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A novel ppm-precise absolute calibration method for precision high-voltage dividers

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Abstract

The most common method to measure direct current high voltage (HV) down to the ppm-level is to use resistive high-voltage dividers. Such devices scale the HV into a range where it can be compared with precision digital voltmeters to reference voltages sources, which can be traced back to Josephson voltage standards. So far the calibration of the scale factors of HV dividers for voltages above 1 kV could only be done at metrology institutes and sometimes involves round-robin tests among several institutions to get reliable results. Here we present a novel absolute calibration method based on the measurement of a differential scale factor, which can be performed with commercial equipment and outside metrology institutes. We demonstrate that reproducible measurements up to 35 kV can be performed with relative uncertainties below $1 \cdot 10^{-6}$. This method is not restricted to metrology institutes and offers the possibility to determine the linearity of high-voltage dividers for a wide range of applications.

Keywords: high-voltage divider, high-voltage calibration, HVDC metrology, ppm-level calibration

(Some figures may appear in colour only in the online journal)

1. Introduction

Precision measurements of direct current (DC) high voltage (HV) are important for many applications in physics, e.g. to record an integral spectrum of tritium-$\beta$-electrons with the KATRIN neutrino mass experiment [1] or for determining kinetic energies of electrons with electron coolers at ion storage rings [2]. The scope of applications is not limited to fundamental research, but is also important for high-voltage direct current (HVDC) electric power transmission systems, which are currently discussed and planned as part of the ‘energy transition’ in many European countries. In other countries, e.g. China, Brazil and India, huge HVDC traces and grids are already used for the transmission of large energy amounts [3–7].

The general approach to measure high voltage is to scale it with a HV divider to a range, where it can be compared to a reference voltage source ⁵, which is calibrated by a metrology laboratory like the German National Metrology Institute Physikalisch-Technische Bundesanstalt (PTB) with a Josephson voltage standard [8].

Precision HV dividers to the ppm⁶-level are commercially available only for voltages up to 1 kV. One key problem for

5 E.g. a Fluke 732A 10 V reference voltage source.
6 Parts per million, 1 ppm = $1 \cdot 10^{-6}$
the operation of ppm-precise HV dividers for higher voltages is the lack of traceable calibration methods with the required precision. HV dividers are composed of resistors and therefore generally show a voltage- and time dependent behavior. This is mainly caused by thermal loads and leakage currents with respect to different voltage ranges and powers. Hence, calibration values obtained at low voltages in the order of 1 kV can not be extrapolated for higher voltages without corrections.

Up to now the only possibility to calibrate a HV divider to the ppm-level is to transport the unit under test to a metrology center and compare it to a well-known standard HV divider like the MT100 [9] of PTB for direct voltages up to 100 kV. The voltage dependency of the MT100 is proven at the nominal voltage of each resistor. But the traceable comparison of the entire divider with a known reference is not possible at high voltages. Therefore, the uncertainty budget of the MT100 has a major contribution caused by the linearity extension leading to an overall expanded uncertainty of 2 · 10⁻⁶.

Recently two new methods for an absolute calibration of HV dividers were reported in [10] and [11], where uncertainties in the range of 5 · 10⁻⁶ could be achieved. However, these methods require a complex and partially unique experimental set-up (e.g. an ion beamline with a laser spectroscopy set-up or the 70 m long KATRIN neutrino mass experiment), making these methods very difficult to apply in laboratories with only commercially available equipment.

In this paper we present a newly developed method for absolute calibrations of HV divider to the ppm-level by measuring a traceable differential voltage under HV conditions, which can be performed with commercially available devices. The next section gives an overview over the basic set-up of HV dividers and their former calibration techniques. Subsequently, the newly developed calibration method will be explained and first measurement results with achieved relative uncertainties of less than 1 · 10⁻⁶ will be presented.

2. High-voltage divider characterization

Since high voltages can not be measured directly with ppm-precision, HV dividers are used to scale voltages into the range of typically below 20 V. Here precision digital voltmeters (DVM) are calibrated with 10 V reference sources, which are traceable to a natural standard at metrology institutes.

Figure 1 shows a schematic overview of a simple HV divider. It consists of a chain of multiple resistors \( \sum_{i=1}^{n} R_i \) and a low voltage resistor \( R_{LV} \) connected in series. The output voltage \( U_{LV} \) measured over \( R_{LV} \) is proportional to the input voltage \( U_{HV} \) of the divider. The characteristic observable is the so-called scale factor \( M \):

\[
M = \frac{U_{HV}}{U_{LV}} = \frac{\sum_{i=1}^{n} R_i + R_{LV}}{R_{LV}} = \sum_{i=1}^{n} \frac{R_i}{R_{LV}} + 1. \tag{1}
\]

Depending on the properties of \( R_{LV} \) compared to the overall resistance, arbitrary and also—if \( R_{LV} \) consists of multiple resistors—numerous scale factors can be realized. Following equation (1), \( M \) depends on the ratio of \( R_{LV} \) and \( \sum_{i=1}^{n} R_i \). If HV is applied to a voltage divider, its individual resistances might change due to dissipated power caused by Joule heating. Since the power of heating \( P \) scales quadratically with the current \( I \) and linearly with a resistance \( R \)

\[
P \propto I^2 \cdot R = \frac{U^2}{R}, \tag{2}
\]

one can conclude, that the resistances \( R_{LV} \) and \( R_i \) and thus the scale factor \( M \) are voltage dependent:

\[
M = M(U_{HV}). \tag{3}
\]

To mitigate this effect, the total resistance of precision HV dividers is typically in the MΩ-range or higher, limiting the electrical current through the system to less than 1 mA. Furthermore, usually high-quality resistors (e.g. [12]) with a low temperature coefficient in a closed stabilized thermal environment are used, resulting in low temperature dependency and long term stability of the scale factor in the (sub)-ppm-range [9, 13, 14].

In order to calibrate the scale factor \( M_A \) of a HV divider, the general procedure is to apply a calibration input voltage \( U_{HV} \) and measure the output voltage \( U_1 \) with a precision DVM\(^7\). The input voltage has to be determined with a reference HV divider with well known scale factor \( M_B \) and a second precision DVM measuring its output voltage \( U_2 \):

\[
U_{HV} = M_B \cdot U_2. \tag{4}
\]

Figure 1. Schematic overview of a simple HV divider. The output voltage \( U_{LV} \) measured over a part \( R_{LV} \) of the resistor chain \( R_i \) is proportional to the input voltage \( U_{HV} \). The proportionality factor is called the scale factor \( M \).

\(^7\)In the ideal case the input resistance of a DVM is infinitely high. In reality, the input resistance of the DVM \( R_{in,DVM} \) (in the 100 GΩ to 1 TΩ range for high-end DVM) has to be more than a million times larger than \( R_{LV} \) to determine the scale factor with ppm-precision. Otherwise the scale factor has to be corrected for \( R_{LV} = R_{LV}|R_{in,DVM} \).
The output voltage of the scale factors of a HV divider under test has to be calibrated with the direct method as defined in equation (1) the scale factor is the possible voltage dependent factor between the input- and output voltage of a HV divider. For a given input voltage the corresponding output voltage can be approximated by a Taylor expansion around $U_{HV} = 0$:

$$U_{LV} = a \cdot U_{HV} + b \cdot U_{HV}^2 + c \cdot U_{HV}^3 + d \cdot U_{HV}^4 + ...$$  \hspace{1cm} (7)

One disadvantage of this method is, that the upper part of the divider with the resistors $R_i$ is not loaded with the correct voltage $M_A \cdot U_{HV}$. This means, that the voltage dependency of the scale factor $M_A$ is not determined and included in the analysis properly. For a completely traceable calibration of a HV divider, the voltage dependency of the scale factors has to be taken into account correctly. In order to do so, we developed a novel ppm-precise absolute calibration method for HV dividers, which uses the low voltage equipment described above, elevated on a high-voltage potential.

### 3. Novel absolute calibration method

The basic idea of the novel absolute calibration method is to determine the voltage dependency of the scale factors of a HV divider by measuring a differential scale factor directly at high voltages with commercially available equipment. This is especially important for scale factors up to 100:1, since they are used in a step-up technique to calibrate higher scale factors (see section 2).

As defined in equation (1) the scale factor is the possibly voltage dependent factor between the input- and output voltage of a HV divider. For a given input voltage the corresponding output voltage can be approximated by a Taylor expansion around $U_{HV} = 0$:

As described above, the traceability of the single resistors is possible.
with the coefficients \(a\), \(b\), \(c\) and \(d\) (neglecting higher orders\(^9\)). For the voltage independent case the parameters \(b\), \(c\) and \(d\) are zero and \(a\) is the inverse of the constant part of the scale factor \(M_0\):

\[
a = \frac{1}{M_0}. \tag{8}\]

For the realistic case of a voltage dependent scale factor we can derive from equation (1) and (7):

\[
M = \frac{1}{a + b \cdot U_{HV} + c \cdot U_{HV}^2 + d \cdot U_{HV}^3}. \tag{9}\]

We define a differential scale factor \(\tilde{M}\) as the derivative of \(U_{HV}\) with respect to \(U_{LV}\):

\[
\tilde{M} = \frac{\delta U_{HV}}{\delta U_{LV}} \bigg|_{U_{HV}} = \frac{1}{a + 2 \cdot b \cdot U_{HV} + 3 \cdot c \cdot U_{HV}^2 + 4 \cdot d \cdot U_{HV}^3}. \tag{10}\]

The measurement of \(\tilde{M}\) at \(U_{HV}\) is done with the following procedure: at certain input voltages we increase \(U_{HV}\) by a small amount of \(\delta U_{HV}\) and measure the change of the output voltage \(\delta U_{LV}\). In the ideal case the voltage increase \(\delta U_{HV}\) is infinitesimal small in order to determine the slope of the scale factor curve at \(U_{HV}\). However, due to technical limitations and because of the ambition to trace the voltage measurement back to a 10 V reference, this is not possible. Hence, we increase the voltage by \(\delta U_{HV} = 1\) kV, which can be measured
with traceable equipment with ppm-precision. Therefore we assume, that the determined scale factor is valid for the input voltage $U_{HV} + \delta U_{HV}/2$. The two cases of the constant and voltage dependent scale factor are sketched in figure 4. Additionally $M$ is illustrated for an exemplary input voltage $U_{HV,0}$. By measuring the differential scale factor for different input voltages the coefficients $a, b, c$ and $d$ can be determined and used to calculate the scale factor $M$ for any given input voltage.

The measurement of $\tilde{M}$ is split into two steps: figure 5 shows the experimental set-up for the first step. A high voltage $U_{HV}$ is connected to the HV divider whose scale factor $M_B$ is to be calibrated. Its output voltage $U_2$ is measured with a precision DVM versus a very stable counter voltage $U_{HV}/M_A$ as a null volt measurement. By using a counter voltage instead of a measurement versus ground potential it is ensured, that the measured voltage is below 20 V, which can be traced back to a 10 V reference source. The counter voltage is either directly monitored with a third DVM $U_3$ or converted via a reference divider into the 0 to 20 V range. Additionally a second HV divider ($M_A$) is needed as reference for the unit under test, which is connected to the same HV source. The output voltage of the reference HV divider is also measured with a DVM $U_1$ versus the counter voltage. In this measurement the ratio of the scale factors $\mu$ can be determined applying Kirchhoff’s circuit laws. The approximation on the right of equation (11) is only valid for $U_1 \approx 0$ and should only illustrate that $\mu$ does not require a precise determination of $U_3$. This counter voltage is a key to achieve the ppm-precision for the novel absolute calibration method. The ratio $\mu$ can be measured with a short-term precision of the order of below $10^{-7}$ without knowing the single scale factors $M_A$ and $M_B$, since it only depends on the

$$\mu := \frac{M_A}{M_B} = \frac{U_2 + U_3}{U_1 + U_3} \approx \frac{U_2}{U_3}$$ (11)
measured voltages $U_{1,2,3}$, which are determined with precision DVMs. Since both null volt measurements $U_1$ and $U_2$ are measured with the same counter voltage, both scale factors have to be of similar magnitude in order to not exceed the 20 V range of the DVM.

In the second step the input voltage of the HV divider under test is increased by $\delta U_{\text{HV}}$, which is generated and measured on top of the HV potential $U_{\text{HV}}$ (see figure 6). The input voltage of the reference HV divider stays constant as well as the counter voltage, any potential change would be detected by continuously measuring $U_1$ and $U_3$. The DVM, which is used to measure the output voltage of the divider under test, will measure a voltage increase of $\delta U_{\text{HV}}/M_B$. For this as well as for all other used DVMs the measurement range has been kept fixed during the whole calibration procedure in order to avoid a change of input resistances and leakage currents.

According to Kirchhoff’s circuit- and Ohm’s laws the differential scale factor is given by

$$ \tilde{M}_B = \frac{U_1 \cdot M_A + U_4 \cdot M_C}{U_2 + (1 - \mu) \cdot U_3}. \quad (12) $$

As denoted in equation (12) the scale factor of the reference HV divider $M_A$ is needed to calculate $M_B$. However, the term $U_1 \cdot M_A$ is close to zero since $U_1$ is a null volt measurement against the stable counter voltage adjusted to $U_1 \approx 0$. Hence, the dominant factor of the numerator is $U_4 \cdot M_C$, which means, that the absolute value of $M_A$ needs to be stable but does not have to be known precisely in order to calibrate the unit under test to the ppm-level. The measurements, which are presented in the next section, showed, that an uncertainty of up to $1 \cdot 10^{-3}$ can be allowed for $M_A$, without changing the calibration result for $M_B$ on the $1 \cdot 10^{-7}$ level. Secondly, the uncertainty of $U_3$ is not important since the ratio of the scale factors $\mu$ is close to 1. Therefore $U_2$ and its uncertainty are dominating the denominator for the determination of $M_B$.

### 4. Calibration results for 100:1 scale factor

During a measurement campaign in early 2018 numerous calibrations of different HV dividers have been performed. The main goal was to check the reproducibility and long-term stability of the newly developed absolute calibration method as well as its capability to measure the voltage dependency of scale factors. The measurements were performed with two ppm-precise HV dividers K65 [14] and G35 [15], which were also used as reference mutually to crosscheck the results. In addition we built a HV divider with precision resistors [16] with a scale factor $M_A \approx 100 : 1$ and a relative uncertainty of in the order of $1 \cdot 10^{-5}$, which was used as reference unit (see figure 7). Commercial HV dividers [13] were used to measure the calibration voltage $\delta U_{\text{HV}}$ up to 1 kV. The voltage measurements were performed with 8.5 digit precision DVM [14]. Our HV source $U_{\text{HV}}$ and HV divider G35 were limited to 35 kV.

As described in section 3 the stability of the ratio-measurement of the scale factors has been investigated. In order to account for the warm-up behavior of the HV dividers, after applying the HV the measurements were not started immediately, but after about 30 min.

Figure 8 shows a single $\mu$ determination run consisting of 17 measurements before and 17 measurements after the calibration result for $U_{\text{HV}} = -18.6$ kV. As both scale factors are about 100:1, the ratio is close to one. The data has been fitted with a constant in order to determine the mean value. We did not use a polynomial of first order because of the smallness of the effect ($1 \cdot 10^{-8}$ level). Since for short time intervals only transfer uncertainties are known, which are valid for 20 min, we use the measured fluctuations in order to determine the statistical uncertainties for longer periods. Therefore the error bars are scaled such, that the quadratic deviation per number of degrees of freedom is equal to one ($\chi^2 = 1$). For the systematic uncertainties we determined the 24 h uncertainties of each DVM with a reference voltage source.

\[ \text{Figure 8. Exemplary measurement of the scale factor ratio } \mu \text{ of the unit under test and a reference HV divider measured at } U_{\text{HV}} = -18.6 \text{ kV. As both scale factors are about 100:1, the ratio is close to one. The data has been fitted with a constant in order to determine the mean value. We did not use a polynomial of first order because of the smallness of the effect (1 \cdot 10^{-8} \text{ level}). Since for short time intervals only transfer uncertainties are known, which are valid for 20 min, we use the measured fluctuations in order to determine the statistical uncertainties for longer periods. Therefore the error bars are scaled such, that the quadratic deviation per number of degrees of freedom is equal to one (} \chi^2 = 1\). \]
In order to determine its mean value, which according to equation (12) is needed to calculate the differential scale factor, the data has been fitted with a constant. As described in the previous section, the ratio can be determined without knowing the individual scale factors of both dividers with relative uncertainties smaller than $1 \cdot 10^{-7}$. Subsequently, $\tilde{M}_B$ has been measured according to figure 6. Here the measurement was directly started after $\delta U_{HV}$ was applied, since the increase of 1 kV is considered to be small compared to the absolute applied voltage and the additional thermal heating is expected to be negligible.

The differential scale factor was derived with equation (12), including the calculated mean $\mu$-value determined directly before and after the calibration measurement. Figure 9 shows a single measurement of the differential scale factor. The standard deviation is below $5 \cdot 10^{-7}$. The differential scale factor, always together with the ratio $\mu$, has been measured multiple times each day during the calibration campaign at different voltages. They agreed very well within uncertainties.

Figure 9. Exemplary measurement of differential scale factor determined with the newly developed absolute calibration method measured at $U_{HV} = -18.6$ kV. The data has been fit with a constant in order to determine the mean value. Since for short time intervals only transfer uncertainties are known, which are valid for 20 min, we use the measured fluctuations in order to determine the statistical uncertainties for longer periods. Therefore the error bars are scaled such, that the quadratic deviation per number of degrees of freedom is equal to one ($\chi^2 = 1$). For the systematic uncertainties we determined the 24 h uncertainties of each DVM with a reference voltage source.

Figure 10. Voltage dependency of the K65 100:1 scale factor determined with the newly developed absolute calibration method. The differential scale factors $\tilde{M}$ measured at different voltages (red points) and the low voltage scale factor $M_{1kV}$ (blue point) are fitted with a polynomial of first order (red line). The error-bars include the statistical and systematic uncertainties. The obtained coefficients are used to calculate the real scale factor $M$ for a voltage range from 0 to 35 kV (blue line).
In order to derive the real scale factor \( M_R \) from \( \tilde{M}_R \) we measured the differential scale factor for different voltages up to 35 kV (see figure 10 and 11) and fitted the data\(^{15}\) according to equation (10) to obtain the coefficients \( a, b, c \) and \( d \). We also included the low voltage calibration values measured as described in section 2 (see set-up in figure 2) into the analysis. Since in that measurements the real scale factor is determined, we used a combined fit to describe all data points\(^{16}\). Subsequently \( M_R \) is calculated using equation (9). For the K65

\(^{15}\)The data was fitted with MINUIT [17]

\(^{16}\)The fit function is a sum of equations (9) for the data point obtained with the low voltage calibration measurement and (10) for the data points of the differential scale factor determination.
The scale factor $M_A$ derived this way for the G35 HV divider showed deviations of up to $3.3 \cdot 10^{-6}$ at $-35$ kV compared to the low voltage scale factor $M_1$ kV. We cross-checked this by comparing the scale factor $M_B$ of G35 with the one measured directly with the help of K65 using a set-up as shown in figure 2 two months later. Thus, we could confirm the result obtained for the linearity measurement with the novel absolute calibration method. To get an excellent agreement the absolute value of the scale factor required a constant offset of $-2 \cdot 10^{-7}$ over the full range of $-35$ kV. This shift exceeds the combined short-term uncertainties (voltage dependent, average about $1 \cdot 10^{-7}$) for the real scale factor. However, we consider an additional relative uncertainty of $\pm 5 \cdot 10^{-7}$ for the absolute value of the scale factor to be realistic, since all previous low voltage- and high-voltage measurements showed this level of uncertainty, when repeated later on a time scale of weeks or months. Therefore it is reasonable to shift data points of measurements with a significant time difference (here more than 2 months for the comparison shown in figure 11) with a constant offset, in order to check the voltage dependency. For future HV measurements with the G35 the ppm-precise voltage-dependent scale factor obtained with the presented work in this article can be used considering the corresponding uncertainties.

We investigated also the long term stability of $\dot{M}$. Figure 12 shows the differential scale factor of the K65 HV divider measured over a time period of about 330 d. The scattering of the determined values of $\dot{M}$ is below $\pm 5 \cdot 10^{-7}$. Compared to the stability of the K65 of $2 \cdot 10^{-8}$ per month determined at PTB in 2011 (for the 100:1 scale factor), the results obtained with the newly developed absolute calibration technique are in good agreement, confirming the general principle and functionality of this method.

Our estimated uncertainty budget for the differential scale factor is shown in table 1. The overall relative uncertainties of about $4 \cdot 10^{-7}$ are mainly dominated by the two devices, which are operated on the HV potential (about 50%): the 1 kV reference divider and the corresponding DVM. Accordingly their calibration before the measurement is of crucial importance. Furthermore at this level of precision also the resistances of the cabling becomes relevant. Especially on the HV side of the set-up cable resistances, which can be in the order of 1 $\Omega$, can influence the calibration result when they are not

### Table 1. Estimated uncertainty budget for the systematic uncertainty of the differential scale factor with most important contributions (shown for an exemplary measurement). For all parameter values $p$ we considered a Gaussian distribution ($1 \sigma$) for the uncertainty $\Delta p$ (see section 4 for details about the used devices and their uncertainties). The contribution of each parameter is the product of the sensitivity coefficient ($\frac{\partial \Delta \dot{M}}{\partial \Delta p}$) and $\Delta p$. The relative importance of each contribution is calculated by $\frac{(\frac{\partial \Delta \dot{M}}{\partial \Delta p})^2}{\Delta \dot{M}}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value $p$</th>
<th>abs. uncertainty</th>
<th>Unit</th>
<th>Sensitivity coeff.</th>
<th>Contribution</th>
<th>rel. importance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_C$ DVM (see figure 6)</td>
<td>100.0000000</td>
<td>0.000017</td>
<td>V</td>
<td>1.01</td>
<td>0.000017</td>
<td>22.59</td>
</tr>
<tr>
<td>$U_4$ DVM (cal. with 10 V)</td>
<td>$-10.00000028$</td>
<td>0.0000012</td>
<td>V</td>
<td>$-10.05$</td>
<td>$-0.000012$</td>
<td>11.32</td>
</tr>
<tr>
<td>$U_4$ DVM ($M$, see figure 6)</td>
<td>$-10.00027489$</td>
<td>0.0000012</td>
<td>V</td>
<td>$-10.05$</td>
<td>$-0.000012$</td>
<td>11.32</td>
</tr>
<tr>
<td>$U_2$ DVM ($\mu$, see figure 5)</td>
<td>0.0935306</td>
<td>0.0000011</td>
<td>V</td>
<td>$-10.10$</td>
<td>$-0.000012$</td>
<td>10.67</td>
</tr>
<tr>
<td>$U_2$ DVM ($M$, see figure 6)</td>
<td>$-9.8580844$</td>
<td>0.0000011</td>
<td>V</td>
<td>$10.10$</td>
<td>0.000012</td>
<td>10.67</td>
</tr>
<tr>
<td>$U_2$ DVM (cal. offset)</td>
<td>$-0.0000067$</td>
<td>0.0000011</td>
<td>V</td>
<td>$-10.05$</td>
<td>0.000011</td>
<td>10.57</td>
</tr>
<tr>
<td>$U_2$ DVM (cal. with 10 V)</td>
<td>$-10.0000948$</td>
<td>0.0000011</td>
<td>V</td>
<td>$-10.05$</td>
<td>$-0.000011$</td>
<td>10.57</td>
</tr>
<tr>
<td>Other uncertainties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.000012</td>
<td>12.28</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>100.514876</td>
<td>0.000035</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Figure 13. Connection scheme for the corrected determination of $M_A'$. The input voltage $U_{HV}$ is connected to the scale factor output $M_A$ of the unit under test. The upper part of the HV divider with the resistors $R_i$ is loaded with the voltage $U_{load} = U_{HV} \cdot M_A$ created by an additional HV supply, which is operated on the potential of $U_{HV}$ in a HV cage. A second HV divider with the well known scale factor $M_B$ is used to determine $U_{HV}$. HV divider a negligible linearity below $1 \cdot 10^{-6}$ over the whole input range was observed, which is within the uncertainties in agreement with former calibration measurements at PTB [14]. Here a linear voltage dependency ($c = 0 = d$) was assumed for the fit, as indicated by $\chi^2$-studies of higher orders.


5. Calibration of higher scale factors

For the calibration of scale factors $M_A > 100 : 1$ the procedure similar to the one described in figure 3 can be used, but to load the resistors $R_i$ correctly, the corresponding HV is additionally given to the input of the HV divider under calibration using a HV cage (see figure 13). The wanted scale factor $M_A$ can be calculated according to equation (6). The critical scale factor $M_A \leq 100$ is determined with the novel absolute calibration method. Thus, the issues regarding traceability and the previously neglected voltage dependencies of $M_A$ and $M_A^\prime$ vanish.

6. Conclusion

Precision measurements of DC high voltages are important for different applications in fundamental research and applied sciences. In order to measure HV to the ppm-level precision HV dividers are used to scale the voltage into ranges below 20V, where they can be compared to voltage references traceable to natural standards at metrology institutes. The scale factors of HV dividers usually are voltage- and time dependent and have to be calibrated regularly. Former calibration methods could only consider this by extrapolating the voltage dependency of individual resistors. In this work we presented a newly developed absolute calibration method for HV dividers, which overcomes issues and allows a traceable calibration by determining a differential scale factor measured directly at high voltages. We have shown that the systematic uncertainty is in the order of less than $1 \cdot 10^{-6}$. This method can be performed with commercially available equipment and therefore is not restricted to metrology institutes, but offers measurements of linearity of HV dividers with ppm-precision for a wide range of applications. A comparison of this work and other, recently developed calibration techniques is given in [18].

There are also investigations to apply this method in order to measure the linearity behaviour of precision compressed gas HV capacitors.

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17 The used reference HV divider Fluke 752A has an input resistance of 2 MΩ. This means, that a cable resistance in the order of 1 Ω can influence the calibration result on the ppm-level. However, this is more important for the low voltage calibration described in section 2, since the effect nearly cancels out in the two steps of the differential scale factor measurement of the novel absolute calibration method.