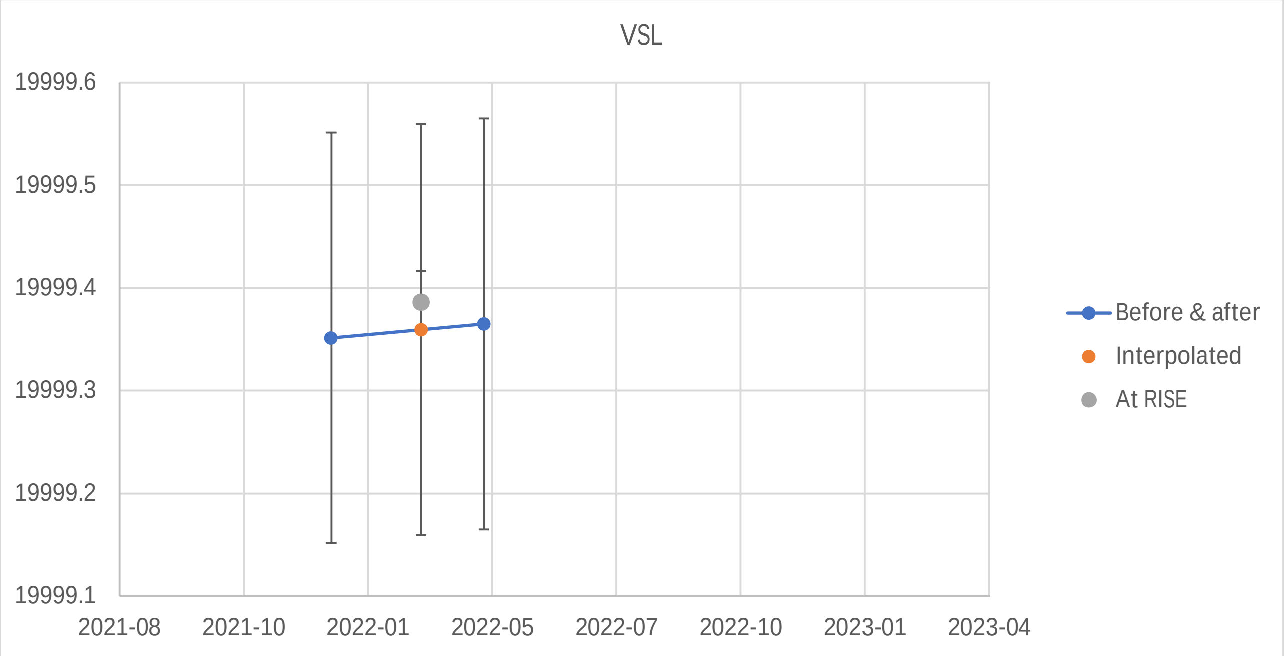
2022-10
2023-01
2023-04
Before & after
Interpolated
At RISE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19999.2
19999.1
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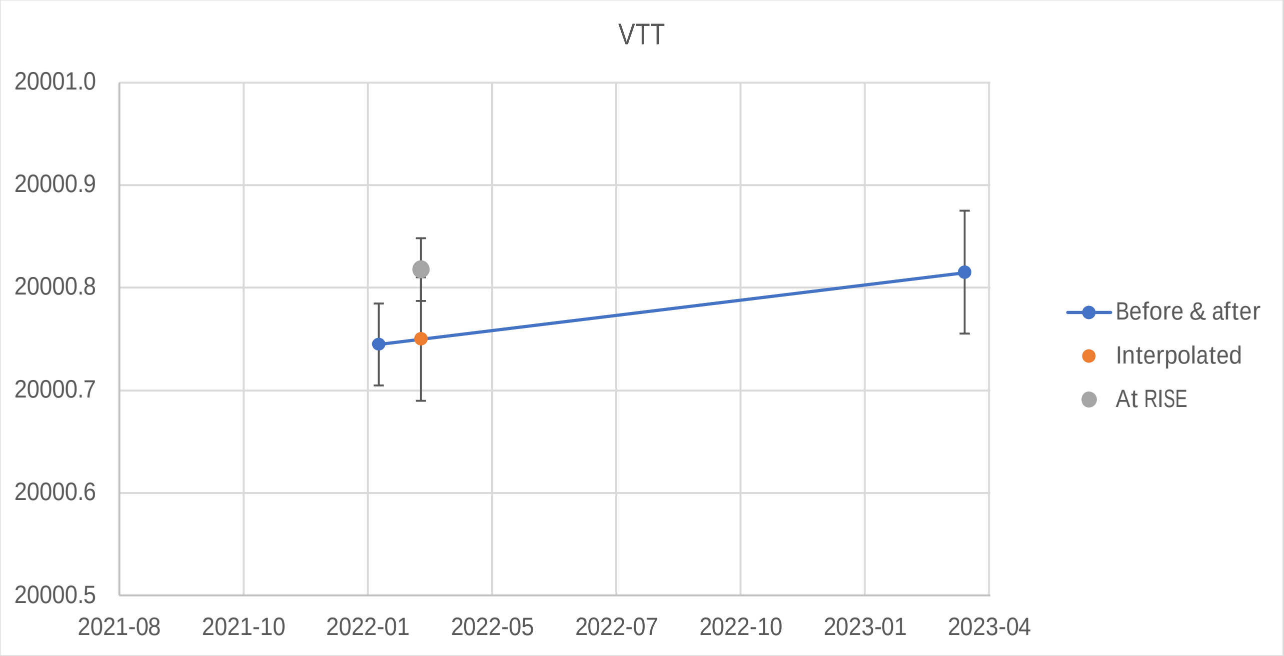
2023-04
Before & after
Interpolated
At RISE


VTT
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2022-05
2022-07
2022-10
2023-01
2023-04
Before & after
Interpolated
At RISE

Annex B Description of calibration method and traceability

B.1 RISE

The traceability is established at RISE for all quantities; the voltage by the Josephson reference; the realization of time with atomic clocks; and the resistance by quantum Hall (now using graphene).

Two methods are available for stablishing traceability of the DC ratio. A direct determination of the scale factor applying a voltage, is the method with lowest measurement uncertainty for dividers up to 200 kV. For the scale factor determination of larges voltage divider configurations, up to 1200 kV, the high voltage arm and low voltage arm resistances are calibrated, and the DC ratio is calculated. The measurement uncertainties from both methods are compared for the 200 kV reference divider in this intercomparison.

The first method for traceability of DC ratio is established by a direct measurement of the scale factor applying a voltage of 1 kV from a calibrator Datron 4000A and measuring the output of the low voltage arm with a DMM Datron 1281. The uncertainty budget is presented in the Table B.1-1.

Table B.1-1: Uncertainty budget for the scale factor determination of a 200 kV HVDC divider (k=2)

Inputs	**Uncertainty**		**Type**	**Distr.**	**Multi-plier**	**Standard Uncertainty**	
	Value	**Unit**				**Value**	**Unit**
Calibration of calibrator (Datron 4000A, 1 kV)	3.0	µV/V	B	Normal	0.50	1.5	µV/V
Uncertainty of DMM reading (Datron 1281)	4.0	µV/V	B	Normal	0.50	2.0	µV/V
Uncertainty of method (102 kΩ/ >40 GΩ)	3.0	µV/V	B	Normal	0.50	1.5	µV/V
Statistical spread	0.54	µV/V	A	Normal	0.50	0.27	µV/V
			Combined std uncertainty (k=1)			2.93	µV/V
			Expanded uncertainty (k=2)			5.9	µV/V
			Claimed exp. unc. (k=2, 95%)			**6**	µV/V

Measurement standards used for the DC ratio calibration.

1. Multimeter Datron 1281, nr 21159-6, inv.nr 501224
2. Calibrator Datron 4000A, nr 12742, inv.nr 602858

The second method for DC ratio for the 200 kV divider traceability is established by calibration of the resistance of the HV module HVDC 1.1 and the LV arm #6 in the primary lab for DC-LF metrology. The resistance calibration is performed in the primary lab using a guarded Wheatstone bridge as depicted in Figure B.1-1.

Calibrating the high ohmic resistance of the HVDC modules, having a resistance of 2.04 GΩ a reference resistor 10 MΩ Mashpriborintorg P4020 is used. The calibrator Vx (Datron 4708) is kept at 1000 V and the other Vs (Wavetek 4808) is adjusted to get a zero reading of the electrometer.

The scale factor, i.e. DC ratio, is calculated with different HV and LV arm configurations. with the expanded measurement uncertainty of the HV arm resistance expanded measurement uncertainty of 8.3 µΩ/Ω (Table B.1-2), with the LV arm resistance expanded measurement uncertainty of 0.2 µΩ/Ω (table B.1.3), gives a total rounded expanded measurement uncertainty of 9 µΩ/Ω.

Comparing these two methods, i.e. the first method using a DC ratio direct calibration and the second method DC ratio calculation of HVDC 1.1 with the LV arm #6 used in this study, we have a difference of -0.3 µV/V between methods. The direct measurement method with the expanded uncertainty of < 6 µV/V is used in this comparison.

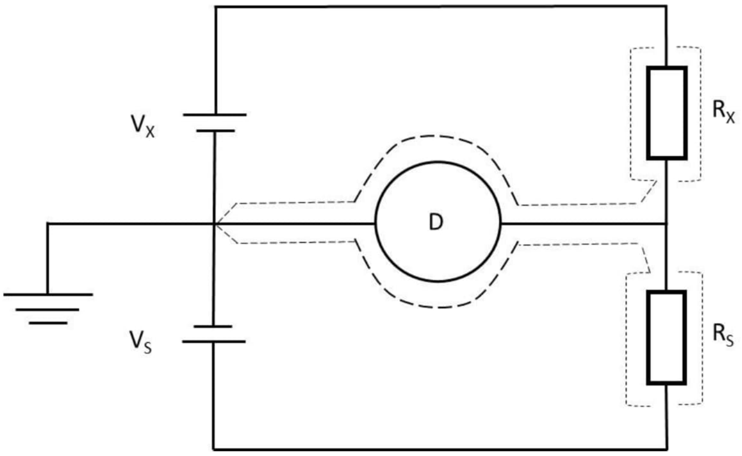


Figure B.1.1 Wheatstone bridge with two calibrators as sources for Vs and Vx, a reference resistor Rs the unknown resistance Rx, and an electrometer D.

The value of the unknown resistance is obtained from:

$$R_x = R_s \cdot r \cdot (1+\delta r)\cdot(1+\delta_{res})\cdot(1+\delta_{bal})\cdot(1+\delta R_{xbal}),$$

where:

R_x - value of the unknown resistor
R_s - value of the reference resistor
r - measured voltage ratio
δr - correction for error in voltage ratio due to calibration and stability of voltage ratio
δ_{res} - correction for error due to detector resolution
δ_{bal} - correction for error in bridge balance due to leakage and uncompensated offset effects in detector
δR_{xbal} - correction for error due to voltage change over unknown resistor during the bridge balancing process caused by potential voltage dependence of unknown resistor

Based on the model equation above, the relative standard uncertainty for the measured resistor $u(R_x)/R_x$ can be determined as:

$$\left(\frac{u(R_x)}{R_x}\right)^2 = \left(\frac{u(R_s)}{R_s}\right)^2 + \left(\frac{u(r)}{r}\right)^2 + u^2(\delta r) + u^2(\delta_{res}) + u^2(\delta_{bal}) + u^2(\delta R_{xbal})$$

where:

$u(R_s)$ - uncertainty in reference resistor value due to step up procedure from QHR, stability, temperature and voltage dependence
$u(r)$ - mean value standard deviation of measured voltage ratio
$u(\delta r)$ - voltage ratio uncertainty due to calibration and stability of voltage ratio
$u(\delta_{res})$ - uncertainty due to detector resolution

$u(\delta_{bal})$ - bridge balance uncertainty due to leakage and uncompensated offset effects of detector

$u(\delta R_{xbal})$ - uncertainty due to voltage change over unknown resistor during bridge balancing process, caused by potential voltage dependence of unknown resistor

Table B.1.2: Uncertainty budget for the resistance determination of a 200 kV HVDC divider HV arm (k=2)

Quantity X_i	Estimation x_i	Relative standard Uncertainty (10^{-6}) $u(x_\mathrm{i})$	Probability distribution / evaluation (A, B)	Sensitivity factor c_i	Relative uncertainty contribution, (10^{-6}) $u(R_\mathrm{i})$	Number of degrees of freedom ν_i
R_s	10 MΩ	1.7	rectangular / B	1	1.7	∞
r	200	0.1	normal / A	1	0.1	9
δr	0	2.9	rectangular / B	1	2.9	∞
δ_{res}	0	0.0	rectangular / B	1	0.0	∞
δ_{bal}	0	2.3	rectangular / B	1	2.3	∞
δR_{xbal}	0	0.0	rectangular / B	1	0.0	∞
Statistical spread	0	0.1	normal / A	1	0.1	9
R_x	2 GΩ					
		Combined standard uncertainty:			4.1 μΩ/Ω	
		Effective number of degrees of freedom:			2644	
		Expanded measurement uncertainty (95% coverage factor):			8.2 μΩ/Ω	

Table B.1.3: Uncertainty budget for the resistance determination of a 200 kV HVDC divider LV arm (k=2)

Quantity X_i	Estimation x_i	Relative standard uncertainty (10^{-6}) $u(x_\mathrm{i})$	Probability distribution / evaluation (A, B)	Sensitivity factor c_i	Relative uncertainty contribution, (10^{-6}) $u(R_\mathrm{i})$	Number of degrees of freedom ν_i
R_s	10 kΩ	0.031	rectangular / B	1	0.031	∞
r	10	0.017	normal / A	1	0.017	2
δ_{bal}	0	0.050	rectangular / B	1	0.050	∞
Zener	10 V	0.050	rectangular / B	1	0.050	∞
Statistical spread	0	0.070	normal / A	1	0.070	2
R_x	100 kΩ					
		Combined standard uncertainty:			0.105 μΩ/Ω	
		Effective number of degrees of freedom:			51	
		Expanded measurement uncertainty (95% coverage factor):			0.21 μΩ/Ω	

Measurement standards used for the resistance calibration.

1. LV arm calibration: Standard resistor 10 kΩ ESI SR104, s/n 308019, inv. no. 501166
2. Resistance bridge MI 6000A, s/n 950102, inv. no. 602670
3. Digital multimeter HP 3458A, s/n US28032452, inv. no. 602856
4. DC Reference Standard Fluke 732A, s/n 4385008, inv. no. 603229
5. Digital thermometer Fluke 1529-R, s/n A87800, inv.no 901607
6. Electrometer Keithley 617, s/n 526942, inv.no 501376
7. Calibrator Datron 4708, s/n 20463-2, inv.no 501237
8. Calibrator Wavetek 4808, s/n 29567, inv.no 603217
9. Standard resistor 10 MΩ Mashpriborintorg P4020, s/n 1152, inv.no 501188
10. Software MI 6000B Software, version 6.7.0
11. Software MULTIKAL R, version 1.7.1

B.2 PTB

Calibration method

The calibration of the divider was done according to the internal procedure „A2.3-AA-3201HVDC” of the PTB.

Input voltage of the divider under calibration was measured with a reference voltage divider MT100 and a digital voltmeter HP 3458A. Output voltage of the divider under calibration HVDC2.1 was measured with an other digital voltmeter HP 3458A. Scale factor of the divider under calibration was calculated as the ratio of input and output voltages.

Measurements were performed up to 100 kV. Both voltmeters were used in fixed 10 V voltage range.

Calibration of the reference MT100

To enable traceability for the DC voltage divider, the step-up method is used to get from the very precise but low voltage of the Josephson-Standard into the range of 100 kV. The equipment required for this including the measurement uncertainties are shown in Table B.2-1.

A reference voltage source (Fluke 732A) is calibrated in PTBs Working Group 2.63 on the Josephson primary standard with an uncertainty of $1\cdot10^{-10}$ and thus forms the basic building block of the traceability. It supplies the voltages 1 V, 1.013 V and 10 V. At this source, the DC voltage gain of the digital voltmeters are determined in the required measuring ranges. This check must be repeated after all essential steps in order to exclude possible changes.

Table B.2-1. Required devices and specifications

Device	*Device Name*	*Uncertainty k = 2*
Voltage source	Fluke 5440A	$4\cdot10^{-6}$
Calibrator	Fluke 5700A	$5\cdot10^{-6}$
Reference divider	Fluke 752A	$0{,}5\cdot10^{-6}$
DVM	HP 3458A	$0{,}6\cdot10^{-6}$
Divider under test	MT100 (M=100)	$2\cdot10^{-6}$
Zero voltmeter	Fluke 8508A	$0{,}5\cdot10^{-6}$

Using a Fluke 8508A digital voltmeter and the Fluke 5700A calibrator, the 100:1 scale factor of the Fluke 752A reference voltage divider is calibrated. This is done by adjusting all measurement ranges and checking the polarity independence of the scale factor of 100:1 with an uncertainty of $0.2\cdot10^{-6}$.

Figure B.2-1 shows the procedure for voltages up to 1000 V. With the now known scale factor M_A of 100:1, the exact voltage of a stable 1000 V voltage source (source V_x) can be determined with an uncertainty of $0.5\cdot10^{-6}$. At the same time, this voltage is applied to the test divider (MT100 – 100:1) whose scale factor M_B is to be determined. In our case, this is the 100:1 scale factor of the MT100. In order to enable a bridge measurement of the output voltage of the MT100, a manually adjustable reference voltage V_S is generated using a precision calibrator and superimposed on the output voltage of the MT100. This is measured with a zero voltmeter as shown in the following Figure.

The reference voltage Vs is then measured with the same digital voltmeter. The quotient of the input voltage (measured using the Fluke 752A) and the reference voltage measured back then represents the scale factor of the MT100 in the 100:1 measuring range.

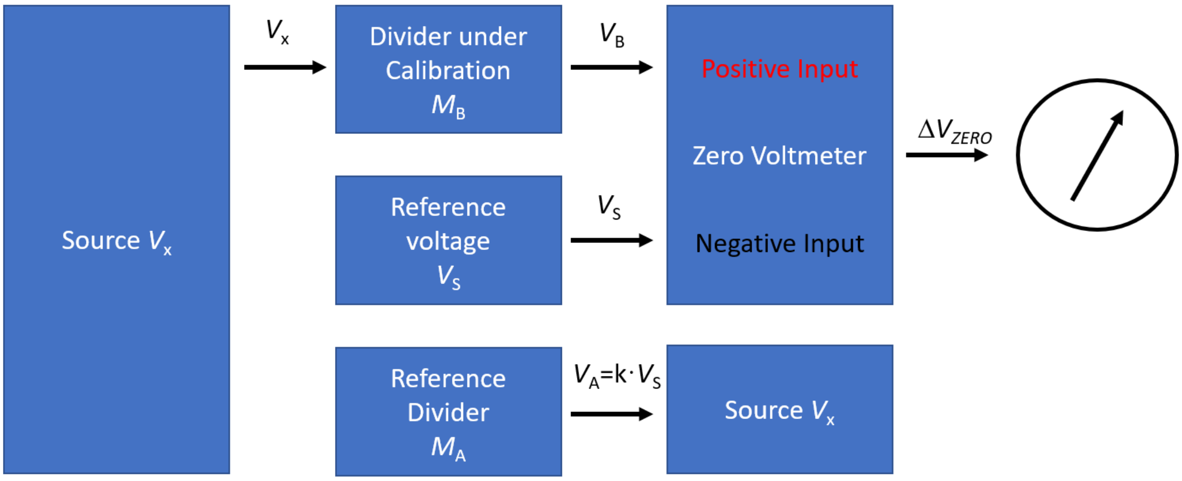


Figure B.2-1. Measurement setup for traceability up to 1000 V at PTB

Once the 100:1 scale factor has been verified in several measurements, calibration can be performed at higher voltages. In addition to the 100:1, the MT100 also has a 10000:1 scale factor. To calibrate this scale factor an additional divider (HVDC 2.1) and a high voltage source are required. The special requirement for the additional high-voltage divider and the source is the high stability of the scale factor and the high voltage generated. For this reason, the high voltage of 50 kV is applied to the high-voltage divider several hours before the actual calibration. In this way, the run-in behavior of the dividers and the high-voltage source are excluded from the measurement.

The Fluke 752A reference voltage divider with a scale factor of 100:1 is also connected to the output of the MT100 with the 100:1 scale factor in order to obtain the voltage range of 5 V. Once the high voltage has stabilized, the scale factor of the additional high voltage divider HVDC 2.1 is calibrated in the heated state using the two 100:1 dividers connected in series. The HVDC 2.1 is now used as the standard for calibrating the MT100's 10000:1 scale factor. For this purpose, the low voltage part of the MT100 is switched when a voltage of 50 kV is applied. This has the advantage that the behavior of the additional voltage divider does not change in this short time and with a constant voltage. The output voltage of the MT100 is now 5 V in the 10000:1 range.

Both before and after the measurement, all zero point voltages of the measuring dividers must be checked with the connected voltmeters. To do this, the dividers are short-circuited at the input. The output voltages are measured and averaged over a longer period of time. This step is necessary because, despite specially adapted copper-tellurium contact materials, thermal stresses can lead to a DC offset.

After repeating this process several times and taking into account the deviation of the individual runs, the traceability of the MT100 is completed in all measuring ranges. The standard deviation of the determined scale factors can be used to check the measurement results. The comparison of the scale factors determined for positive and negative polarity allows the offset corrections to be checked. The MT100 validated in this way with its measuring ranges can now be used as a primary standard and all other measuring dividers can be calibrated against it.

Before the other dividers can be calibrated, the offset voltages and the gains of the digital voltmeters must also be determined for them. Then both the primary standard and the divider to be calibrated can be connected to a common high-voltage source. The maximum voltage here is 100 kV due to the MT100. The voltage is now increased in defined steps and the output voltage is read out simultaneously on both dividers using the digital voltmeters. Depending on the area of application, the duration of the measurement must be selected in such a way that the temperature-related drift of the scale factor either tends towards a stationary final value or has as little influence as possible. In order to ensure that the MT100 itself has the least possible influence on the measurement, its voltage dependance and stability behavior was examined.

Measurement uncertainty

While calculating the uncertainties of the calibrations, the following contributions were considered:

- standard deviation of the readings;
- stability of the digital voltmeters;
- uncertainty of the reference voltage divider.

Measurement uncertainty is estimated and stated according to GUM (Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100:2008) using the coverage factor $k = 2$, which for a normal distribution corresponds to a probability of approximately 95 %.

B.3 TUBITAK

Calibration method

The high-voltage DC divider was calibrated at 1 kV direct voltage and the scale factor was determined according to internal procedure ”Instruction for the determination of the scale factor on HVDC divider” (TLM-05-G1YG-04-23).

The 1 kV was applied by Fluke 5500A calibrator directly and the input voltage at the top of HVDC divider was measured by Agilent 3458A precision multimeter. The divided voltage called output voltage of the HVDC divider under calibration was measured with another 8,5 digital multimeter synchronically. Scale factor of the divider under calibration was calculated as the ratio of input and output voltages (Figure B.3-1). Devices used in the calibration are given Table B.3-1.

Figure B.3-1. The calibration setup of TUBITAK UME

Table B.3-1. Reference(s) Used in Calibration

No	Device	Manufacturer	Type / Model	Serial No	Traceability
1.	Multimeter	Agilent	3458A	MY45040360	TUBITAK UME, G1YG-0195, 24.08.2022
2.	Multimeter	Agilent	3458A	MY45048927	TUBITAK UME, 24.08.2022
3.	Temperature, Humidity and Pressure Meter	PCE Instruments	PCE-FWS 20	SNB001	TUBITAK UME, G1BA-0107, 09.11.2021 G1NM-0125, 29.12.2021

Measurement uncertainty

The measurement uncertainty is calculated in accordance with the methods described in "Guide to the Expression of Uncertainty in Measurement" (GUM), "IEC 60060-2: High-voltage test techniques Part-2: Measuring systems" and EA-4/02 documents.

The model equation for calculating the value of F_X (the scale factor of reference divider) and its combined standard uncertainty can be developed as follows. In the ideal case, both measuring systems indicate the same value of the DC test voltage V:

$$V_{IN} = F_X \cdot V_{OUT}$$

This leads to the basic equation for calculating the scale factor of reference divider:

$$F_X = \frac{V_{IN}}{V_{OUT}}$$

where F_X is the scale factor of reference divider at low voltage, V_{IN} and V_{OUT} are the input voltage to the divider and low voltage value on the terminal of low voltage part of reference system, respectively.

For the relevant case, the scale factor F_X of the reference divider can be expressed by:

$$F_X = \frac{V_{IN} + \sum \delta V_{IN,j}}{V_{OUT} + \sum \delta V_{OUT,n}}$$

and

$$F_X = \frac{V_{IN} + \delta V_{IN,1} + \delta V_{IN,2}}{V_{OUT} + \delta V_{OUT,1} + \delta V_{OUT,2}}$$

where

F_X	is the scale factor value of reference divider at 1 kV of low voltage,
V_{IN}	is the input voltage applied to the reference divider from calibrator. This voltage is measured by high-resolution multimeter,
V_{OUT}	is the output measured voltage on the terminals of low voltage part of reference divider. This voltage is measured by high-resolution multimeter,
$\delta V_{IN,1}$	is the correction caused by drift of input voltage measuring device connected to the calibrator,
$\delta V_{IN,2}$	is the correction caused by the resolution of input voltage measuring device connected to the calibrator,
$\delta V_{OUT,1}$	is the correction caused by drift of low voltage measuring device connected to the low voltage part of divider,
$\delta V_{OUT,2}$	is the correction caused by the resolution of low voltage measuring device connected to the low voltage part of divider.

Uncertainty Components

u_{VIN}	is uncertainty component of measuring instrument (multimeter/voltmeter) used in measuring of input voltage connected to the reference divider. Device is calibrated at TUBITAK UME (k=2, 95% confidence level). Its probability distribution is normal.
$u_{\delta VIN,1}$	is the uncertainty component caused by the correction for the drift of the multimeter connected to the input of divider since its last calibration. Its probability distribution is rectangular.
$u_{\delta VN,2}$	is uncertainty component caused by the finite resolution of multimeter connected to the input of divider. Its probability distribution is rectangular.
u_{VOUT}	is uncertainty component of multimeter used in measuring of output voltage connected to the reference divider. Device is calibrated at TUBITAK UME (k=2, 95% confidence level). Its probability distribution is normal.
$u_{\delta VOUT,1}$	is the uncertainty component caused by the correction for the drift of the multimeter connected to the output of divider since its last calibration. Its probability distribution is rectangular.
$u_{\delta VOUT,2}$	is uncertainty component caused by the finite resolution of multimeter connected to the output of divider. Its probability distribution is rectangular.
u_A	is the repeatability of measurements. Its probability distribution is normal.

Uncertainty

Uncertainty of the scale factor determined is 3,6 μV/V (k = 2, 95% confidence level). This uncertainty value does not include the long-term stability and the error of the reference.

B.4 VSL

Calibration method

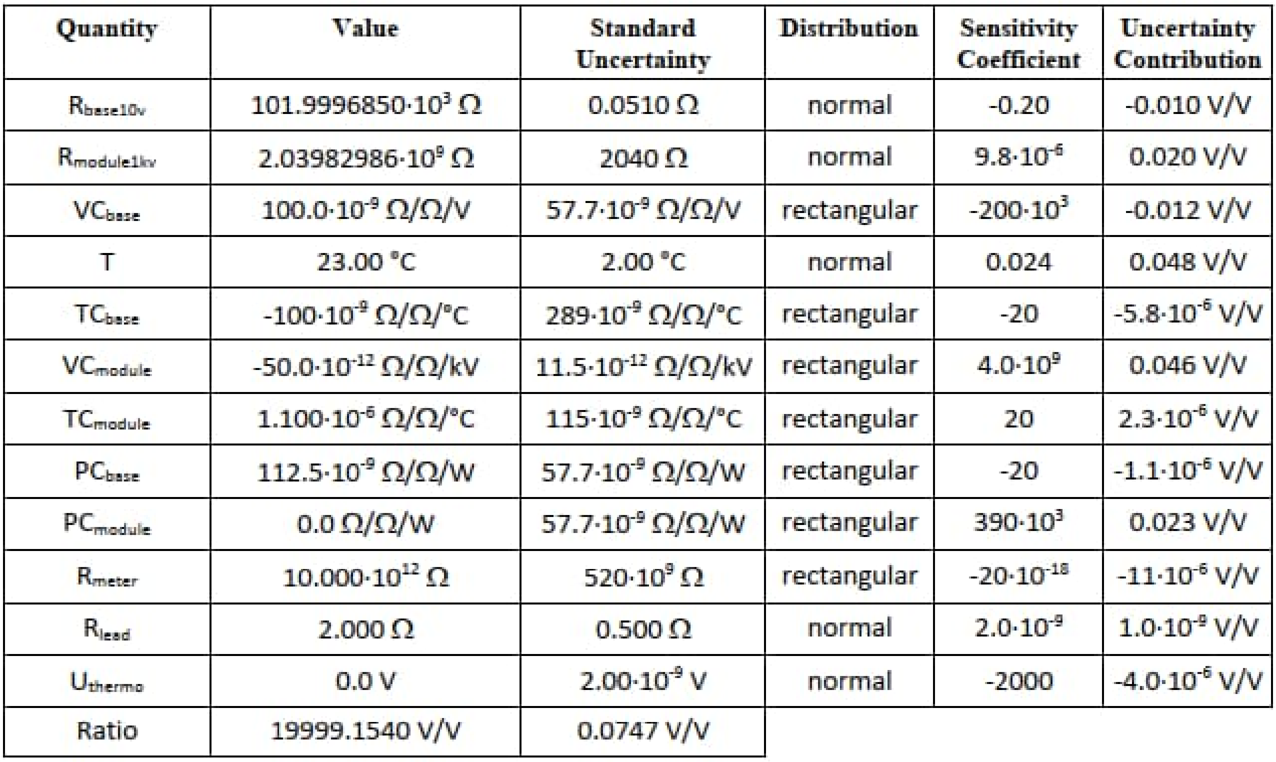
To determine the scale factor, the resistance of both arms is measured with specialized resistance bridges. Afterwards the scaling factor is corrected for the voltage, temperature, and power dependence.

The resistance of both the high-voltage arm and the low-voltage arm were determined just before and directly after transportation to RISE.

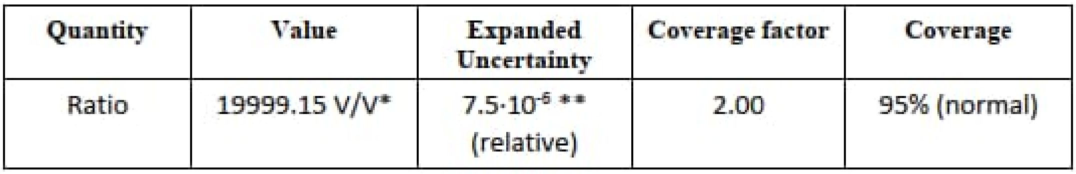
From the measured resistance value at 1 kV of the high-voltage arm and the low voltage arm. The scale factor is calculated. The scale factor is corrected for any voltage, power, and temperature dependence of the high voltage resistor.

Uncertainty calculation high-voltage ratio:

Budget for ratio at 200 kV



Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution
$R_{base10v}$	$101.9996850 \cdot 10^{3}$ Ω	0.0510 Ω	normal	-0.20	-0.010 V/V
$R_{module1kv}$	$2.03982986 \cdot 10^{9}$ Ω	2040 Ω	normal	$9.8 \cdot 10^{-6}$	0.020 V/V
VC_{base}	$100.0 \cdot 10^{-9}$ Ω/Ω/V	$57.7 \cdot 10^{-9}$ Ω/Ω/V	rectangular	$-200 \cdot 10^{3}$	-0.012 V/V
T	23.00 °C	2.00 °C	normal	0.024	0.048 V/V
TC_{base}	$-100 \cdot 10^{-9}$ Ω/Ω/°C	$289 \cdot 10^{-9}$ Ω/Ω/°C	rectangular	-20	$-5.8 \cdot 10^{-6}$ V/V
VC_{module}	$-50.0 \cdot 10^{-12}$ Ω/Ω/kV	$11.5 \cdot 10^{-12}$ Ω/Ω/kV	rectangular	$4.0 \cdot 10^{9}$	0.046 V/V
TC_{module}	$1.100 \cdot 10^{-6}$ Ω/Ω/°C	$115 \cdot 10^{-9}$ Ω/Ω/°C	rectangular	20	$2.3 \cdot 10^{-6}$ V/V
PC_{base}	$112.5 \cdot 10^{-9}$ Ω/Ω/W	$57.7 \cdot 10^{-9}$ Ω/Ω/W	rectangular	-20	$-1.1 \cdot 10^{-6}$ V/V
PC_{module}	0.0 Ω/Ω/W	$57.7 \cdot 10^{-9}$ Ω/Ω/W	rectangular	$390 \cdot 10^{3}$	0.023 V/V
R_{meter}	$10.000 \cdot 10^{12}$ Ω	$520 \cdot 10^{9}$ Ω	rectangular	$-20 \cdot 10^{-18}$	$-11 \cdot 10^{-6}$ V/V
R_{lead}	2.000 Ω	0.500 Ω	normal	$2.0 \cdot 10^{-9}$	$1.0 \cdot 10^{-9}$ V/V
U_{thermo}	0.0 V	$2.00 \cdot 10^{-9}$ V	normal	-2000	$-4.0 \cdot 10^{-6}$ V/V
Ratio	19999.1540 V/V	0.0747 V/V			

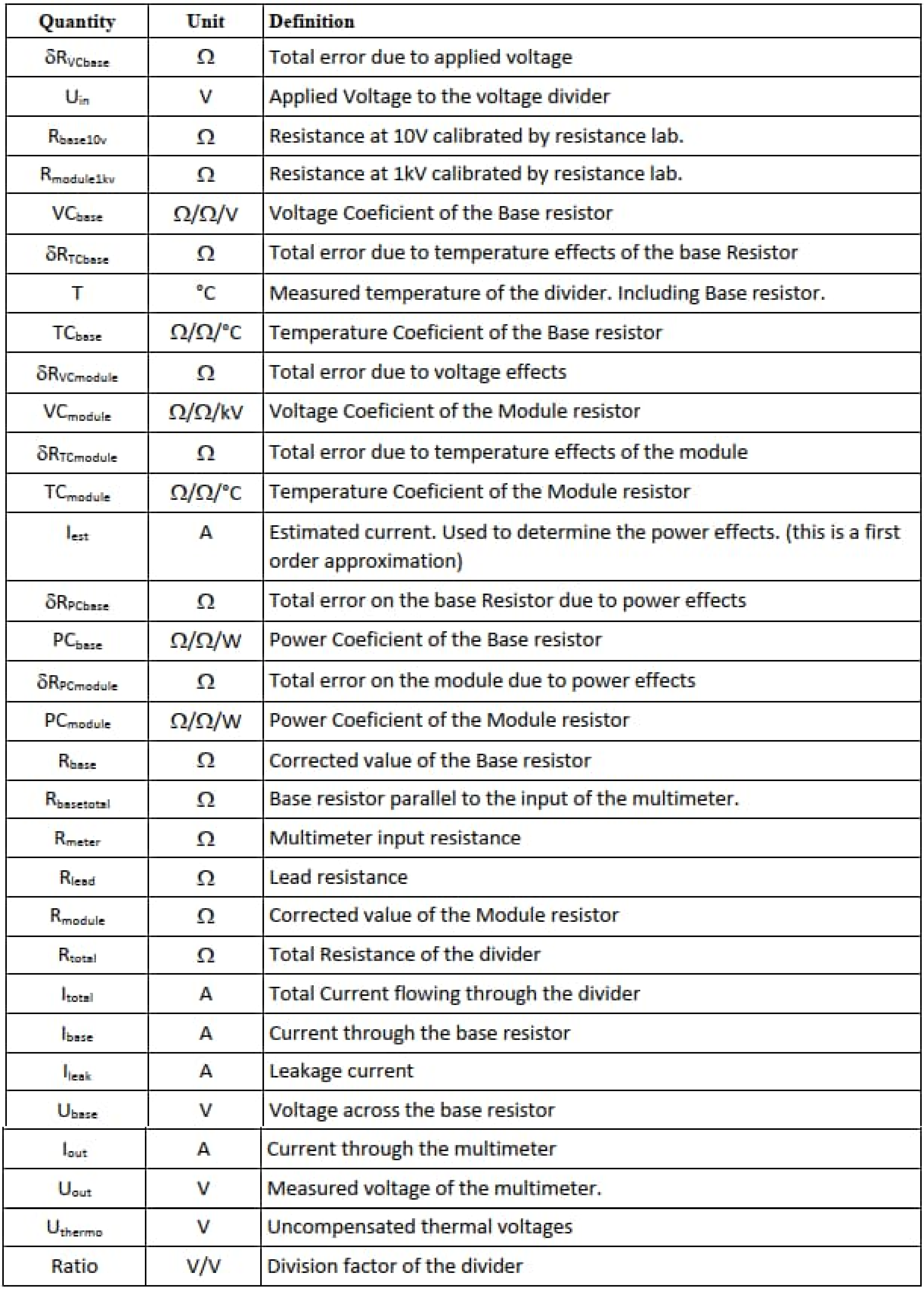


Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
Ratio	19999.15 V/V*	$7.5 \cdot 10^{-6}$ ** (relative)	2.00	95% (normal)

*) for indication only. The uncertainty budget is only used to calculate the uncertainty.

**) The traveling uncertainty of less than 1 ppm is not included in the uncertainty budget.

List of Quantities



Quantity	Unit	Definition
δR_{VCbase}	Ω	Total error due to applied voltage
U_{in}	V	Applied Voltage to the voltage divider
$R_{base10v}$	Ω	Resistance at 10V calibrated by resistance lab.
$R_{module1kv}$	Ω	Resistance at 1kV calibrated by resistance lab.
VC_{base}	Ω/Ω/V	Voltage Coeficient of the Base resistor
δR_{TCbase}	Ω	Total error due to temperature effects of the base Resistor
T	°C	Measured temperature of the divider. Including Base resistor.
TC_{base}	Ω/Ω/°C	Temperature Coeficient of the Base resistor
$\delta R_{VCmodule}$	Ω	Total error due to voltage effects
VC_{module}	Ω/Ω/kV	Voltage Coeficient of the Module resistor
$\delta R_{TCmodule}$	Ω	Total error due to temperature effects of the module
TC_{module}	Ω/Ω/°C	Temperature Coeficient of the Module resistor
I_{est}	A	Estimated current. Used to determine the power effects. (this is a first order approximation)
δR_{PCbase}	Ω	Total error on the base Resistor due to power effects
PC_{base}	Ω/Ω/W	Power Coeficient of the Base resistor
$\delta R_{PCmodule}$	Ω	Total error on the module due to power effects
PC_{module}	Ω/Ω/W	Power Coeficient of the Module resistor
R_{base}	Ω	Corrected value of the Base resistor
$R_{basetotal}$	Ω	Base resistor parallel to the input of the multimeter.
R_{meter}	Ω	Multimeter input resistance
R_{lead}	Ω	Lead resistance
R_{module}	Ω	Corrected value of the Module resistor
R_{total}	Ω	Total Resistance of the divider
I_{total}	A	Total Current flowing through the divider
I_{base}	A	Current through the base resistor
I_{leak}	A	Leakage current
U_{base}	V	Voltage across the base resistor
I_{out}	A	Current through the multimeter
U_{out}	V	Measured voltage of the multimeter.
U_{thermo}	V	Uncompensated thermal voltages
Ratio	V/V	Division factor of the divider

B.5 VTT

Calibration method

The instrument was calibrated according to the internal procedure MIK-S611 of the National Standards Laboratory.

Input voltage of the divider under calibration was measured with a reference voltage divider /1/ and a digital voltmeter /2, 3/. Output voltage of the divider under calibration was measured with a digital voltmeter /2, 3/. Scale factor of the divider under calibration was calculated as the ratio of input and output voltages.

Measurements were performed with ±10 kV voltage to remove possible offsets of the two voltmeters. Both voltmeters were used in fixed 10 V voltage range. After every measurement, the meters were swapped, and the measurement was repeated to reduce the gain errors of the voltmeters. Totally six measurement series were performed using this cycle.

The scale factor of the reference voltage divider /1/ was calibrated against self-calibrating voltage divider /4/ with ±1 kV voltage.

Measurement standards used in calibration

1. 50 kV voltage divider, HUT-50, ID: MIKES005015/MIKES008778,
   calibration certificate M-22E028;
2. Hewlett Packard 3458A digital multimeter, ID: MIKES003643,
   calibration certificate M-21E103;
3. Agilent Technologies 3458A digital multimeter, ID: MIKES003567,
   calibration certificate M-21E106.
4. Fluke 752A voltage divider, MIKES001032
   Self-calibrating voltage divider

Measurement uncertainty

While calculating the uncertainties of the calibrations, the following contributions were considered:

- standard deviation of the readings;
- stability of the digital voltmeters /2, 3/;
- uncertainty of the reference voltage divider /1/.

The long-term stability effects of the device under calibration are not included.

Measurement uncertainty is estimated and stated according to GUM (Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100:2008) using the coverage factor $k = 2$, which for a normal distribution corresponds to a probability of approximately 95 %.

Annex C Comparison protocol

Supplementary Comparison EURAMET.EM-S46 and EURAMET.EM-S47

High voltage comparison of DC ratio and high resistance

TECHNICAL PROTOCOL

version 1.0, Oct 07, 2022

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1. Introduction

Metrology area, branch	Electricity and Magnetism, High Voltage and Current
Description	High DC voltage ratio up to 200 kV
Time of measurement	2022-03-07 – 2022-03-25
Measurand(s)	DC voltage ratio DC resistance
Parameter(s)	Nominal ratio: 20000 Nominal resistance: 2 GΩ Voltage: up to 200 kV
Transfer device(s)	Star comparison, all references in one lab at the same time.
Comparison type	Supplementary comparison
Consultative Committee	CCEM (Consultative Committee for Electricity and Magnetism)
Related regional metrology organizations	EURAMET

The 200 kV reference dividers were built in 2014 for RISE, VTT, PTB, VSL and TUBITAK as part of EMRP project HVDC. These dividers will be transported to RISE in February/March 2022 to compare their ratios and high voltage arm resistances.

2. Standards

The standards to be compared are identical 200 kV divider modules shown in Figure 1.

Figure 3 The five high voltage dividers to be compared (coloured).

The outer diameter of a module is 480 mm, it is 1500 mm high, and it weighs about 150 kg. The internal structure of the module is shown in Figure 2. The components are enclosed in an SF6 filled fiberglass tube. The top endplate houses a gas valve, pressure gauge and a feed-through for the reference divider signal. The bottom plate has a mating feed-through, so that the modules can be directly stacked and mounted on top of each other.

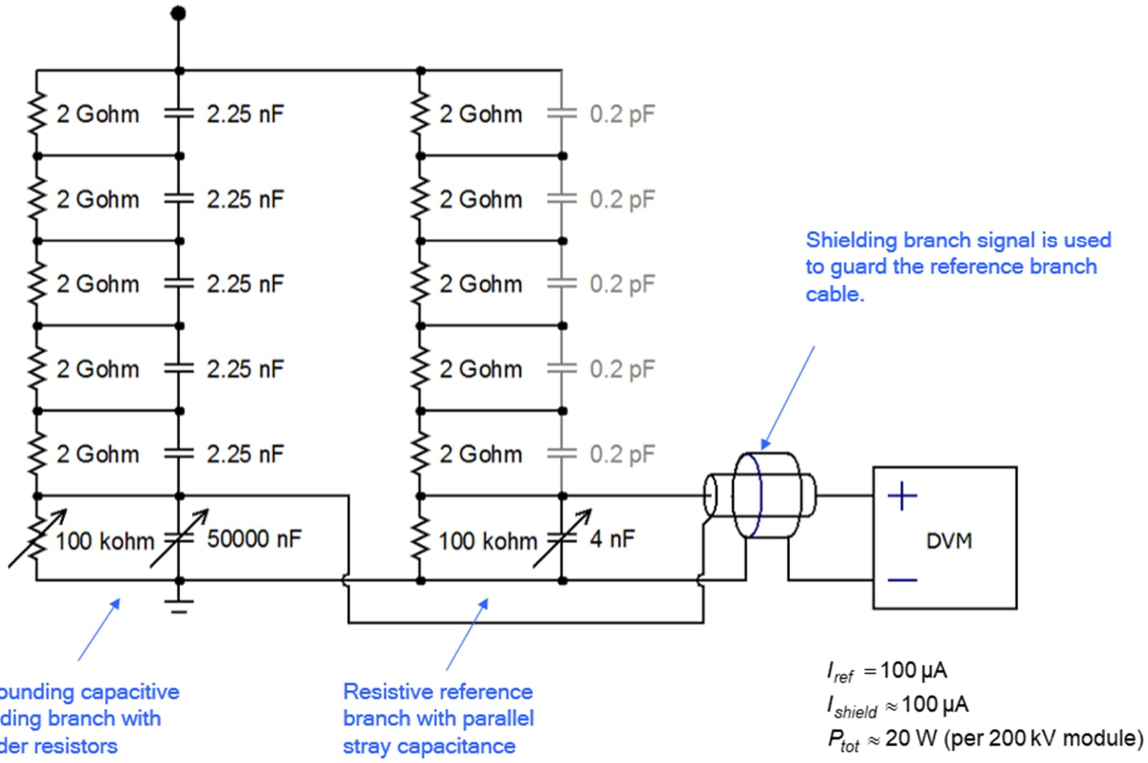

Figure 4 Internal structure of the dividers. The adjustments are used to optimise the AC behaviour, when needed.

3. Measurement methods

3.1 General

Participants shall define the scale factor (ratio) and the resistance of the reference branch high voltage resistor of their divider using existing home laboratory procedures before sending the divider for comparison measurements at RISE. Each participant shall repeat their home calibration after the divider has returned after comparison.

4. Quantities to be measured

1. The DC ratio of the divider, with nominal value of 20000; and
2. The resistance of the high voltage reference branch resistor, with nominal value of 2 GΩ.

4.1 Ambient conditions

Ambient conditions shall be reported for each home calibration (before and after measurements at RISE), and for measurements at RISE. Recorded temperature values will be used for correcting the final report results to reflect performance at e.g. 22.0 °C. Humidity does not have to be controlled, but shall be reported.

The dividers must be acclimatized for a suitable duration (not less than 7 days) in the laboratory before the measurements in order to reach stable temperature.

4.2 HVDC ratio

The scale factor (ratio) of the dividers will be compared at RISE on the voltage levels shown in **Table 10**.

Table 10 Voltages for ratio comparison

Nominal voltage [kV]
1
10
100
200
-200

The comparison at RISE will be performed by connecting two or several dividers in parallel to measure the high voltage. The output of each divider will be measured using calibrated 3458A multimeter(s).

4.3 High voltage arm resistance

The high voltage arm resistance of each divider will be separately measured at RISE at 1 kV using voltage bridge method.

3. Measurement reporting

5.1 Before RISE comparison measurements

Each participant shall calibrate their divider before the comparison session. The calibration certificate shall be signed before the start of the RISE session and, at minimum, it shall contain the following:

- description of the measuring set-up(s) including the electrical circuit configuration;
- traceability scheme; if the traceability to the SI is provided by another NMI, the name of the NMI has to be stated (needed to identify possible sources of correlation);
- value and uncertainty of the scale factor, and respective voltage level(s);
- value and uncertainty of the reference branch high voltage resistor, and respective voltage level(s);
- description of the measurement procedure(s);
- the ambient conditions of the measurement: the temperature and humidity with limits of variation.

5.2 RISE comparison measurements

The pilot (RISE) prepares a report summarising the results of the measurements described in chapters 0 and 0. RISE will not disclose this report to other participants until all calibration certificates described in clauses 0 and 0 are submitted.

5.3 After RISE comparison measurements

Each participant shall repeat the calibration described in chapter 0 within 2 months after return of the divider to their laboratory and send both calibration certificates to the coordinator.

4. Final report of the comparison

Within 3 months after completion of all measurements, the VTT will prepare the first draft report and send it to the participants for comments.

This final report will summarise the results from the calibration certificates and comparison report described in chapter 3.

5. Organization

7.1 Coordinator

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7.3 Participants

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PTB	Physikalisch-Technische Bundesanstalt	Germany	NMI	Dr. Johann Meisner johann.meisner@ptb.de
TUBITAK	TÜBITAK Ulusal Metroloji Enstitüsü	Turkey	NMI	Dr. Ahmet Merev ahmet.merev@tubitak.gov.tr
VSL	VSL National Metrology Institute (VSL)	Netherlands	NMI	Dr. Ernest Houtzager ehoutzager@vsl.nl

7.4 Time schedule

Comparison measurement will be performed in February/March 2022 at RISE according to the schedule shown below.

Timetable

Action	Start	Finish
Arrival of dividers to RISE	20.01.2022	22.02.2022
Temperature stabilization (7 days)	14.01.2022	01.03.2022
2 GΩ measurements	21.01.2022	01.03.2022
200 kV scale factor measurements	7.03.2022	11.03.2022
Divider departure from RISE	21.03.2022	06.04.2022

7.5 Transportation

Participants will be responsible for arranging transportation for their own divider to and from RISE.

7.6 Financial aspects, insurance

Each participating laboratory covers the costs of its own labor and transportation cost, as well as of any possible damage to their own equipment.