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Measurement and generation of small AC voltages with inductive voltage dividers

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Deutscher Kalibrierdienst (DKD)

Since its foundation in 1977, the German Calibration Service has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3 May 2011, the German Calibration Service was reestablished as a *technical body* of PTB and the accredited laboratories.
This body is known as *Deutscher Kalibrierdienst* (DKD for short) and is under the direction of PTB. The guidelines and guides elaborated by DKD represent the state of the art in the respective technical areas of expertise and can be used by the *Deutsche Akkreditierungsstelle GmbH* (the German accreditation body – DAkkS) for the accreditation of calibration laboratories. The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor of the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

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Foreword

DKD guidelines are application documents that meet the requirements of DIN EN ISO/IEC 17025. The guidelines contain a description of technical, process-related and organizational procedures used by accredited calibration laboratories as a model for defining internal processes and regulations. DKD guidelines may become an essential component of the quality management manuals of calibration laboratories. The implementation of the guidelines promotes equal treatment of the equipment to be calibrated in the various calibration laboratories and improves the continuity and verifiability of the work of the calibration laboratories.

The DKD guidelines should not impede the further development of calibration procedures and processes. Deviations from guidelines as well as new procedures are permitted in agreement with the accreditation body if there are technical reasons to support this action.

The present guideline was first prepared in 1999 by the Technical Committee *Direct Current and Low Frequency* in cooperation with PTB and the accredited calibration laboratories.
Only the imprint of this revised new edition has been updated.
It is identical in content to the guideline DAkkS-DKD-R 1-1 (Edition 2010). DAkkS will withdraw the guideline DAkkS-DKD-R 1-1 by 1 January 2021 at the latest.

Edition: 01/1999, published by DKD

1. New edition: 08/2002, by DKD
2. New edition: 2010, by DAkkS
3. New edition: 09/2018, by DKD, identical in content to the 2nd edition

Note: The German version of the DKD guideline DKD-R 1-1 (edition 01/1999) is originally based on EA-10/09 (EAL-G32), Edition 1, October 1997 “Measurement and Generation of Small AC Voltages with Inductive Voltage Dividers”.

0 Introduction

0.1 One of the tasks of the technical committees of the European co-operation for Accreditation (EA) is to draw up technical guidelines that can be used by accredited calibration laboratories. This ensures the equal treatment of the instruments to be calibrated in the different calibration laboratories and improves the transparency of the work of the calibration laboratories.

0.2 The guidelines do not claim to completely cover all details of the respective measuring devices. They are intended for experts and only establish what is necessary in accordance with their own objectives. They can serve as internal process instructions and thus become part of quality assurance manuals of the calibration laboratories.

0.3 This guideline deals with the generation and measurement of small AC voltages for calibration purposes by means of inductive voltage dividers. It describes the procedures for accreditation with regard to the generation and measurement of small AC voltages.

1 Scope of application

1.1 This guide applies to the generation and measurement of small AC voltages from 1 mV to 1 V, and in dependency on the selected procedure and method used in the frequency range from 50 Hz to 100 kHz. The accreditation of the measurand “AC voltage” for voltages above 1 V is required.

1.2 The measurement procedures and instruments used by the accredited laboratory for conducting the calibration must be such that all the parameters necessary for calibration are traceable to the accredited quantities of the laboratory. The traceability to national standards as well as the laboratory-specific measurement procedures must be documented and traceable.

2 Terms and abbreviations

D	nominal value of the division ratio (set value)
IVD	inductive voltage divider
$\underline{K}$	complex correction of the division ratio
K_B	reactive component of the complex correction of the division ratio
K_W	active component of the complex correction of the division ratio
PC	personal computer
R_S	series resistance
$\underline{U}_a$	complex output voltage
$\underline{U}_e$	complex input voltage
$\underline{Z}_a$	complex output impedance of the inductive divider
$\underline{Z}_2$	complex load impedance

3 Calibration devices

3.1 Requirements concerning the calibration devices

3.1.1 The calibration has to be carried out with measuring devices that have been traced back to national standards by direct or indirect comparison and with a known measurement uncertainty.

3.2 Reference conditions

3.2.1 The conditions for carrying out the calibration of small AC voltages must be the same as for the calibration of the specific measurement set-up.

3.2.2 Before starting the measurements, it must be ensured that warm-up times are observed, that the measurement set-up is in thermal equilibrium, and that interfering fields – where relevant – are screened.

4 Preparation for calibration

4.1 The measuring device or system has to undergo an external inspection and a functional test. Defects that are detected have to be eliminated. If this is not possible, the calibration is to be rejected.

5 Description of the calibration procedure

5.1 Generation of small AC voltages for calibration purposes by means of an inductive voltage divider

5.1.1 Scope of the procedure (validity range)

5.1.1.1 Under the above-described conditions, this calibration procedure can be used in accredited laboratories for generating small AC voltages in a voltage and frequency range established by the inductive divider (e.g. 1 mV to 1 V and 50 Hz to 1 kHz).

5.1.2 Measurement procedure

5.1.2.1 Small AC voltages can be generated by dividing a known higher voltage of, for example, 1 V by using a calibrated inductive voltage divider. By means of the voltage divider, voltage ratios are traced back to turns ratios.

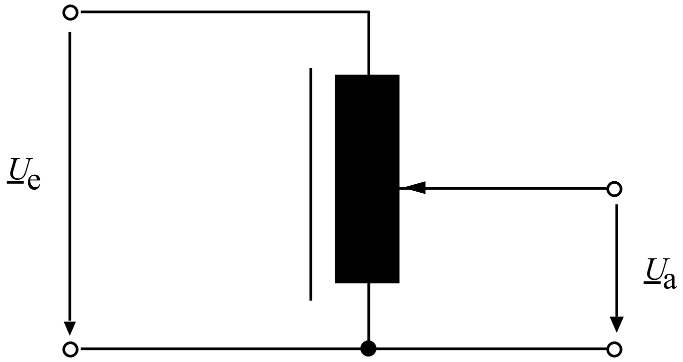

Figure 1: Basic circuit diagram of an unloaded inductive voltage divider

5.1.2.2 The complex relationship between the output voltage $\underline{U}_a$ of an unloaded inductive voltage divider to its input voltage $\underline{U}_e$ is given by the equation

$$\underline{U}_a / \underline{U}_e = D + \underline{K} = D + K_W + jK_B \qquad (1)$$

Here, D is the nominal value of the division ratio. The value is determined by the switch setting. $\underline{K}$ is the complex correction of the division ratio. It consists of the active component (real part) K_W and the reactive component (imaginary part) K_B. Assuming that K_W and $K_B << D$, then K_W is the correction of the modulus of $\underline{U}_a / \underline{U}_e$, while the quotient K_B/D approximately describes the phase angle in radians between $\underline{U}_a$ and $\underline{U}_e$.

5.1.2.3 Accordingly, the following is valid for the modulus of the output quantity of the unloaded divider:

$$|\, U_a | \approx | \underline{U}_e | \times [D + K_W] \qquad (2)$$

5.1.2.4 The output voltage of a divider loaded with the impedance $\underline{Z}_2$ can be calculated as follows:

$$\underline{U}_a \approx \underline{U}_e [D + K_W + jK_B - D \times \underline{Z}_a / \underline{Z}_2] \qquad (3)$$

with $\underline{Z}_a$ as output impedance of the inductive voltage divider.

5.1.2.5 For the estimation of a measurement result according to Eq. (3), the following has to be taken into account:

- The input voltage $|\, U_e |$ has to be determined by means of the accredited AC voltage measurement procedure.
- Preferably, the chosen division ratio D is, for example, 0.1; 0.01; 0.001. With these division ratios, the output impedance $\underline{Z}_a$ of inductive voltage dividers is usually small, so that the load dependence is only a minor one.
- With frequencies of 400 Hz and 1 kHz and with the aforementioned division ratios, the complex correction $\underline{K}$ and its parts K_W and K_B are to be traced back to national standards.
- The load influence $\underline{Z}_a / \underline{Z}_2$ is to be considered. To this end, the output impedance $\underline{Z}_a$ of the inductive voltage divider is assumed as a series connection of a resistor R_S and an inductance L_S. Its values must be known for the mentioned frequency range and for the selected division ratios. If $\underline{Z}_a$ is not known, the load influence can be determined experimentally by load doubling (halving $\underline{Z}_2$), while simultaneously measuring $\underline{U}_a$.

5.1.3 Influences on the measurement result

5.1.3.1 The measurement result obtained by using the current measurement set-up is subject to a number of factors that must be considered. This section describes different factors that may affect the measurement result. Likewise, *measures* to minimize those influences are proposed.

- Load on the voltage source (calibrator) by the input impedance of the inductive voltage divider.

  The measurement of $|U_\mathrm{e}|$ *is necessary, if the internal resistance is not negligible.*

  It has to be taken into account that an inductive load, such as an inductive voltage divider, can increase the output voltage of some sources.

- Ground loops

  Apply the defined Guard technique.

- Irradiation by external fields.

  If necessary, the measurements have to be carried out in shielded rooms. Irradiation by data processing devices (PCs, printers) as well as the rules for electromagnetic compatibility must be observed.

- Noise voltage of the AC voltage source or the measuring device used for measuring $|U_\mathrm{e}|$. In no case this noise voltage will be divided by the division ratio. With capacitive coupling, the noise voltage at the divider output can be almost as large as the input noise voltage.

  If necessary, a filter has to be used to reduce the input noise voltage.

- Noise voltages generated by the measuring device and by the source that is to be calibrated must be observed.

- The influence of the loading on the divider, especially by longer measuring cables, has to be taken into account.

  Shielded measuring cables are to be used.

- The operating conditions of the inductive divider must be observed.

- Systematic influence of the instrument to be tested.

- Contact resistances of the divider (instability of the output voltage).

5.1.4 Uncertainty analysis

5.1.4.1 The uncertainty belonging to the measured voltage $|\underline{U}_\mathrm{a}|$ has to be determined according to EA-4/02 [4] on the basis of the above-mentioned equations (2) or (3).

5.1.4.2 The estimations should take into account all factors mentioned in Section 5.1.3. The surge of the correction K_W and its uncertainty at small division ratios is to be taken into account; it is not negligible.

5.1.5 Traceability

5.1.5.1 The voltage $|\underline{U}_e|$ must be traceable to national standards. The inductive voltage divider must be traceable to national standards according to section 5.1.2. If other than the calibrated frequencies are used, the additional shares of the uncertainty should be estimated, taking into account the manufacturer's specifications.

5.2 Generation of small AC voltages for calibration purposes according to the voltage ratio method

5.2.1 Scope of the procedure (validity range)

5.2.1.1 This procedure for generating and measuring small AC voltages in the range from 1 mV to 1 V can be used in accredited laboratories in the frequency range from 50 Hz to 100 kHz, depending on the inductive divider that is applied and taking into account the specified requirements. It is assumed that the laboratory is accredited for the measurement of AC voltages of 1 V and more at these frequencies.

5.2.1.2 This procedure can be used for the calibration of both indicating measuring devices (see UUT in Figure 2) and AC calibrators (see AC-CAL in Figure 2).

5.2.2 Measurement procedure

5.2.2.1 Principle

a) This procedure is based on the determination of the division ratio of the inductive voltage divider in the V range with the known AC voltages U_e and U_a. Basically, this includes two steps:

   1. Determination of the division ratio of the inductive divider used at voltages in the V range.

   2. Generation and measurement of small AC voltages by means of the calibrated divider.

5.2.2.2 Description of the procedure

a) Determination of the division ratio of the inductive voltage divider

The exact 1:10 division ratio of the inductive divider is determined by AC voltage measurements at 1 V and 10 V. The calibration is carried out using the measurement set-up according to Figure 2 and following the steps shown in Table 1.

A The AC calibrator (AC-CAL) is to be set at the known voltage of 10 V, with the frequency f.

The division ratio of the inductive voltage divider (IVD) must be set to 0.1.

The low-noise pre-amplifier (AMP) is used to change the amplification, in order to set the reference value (e.g. 1,000... V) on the display of the AC measurement device (DMM).

B The AC-CAL is to be set at the known voltage of 10 V, with the frequency f. At the IVD, the division ratio should be set in such a way that the indicating DMM shows the reference value of 1,000.... V. The amplification of the AMP is not changed. This division ration is recorded as R.

b) Calibration of the voltages 100 mV, 10 mV, 1 mV

100 mV

C The voltage value of 1 V, which is set on the AC-CAL according to (B), and the frequency f are to be left unchanged.

The IVD has to be set to the division ratio 0.1.

The amplification of the AMP has to be changed in order to again adjust the reference value in the display of the DMM.

D The AC-CAL is to be set at 100 mV, with the frequency f.

The division ratio at the IVD is to be set at R, as determined under B. The AMP amplification is left unchanged. The AC-CAL should be set in such a way that the display of the DMM shows the reference value of 1,000.... V. Within the stated uncertainty, the output voltage of the AC-CAL is equal to 100 mV.

10 mV

E The setting of AC-CAL must remain at 100 mV, and at frequency f.

The IVD has to be set to the division ration 0.1. The amplification of the AMP has to be changed in order to again adjust the reference value in the display of the DMM.

F The AC-CAL is to be set at 10 mV, with the frequency f.

The division ratio at the IVD is to be set at R, as determined under B. The AMP amplification is left unchanged. The AC-CAL should be set in such a way that the display of the DMM shows the reference value of 1,000.... V. Within the stated uncertainty, the output voltage of the AC-CAL is equal to 10 mV.

1 mV

The calibration at 1 mV is carried out in analogy to the previously described steps in accordance with Table 1, point g) and h). In Table 1 summarises the procedure for determining the division ratio of the inductive divider and the derivative of the calibrated voltage values for 100 mV, 10 mV und 1 mV are.

Table 1: Steps for the calibration of 100 mV, 10 mV and 1 mV and sources of uncertainty

<table>
<tr><th>AC-CAL</th><th>IVD</th><th>AMP</th><th>DMM</th><th>Objective</th><th>Sources of uncertainty</th></tr>
<tr><td>a) apply 10 V

b) apply 1 V</td><td>Division ratio 0.1

Setting of the reference value with division ratio</td><td>Reference value

no change</td><td>e.g. 1.000...

read 1.000...</td><td>Determination of the division ratios</td><td>Division ratio 1:10 with AC/DC transfer standard;
for further steps, correlation has to be taken into account</td></tr>
<tr><td>c) maintain 1 V

d) apply 100 mV adjust the AC-CAL in such a way that the DMM shows 1.000...</td><td>Division ratio 0.1

Division ratio as in b)</td><td>set to x10/ref.

x10/no change</td><td>e.g. 1.000...

read 1,000...</td><td>100 mV

setting</td><td rowspan="2">Influence of the load of the divider eliminated by measurements a) and b) and procedure

Temporal instabilities</td></tr>
<tr><td>e) maintain 100 mV

f) apply 10 mV adjust the AC-CAL in such a way that the DMM shows 1.000...</td><td>Division ratio 0.1

Division ratio as in b)</td><td>set to x100/ref.

x100/no change</td><td>e.g. 1.000...

read 1.000...</td><td>10 mV

setting</td></tr>
<tr><td>g) maintain 10 mV

h) apply 1 mV adjust the AC-CAL in such a way that the DMM shows 1.000...</td><td>Division ratio 0.1

Division ratio as in b)</td><td>set to x1000/ref.

x1000/no change</td><td>e.g. 1.000...

read 1.000...</td><td>1 mV

setting</td><td>Noise, ground loops, etc.</td></tr>
</table>

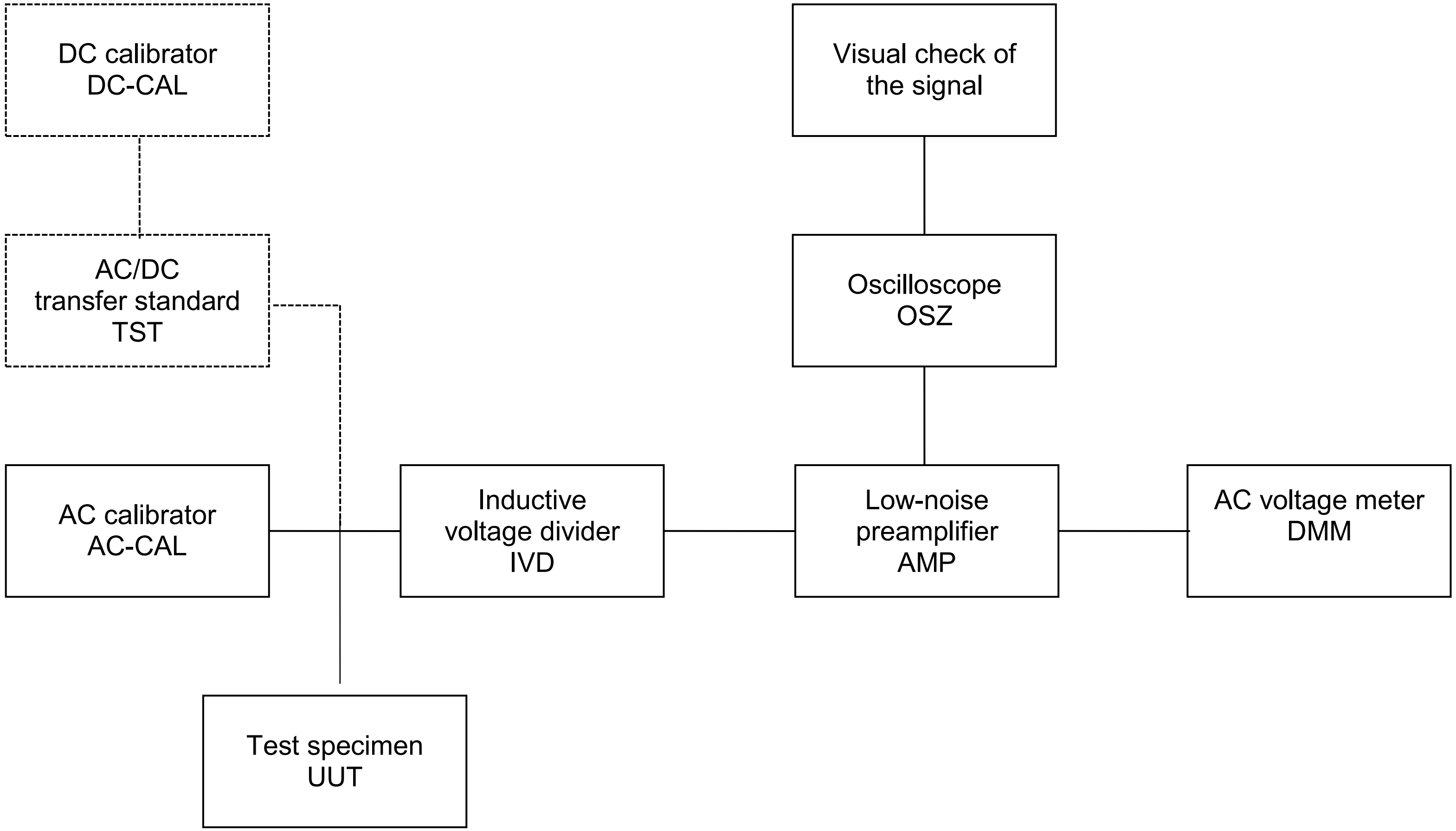

Figure 2: Set-up for the calibration of low AC voltages according to the voltage ratio method

5.2.3 Uncertainty analysis

5.2.3.1 The measurement uncertainty for the procedure has to be determined according to EA-4/02. The measurement uncertainties that are to be attributed to the voltage levels of the individual 1:10 steps are correlated, since the same inductive voltage divider is used for the transmission of the ratio. Therefore, the measurement uncertainties for each 1:10 step have to be determined by taking into account these correlations which are mainly a result of the 1 V and 10 V voltage levels of the uncertainties to be attributed to the AC calibrator (AC-CAL).

5.2.3.2 The loading of the divider output does not generate any additional uncertainty components, since within the course of the procedure they are already incorporated in the calibration. This applies as long as the input impedance of the low-noise pre-amplifier (AMP) does not change with its amplifier setting.

5.2.3.3 The stability of the comparison chain (IVD, AMP und DMM) is an essential source of uncertainty. Here, the short-term stability between two successive measurement steps is the deciding factor. The importance of the short-term stability of the pre-amplifier as a significant source of uncertainty rises with a decreasing input voltage. The same is valid for external influences caused by ground loops, noise voltages, electromagnetic interference, etc.

5.2.3.4 With a decreasing input voltage level, the resolution of the measuring instruments AMP and DMM for the relative measurement uncertainty is gaining in importance. The same is valid for external influences caused by ground loops, electromagnetic fields, noise voltages, etc.

5.2.3.5 Other sources of uncertainty, such as the noise or the DC offset of the AC calibrator (AC-CAL), can be eliminated by appropriate filtering.

5.2.4 Example of an uncertainty analysis

(The figures are for illustration purposes only.)

5.2.4.1 The determination of the measurement uncertainty is divided into two steps: the determination of the uncertainty to be attributed to the IVD ratio and the determination of the uncertainties to be attributed to the results of the calibrations at 100 mV, 10 mV and 1 mV.

5.2.4.2 When determining the IVD division ratio, the levels of the input voltages applied to the IVD are not directly measured during the process, but are derived from the calibrated AC-CAL. The ratio is determined according to steps a) and b) in Table 1:

$$R = \frac{r_{0,1}}{r_{1,0}} = \frac{V_1}{V_{10}} v_\mathrm{N} v_\mathrm{i} \qquad (1)$$

wherein

$r_{0,1}$, $r_{1,0}$	Transfer ratios of output and input voltages of the inductive voltage divider with its 0.1 and 1.0 settings
$v_\mathrm{N} = \dfrac{1+\dfrac{\delta V_{\mathrm{N1}}}{V_\mathrm{in}}}{1+\dfrac{\delta V_{\mathrm{N10}}}{V_\mathrm{in}}}$	Ratio of the corrections due to the instability of the pre-amplifier and other disturbing influences

$V_{\mathrm{in}} = r_{1,0} V_1 = r_{0,1} V_{10}$	Voltage at the pre-amplifier input for both settings
$\delta V_{\mathrm{N1}}, \delta V_{\mathrm{N10}}$	Corrections with regard to the instability of the pre-amplifier and other interfering effects
$v_{\mathrm{i}} = \dfrac{1 + \dfrac{\delta V_{\mathrm{i10}}}{V_{\mathrm{i}}}}{1 + \dfrac{\delta V_{\mathrm{i1}}}{V_{\mathrm{i}}}}$	Ratio of the voltages at the DMM with the calibrator set at 10 V and 1 V (the Index i means ‘indicated’)
V_{i}	Voltage indication (e.g. 1.000... V) at the DMM for the settings (the Index i means ‘indicated’)
$\delta V_{\mathrm{i1}}, \delta V_{\mathrm{i10}}$	Correction of the voltage values indicated by the DMM due to its finite resolution (the Index i means ‘indicated’)

5.2.4.3 The model function in Eq. (1) is a product of terms. In this case, the relative standard uncertainty, which is to be attributed to the calibration of the division ratio R, is the appropriate quantity for evaluation. Its square is given by the sum of squares:

$$w^2(R) = w^2(V_1) + w^2(V_{10}) + w^2(v_{\mathrm{N}}) + w^2(v_{\mathrm{i}}) \qquad (2)$$

5.2.4.4 **AC calibrator** (V_1, V_{10}): For the frequency range from 30 Hz to 100 kHz, the values of the generated AC voltage agree with the corresponding voltage settings for the 1 V and the 10 V voltage level with an attributed expanded relative uncertainty of $W = 0{,}1\text{x}10^{-3}$ (coverage factor $k = 2$). This value indicates the attributed relative uncertainty at the time of measurement. It contains an uncertainty contribution resulting from the values taken from the calibration certificate, and an uncertainty contribution of the drift from the last calibration which is determined from the calibration history of the reference source. If an AC/DC transfer measurement is available, the relative uncertainty attributed to the above-mentioned voltage levels can be determined by a calibration of the levels immediately prior to the determination of the IVD ratio (see 5.2.4.9). As a result, the influence of the drift is suppressed, and the measurement uncertainty is reduced. This case is included in Figure 2.

5.2.4.5 **Stability of the pre-amplifier and other interference voltages** (V_N): Voltage fluctuations due to the short-term stability of the pre-amplifier and other disturbing influences at the amplifier input are known from the manufacturer's specifications and from previous measurements with the following limits:

Input voltage	Limits	Relative limits
1 V	2 µV	$\pm 2 \times 10^{-6}$
100 mV	±4 µV	$\pm 4 \times 10^{-5}$
10 mV	±7 µV	$\pm 7 \times 10^{-4}$
1 mV	±10 µV	$\pm 10 \times 10^{-3}$

For the correction ratio v_N we get a triangular distribution with the expected value of 1.000... and the following limits (see EA-4/02 S1, Example S3):

Input voltage	Limits
1 V	$\pm 4 \times 10^{-6}$
100 mV	$\pm 8 \times 10^{-5}$
10 mV	$\pm 14 \times 10^{-4}$
1 mV	$\pm 20 \times 10^{-3}$

5.2.4.6 **Voltmeter** (v_i): The resolution of the 5 1/2-digit voltmeter used in the 2 V range is 10 µV, which leads to limits of ±5 µV for the finite resolution of the device. For the ratio v_i of the voltage values at the DMM we get a triangular distribution with an expected value of 1.000... and limits of $\pm 10 \times 10^{-6}$. (Only uncorrelated contributions of the corrections have to be taken into account; see EA-4/02 S1, Example S3).

5.2.4.7 **Uncertainty budget (Ratio R of the inductive divider):**

Quantity X_i	Estimate x_i	Rel. standard uncertainty $w(x_i)$	Probability distribution	Sensitivity coefficient c_i	Relative uncertainty contribution $w_i(y)$
V_1	1.000 00 V	50×10^{-6}	normal	1.0	50×10^{-6}
V_{10}	10.000 0 V	50×10^{-6}	normal	1.0	50×10^{-6}
v_N	1.000 000	1.63×10^{-6}	triangle	1.0	1.63×10^{-6}
v_i	1.000 000	4.08×10^{-6}	triangle	1.0	4.08×10^{-6}
R	0.100 000				70.8×10^{-6}

5.2.4.8 **Relative expanded uncertainty**

$$W = k \times w(R) = 2 \times 0.0708 \times 10^{-3} = 0.14 \times 10^{-3}$$

5.2.4.9 **Note:** If the output voltages of the calibrator are calibrated by connection to DC reference voltages according to the AC-DC transfer method (see Figure 2), the measurement uncertainty to be attributed to the voltage levels V_1 and V_{10} can be determined using the following equations:

$$V_1 = V_{\mathrm{DC1}}(1 + \delta_1) \text{ and } V_{10} = V_{\mathrm{DC10}}(1 + \delta_{10}) \qquad (3)$$

with

δ_1, δ_{10} relative AC/DC voltage transfer differences

V_{DC1}, V_{DC10} DC voltages.

This can lead to a reduction of the uncertainty to be attributed to the IVD ratio R. An uncertainty budget for this internal calibration is not included here.

5.2.4.10 The voltage levels 100 mV, 10 mV and 1 mV are gradually calibrated downwards (see step c) to h) in Table 1), using the previously calibrated 1:10 ratio R of the IVD.

5.2.4.11 The value $V_{0,1}$ of the 100 mV level is calibrated by connecting it to the value V_1 of the 1 V level of the calibrator. It is given by

$$V_{0,1} = R V_1 \nu_{\mathrm{N}} \nu_{\mathrm{l}} \qquad (4)$$

5.2.4.12 When determining the relative standard uncertainty to be attributed to the value $V_{0,1}$, the correlations between R and V_1, which result from the fact that V_1 has been used for the determination of R (see Eq. (1)), have to be taken into account. From this it follows

$$w^2(V_{0,1}) = w^2(R) + 3w^2(V_1) + w^2(\nu_{\mathrm{N}}) + w^2(\nu_{\mathrm{l}}) \qquad (5)$$

The factor 3 results from the above-mentioned correlations. The details of its determination will not be described here.

5.2.4.13 Uncertainty budget (100 mV level)

Quantity X_i	Estimate x_i	Rel. standard uncertainty $w(x_i)$	Probability distribution	Sensitivity coefficient c_i	Relative uncertainty contribution $w_i(y)$
R	0.100 000 V	70.8×10^{-6}	normal	1.0	70.8×10^{-6}
V_1	1.000 00 V	50×10^{-6}	normal	1.732	86.6×10^{-6}
ν_N	1.000 00	32.7×10^{-6}	triangle	1.0	32.7×10^{-6}
ν_i	1.000 000	4.08×10^{-6}	triangle	1.0	4.08×10^{-6}
$V_{0,1}$	0.100 00 V				117×10^{-6}

5.2.4.14 Relative expanded uncertainty

$$W = k \times w(V_{0,1}) = 2 \times 0.117 \times 10^{-3} = 0.23 \times 10^{-3}$$

5.2.4.15 The value $V_{0,01}$ of the 10 mV level is calibrated by connection to the value $V_{0,1}$ of the 100 mV level of the calibrator. It is given by:

$$V_{0,01} = R V_{0,1} \nu_N \nu_i \tag{6}$$

5.2.4.16 When determining the relative standard uncertainty to be attributed to the value $V_{0,01}$, the correlations between R, V_1 and $V_{0,1}$, which result from the fact that R has been used for the determination of $V_{0,1}$ (see Eq. (4)) and that R is correlated with V_1, have to be taken into account. From this it follows

$$w^2(V_{0,01}) = w^2(V_{0,1}) + 3w^2(R) + 2w^2(V_1) + w^2(\nu_N) + w^2(\nu_i) \tag{7}$$

The factors 3 and 2 are a result of the above-mentioned correlations. The details of their determination will not be described here.

5.2.4.17 Uncertainty budget (10 mV level)

Quantity X_i	Estimate x_i	Rel. standard uncertainty $w(x_i)$	Probability distribution	Sensitivity coefficient c_i	Relative uncertainty contribution $w_i(y)$
R	0.100 000 V	70.8×10^{-6}	normal	1.732	123×10^{-6}
$V_{0,1}$	0.100 00 V	117×10^{-6}	normal	1.0	117×10^{-6}
V_1	-	50×10^{-6}	normal	1.414	70.7×10^{-6}
ν_N	1.000 0	572×10^{-6}	triangle	1.0	572×10^{-6}
ν_i	1.000 000	4.08×10^{-6}	triangle	1.0	4.08×10^{-6}
$V_{0,001}$	0.010 000 V				600×10^{-6}

5.2.4.18 **Relative expanded uncertainty**

$$W = k \times w(V_{0,01}) = 2 \times 0.600 \times 10^{-3} = 1.2 \times 10^{-3}$$

5.2.4.19 The value $V_{0,001}$ of the 1 mV level is calibrated by connection to the value $V_{0,01}$ of the 10 mV level of the calibrator. It is given by:

$$V_{0,001} = R V_{0,01} \nu_{\mathrm{N}} \nu_{\mathrm{i}} \tag{8}$$

5.2.4.20 When determining the relative standard uncertainty to be attributed to the value $V_{0,001}$, the correlations between R, V_1 and $V_{0,01}$, which result from the fact that R has been used for the determination of $V_{0,01}$ (see Eq. (6)) and that R is correlated with V_1, have to be taken into account. From this it follows

$$w^2(V_{0,001}) = w^2(V_{0,01}) + 5w^2(R) + 2w^2(V_1) + w^2(\nu_{\mathrm{N}}) + w^2(\nu_{\mathrm{i}}) \tag{9}$$

The factors 5 and 2 are a result of the above-mentioned correlations. The details of their determination will not be described here.

5.2.4.21 **Uncertainty budget (1 mV level)**

Quantity X_i	Estimate x_i	Rel. standard uncertainty $w(x_i)$	Probability distribution	Sensitivity coefficient c_i	Relative uncertainty contribution $w_i(y)$
R	0.100 000 V	0.071×10^{-3}	normal	2.236	0.159×10^{-3}
$V_{0,01}$	0.010 000 V	0.606×10^{-3}	normal	1.0	0.606×10^{-3}
V_1	-	50×10^{-6}	normal	1.414	70.7×10^{-6}
ν_{N}	1.000	8.16×10^{-3}	triangle	1.0	8.16×10^{-3}
ν_{i}	1.000 000	0.004×10^{-3}	triangle	1.0	0.004×10^{-3}
$V_{0,001}$	0.001 000 V				8.19×10^{-3}

5.2.4.22 **Relative expanded uncertainty:**

$$W = k \times w(V_{0,001}) = 2 \times 8.19 \times 10^{-3} \cong 16 \times 10^{-3}$$

5.2.4.23 The voltages generated by the calibrator are:

Setting	Value
100 mV	$100.00\times(1 \pm 0{,}23\times10^{-3})$ mV
10 mV	$10.00\times(1 \pm 1{,}2\times10^{-3})$ mV
1 mV	$1.00\times(1 \pm 16\times10^{-3})$ mV

5.2.4.24 The stated expanded measurement uncertainty is obtained by multiplying the standard uncertainty by the coverage factor $k = 2$; in case of a normal distribution, the coverage factor corresponds to a coverage probability of 95 %.

5.2.5 Traceability

5.2.5.1 The traceability of the results obtained by this procedure requires an accreditation for the AC values of 10 V and 1 V in the corresponding frequency range.

6 Literature

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[1] Replaced by EA-4/02 M: 2013 Evaluation of the Uncertainty of Measurement in Calibration

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