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TECHNICAL REPORT

Aspects and understanding of measurement uncertainty – Background information on measurement uncertainty based on the example of IEC TC 85 (Measuring equipment for electrical and electromagnetic quantities)

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CONTENTS

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ASPECTS AND UNDERSTANDING OF MEASUREMENT UNCERTAINTY –

Background information on measurement uncertainty based on the example of IEC TC 85 (Measuring equipment for electrical and electromagnetic quantities)

FOREWORD

IEC TR 63519 has been prepared by IEC technical committee TC 85: Measuring equipment for electrical and electromagnetic quantities. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
85/918/DTR	85/927/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

ASPECTS AND UNDERSTANDING OF MEASUREMENT UNCERTAINTY –

Background information on measurement uncertainty based on the example of IEC TC 85 (Measuring equipment for electrical and electromagnetic quantities)

1 Scope

This document provides information on terminology and general concepts in the determination of measurement uncertainties (MU). It focuses on application aspects based on the example of IEC TC 85 (Measuring equipment for electrical and electromagnetic quantities) and shows the opportunities and implications for further use of measurement uncertainties.

Measurement uncertainties are relevant for metrological compatibility and metrological traceability. Therefore, information on the role of measurement uncertainty in decisions or conformity assessments is given.

References to documents, standards and guidelines are made but only key results will be stated.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
probability distribution
function giving the probability that a random variable takes any given value or belongs to a given set of values

[SOURCE: IEC 60050-103:2009, 103-08-07]

3.2
distribution function
function f of the argument x giving the probability $f(x)$ that the value ξ of a random variable be less than or equal to the value x, i.e. the probability that $\xi \leq x$

[SOURCE: IEC 60050-103:2009, 103-08-08]

3.3
probability density
probability density function
PDF
for the distribution function f of the argument x, derivative $\mathrm{d}f(x)$ / $\mathrm{d}x$

[SOURCE: IEC 60050-103:2009, 103-08-09]

3.4
calibration
set of operations which establishes, by reference to standards, the relationship which exists, under specified conditions, between an indication and a result of a measurement

Note 1 to entry: This term is based on the "uncertainty" approach.

Note 2 to entry: The relationship between the indications and the results of measurement can be expressed, in principle, by a calibration diagram.

[SOURCE: IEC 60050-300:2001, 311-01-09]

3.5
metrological compatibility of measurement results
metrological compatibility
property of a set of measurement results for a specified measurand, such that the absolute value of the difference of any pair of measured quantity values from two different measurement results is smaller than some chosen multiple of the standard measurement uncertainty of that difference

Note 1 to entry: Metrological compatibility of measurement results replaces the traditional concept of 'staying within the error', as it represents the criterion for deciding whether two measurement results refer to the same measurand or not. If in a set of measurements of a measurand, thought to be constant, a measurement result is not compatible with the others, either the measurement was not correct (e.g. its measurement uncertainty was assessed as being too small) or the measured quantity changed between measurements.

Note 2 to entry: Correlation between the measurements influences metrological compatibility of measurement results. If the measurements are completely uncorrelated, the standard measurement uncertainty of their difference is equal to the root mean square sum of their standard measurement uncertainties, while it is lower for positive covariance or higher for negative covariance.

[SOURCE: ISO/IEC Guide 99:2007, 2.47]

4 Role of the measurement uncertainty

4.1 General

Measurements are subject to influences. Although a single value is measured, the result is an interval of possible values. The measurement uncertainty comes into place in order to define the limits of this interval and give a number to this imperfection.

EXAMPLE Measurement of a voltage of 1 V with a resolution of 1 mV on a digital display. Reading a value of 1,000 V would lead to an interval from 0,999 50 V to 1,000 49 V if only the resolution is considered (see Figure 1). The reading of 1,000 V is in the middle of the interval with a width given by the resolution. It is assumed that the resolution of the display corresponds to the last significant digit of the device.

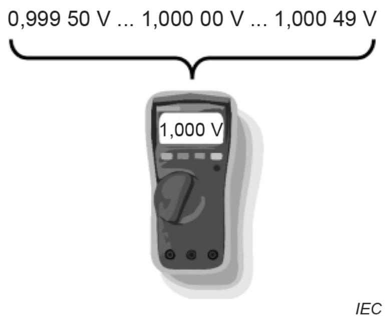

Figure 1 – Measurement of a voltage of 1 V with a resolution of 1 mV on a digital display

When it comes to the determination of the measurement uncertainty, the Guide to the expression of uncertainty in measurement (GUM, [ISO/IEC GUIDE 98-3:2008]) represents a statistical approach with the possibility to combine different influence quantities. The GUM requires the knowledge of the probability density function (PDF, see 3.3) of those influence quantities. It is not always possible to determine or even know all influence quantities together with their PDF. However, the analysis of the measurement process will consider at least the most dominant ones. Otherwise, it is not possible to have a reliable result for the measurement uncertainty.

EXAMPLE For displaying devices, the resolution is an influence quantity. Its PDF is given by a rectangular (uniform) distribution, since all values in the interval are equally probable (see Figure 2).

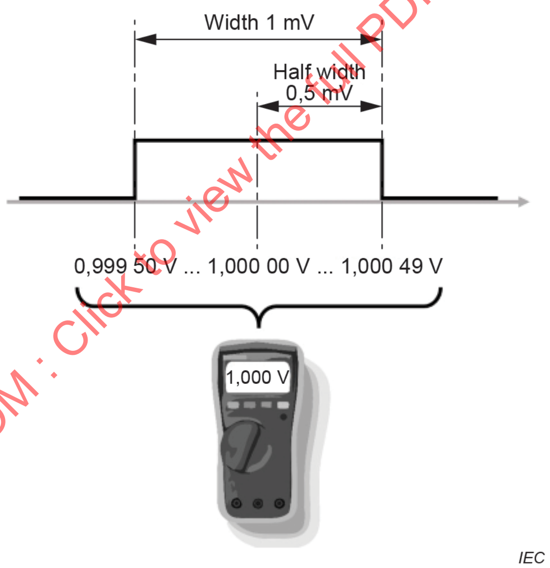

Figure 2 – Rectangular (uniform) distribution for the resolution when measuring a voltage of 1 V with a resolution of 1 mV on a digital display

The measured quantity is a function of the influences, and since each influence quantity has an associated PDF, the measured quantity itself is described by a PDF. Typically, this PDF is considered to be a normal distribution[1]. The normal distribution is characterized by its most probable value (e.g. measured value) and its standard deviation (std. dev.). The latter is a measure of the variation and thus also of the width of this normal distribution. The measurement uncertainty is expressed in multiples (coverage factor) of the standard deviation (see Figure 3). Usually, a coverage factor of $k = 2$ is used as this corresponds to a confidence level of approximately 95 %.

1 According to the central limit theorem, the linear summation of an infinite number of arbitrary PDF (thus also rectangular distributions) ends up in a normal distribution. The normal distribution is also known as Gaussian distribution.

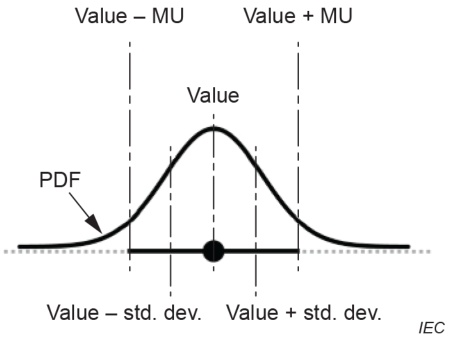

Figure 3 – Value and assigned measurement uncertainty (MU) together with its probability density function (PDF)

Expressions like specification, tolerance, class, precision, error, maximum permissible error or accuracy usually do not provide any information about the underlying shape of a PDF. Moreover, the measurement uncertainty is always assigned to a measured value and manifests the conditions (e.g. measuring process, environmental conditions, impacts of the measuring person) that lead to the measured value, whereas specifications or tolerances are assigned to a device or system and do not change. This means specifications or tolerances represent fixed limits (e.g. guaranteed by a manufacturer or defined by a standard) and the position with respect to these limits of the measured value, together with its measurement uncertainty, can be used for further decisions (see 4.3).

4.2 Compatibility

Without the consideration of the measurement uncertainty, two measurement results will be in agreement only if the two numbers are the same digit by digit. Therefore, the compatibility of two different measured values for the same measurement is not obvious. As pointed out earlier, every measurement value has its measurement uncertainty. This means the result of a measurement is a range of possible values rather than a single value. An agreement can be achieved if the two measured values are (metrological) compatible (see 3.5) with respect to their measurement uncertainties, i.e. the two ranges overlap. The larger the overlap, the higher the probability that the two results comply.

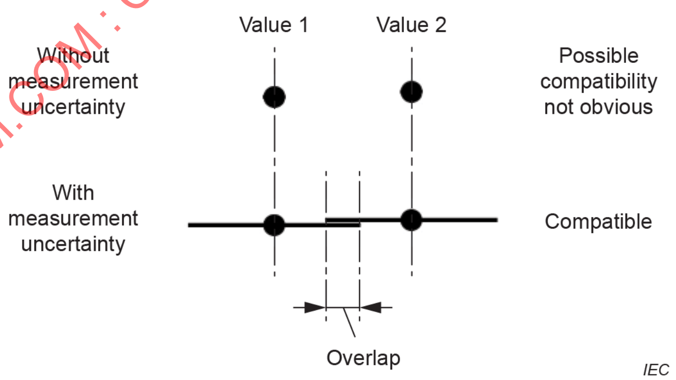

Figure 4 – Compatibility of two measured values with or without measurement uncertainty

A graphical comparison of the overlap as shown in Figure 4 can support a general understanding of the topic but does not reflect statistical considerations.

Typically, this comparison is done mathematically through defined quality factors that consider the statistical properties of the measurement uncertainties (e.g. coverage factor, confidence level and correlations).

The probability of two values being equal or not can only be assessed by the knowledge of the PDF of each measurement uncertainty. The area $P(A)$ shown in Figure 5 represents approximately the probability that both values are in the overlap region. Although these two values seem to be in agreement, since their measurement uncertainties overlap, the probability that they do not coincide is approximately $1 - P(A)$. The determination of the probability is more complex than shown and requires statistical methods.

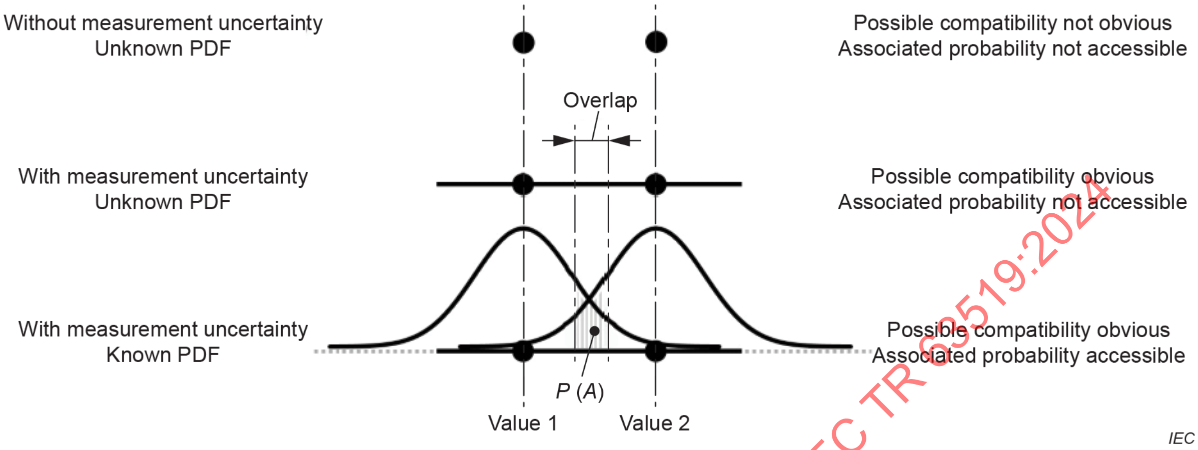

Figure 5 – Probability of compatibility of two values

4.3 Probability of false acceptance or probability of false rejection

Considering the assumed PDF gives the possibility of determining the probability of false acceptance (PFA) or probability of false rejection (PFR) when comparing a measurement result to a specified limit.

With the possibility to state whether the value is less than, greater than or equal to the limit, the decision in tolerance (acceptance) or not in tolerance (rejection) can be made (conformity assessment). The decision seems clear at first glance, yet it is not obvious whether a PFA or PFR is associated with this decision. Only by taking the measurement uncertainty into account can it become obvious that a PFA or PFR is present. This is the case when e.g., the value is less than the upper limit, but the measurement uncertainty exceeds the limit (see Figure 6). Nevertheless, assigning a number to the probability is only accessible with the PDF of the determined measurement uncertainty. As shown in Figure 6 the area $P(A)$ represents the probability that the decision ("in tolerance") is correct. The PFA is given by $1 - P(A)$. In Figure 6 the PFA is the white area under the PDF that exceeds the limit.

Where further information is required regarding the mathematics, see e.g. ISO/IEC Guide 98-4:2012 or more specifically on decision rules, see e.g. ILAC-G8:09/2019.

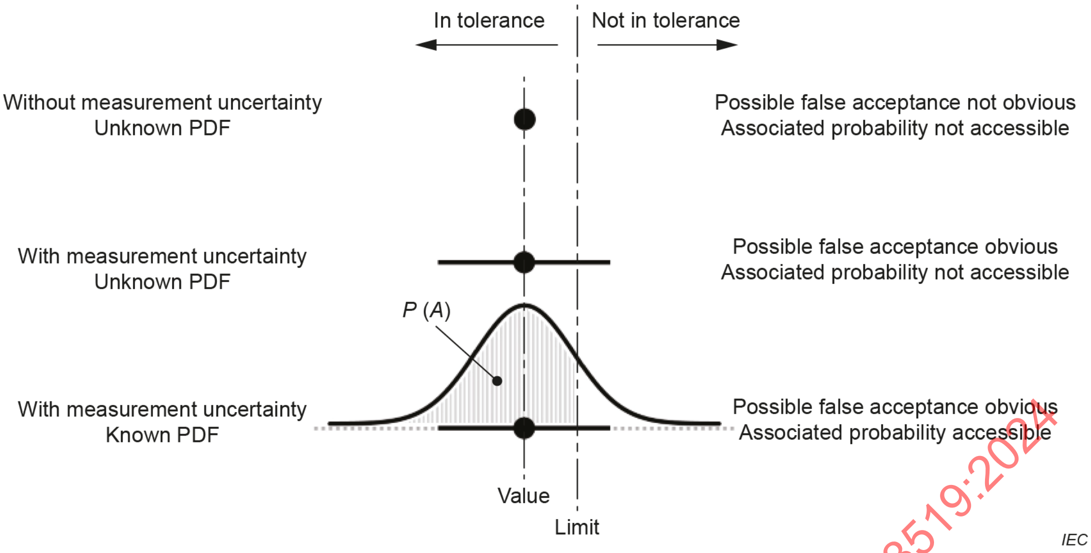

Figure 6 – PFA, given by 1 − $P(A)$, for the in tolerance decision when comparing a value to a limit

4.4 Metrological traceability

Metrological traceability to an SI unit or to primary standards cannot be established without knowing the measurement uncertainty of each level within the metrological traceability pyramid (see Figure 7). To establish metrological traceability to the next higher level, a comparison (calibration, see 3.4) to the higher level (reference) standard is required.

As described in 4.1 and 4.2, each measurement result comes with a measurement uncertainty. Within the metrological traceability pyramid, the deviation of the measured value from the reference and the measurement uncertainty are passed on and are the starting point of the subsequent measurement uncertainty determination. Hence, the resulting measurement uncertainty inherits all measurement uncertainties of the higher level(s) of the metrological traceability pyramid. Therefore, the measurement uncertainty of a lower level device will never be better than the higher level reference used during the calibration.

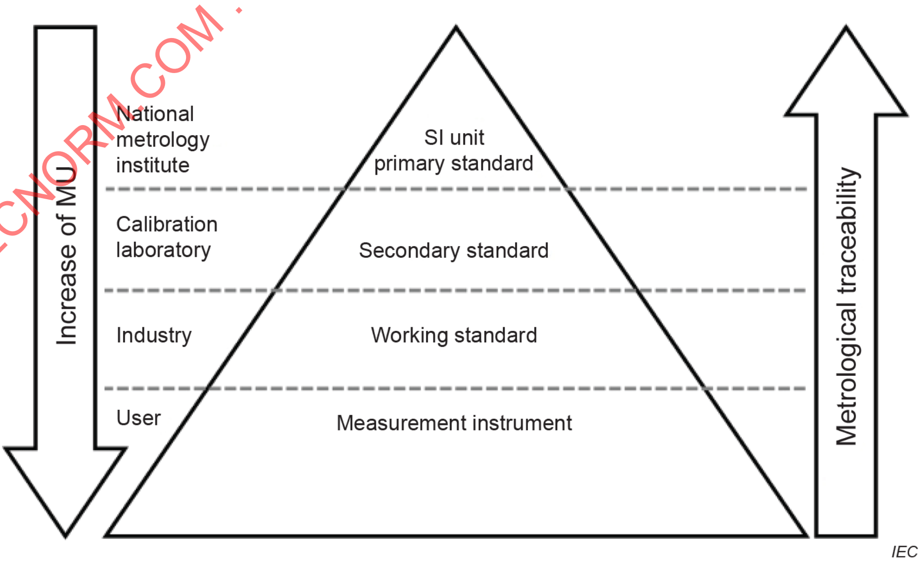

Figure 7 – Pyramid of metrological traceability

4.5 Improvement (influence quantities)

As emphasized in the previous clauses, the full information about a measurement is given by the measured value and its measurement uncertainty as the parameter that considers all known influence quantities. The analysis of the influence quantities opens the possibility of better understanding the measurement process and for improvement. The numerical comparison (ideally of the standard uncertainties) of the influence quantities enables the knowledge of the dominating influence quantities. The improvement (i.e. minimisation) of those dominating influence quantities will have the most significant impact.

4.6 Conclusions

The knowledge of the measurement uncertainty including its PDF opens up the possibility of well-founded comparison (see 4.2 and 4.3), metrological traceability (see 4.4) and improvement of the measurement (see 4.5). By neglecting the measurement uncertainty, those possibilities are limited.

Table 1 shows the importance of the measurement uncertainty for different stakeholders whose emphasis might vary depending on the above-mentioned possibilities.

Table 1 – Role of the measurement uncertainty for different stakeholders

Stakeholder	Usage/Importance of the measurement uncertainty	Reference
Calibration provider	Recipient and provider for metrological traceability.	4.4
	Analyse and improve calibration procedures.	4.5
	Provider of conformity assessment.	4.3
	Validation and verification of calibration procedures and measurement uncertainties through proficiency testing.	4.2
Design engineer (manufacturer)	Verification and improvement of designed equipment, by comparing a resulting measurement uncertainty (from models or prototypes) to specific demands (e.g. normative requirements).	4.3, 4.5
Test engineer	Validation of test equipment by sending it to reference laboratories. The test equipment has to fulfil specific requirements and therefore a conformity assessment by the calibration provider is needed. A positive conformity assessment for the used test equipment to specific requirements can lead to neglecting further measurement uncertainty considerations. The measurement uncertainty when using the test equipment, i.e. including all influence quantities during the test, can play a role in fulfilling (normative) requirements.	4.2, 4.3
End user	A positive conformity assessment for the used equipment to specific requirements leads to neglecting further measurement uncertainty considerations.	

5 Example: Insulation resistance IEC 61557-2:2019

5.1 Concept (IEC 61557-1:2019)

NOTE All terms and definitions of IEC 61557-1:2019 apply to the example from IEC 61557-2:2019 (e.g. "operating uncertainty", "intrinsic uncertainty").

In IEC 61557-1, the term operating uncertainty B is defined and represents a worst-case approach when it comes to estimating and considering all relevant variations E_{i} due to the influence quantities i. For traceability purposes, the intrinsic uncertainty A is the basis for the operating uncertainty. Possible variations due to influence quantities are mentioned in IEC 61557-1 together with a formula in order to combine these variations with the intrinsic uncertainty:

$$B = \pm\sqrt{A^2 + \frac{4}{3}\sum_i E_i^2} \tag{1}$$

where

A is the intrinsic uncertainty with a normally distributed PDF and a coverage factor of k = 2;

E_i is the half width of an assumed rectangular PDF for the variation due to the influence quantity i (worst-case approach);

B is the operating uncertainty with a normally distributed PDF and a coverage factor of k = 2.

Formula (1) shows the square root of a quadratic sum of all considered components (intrinsic uncertainty A and variations E_i). In order to follow the GUM, the half widths E_i have to be scaled by a factor of 1/√3 coming from the assumption of a rectangular PDF. A factor 2 is also needed for the variations' half widths in order to obtain a coverage factor of k = 2 for the resulting operating uncertainty. This leads to a factor of 4/3 = $(2 / \sqrt{3})^2$ under the square root. Furthermore the consistency is only guarantied if all components (intrinsic uncertainty A and variations E_i) are in the same unit as the resulting operating uncertainty B. Within the framework of IEC 61557-1, this is ensured by the particular definition of the variations containing the required consideration of the sensitivity coefficients (see GUM).

According to IEC 61557-1, the operating uncertainty is converted into a relative expression in percent, defined as fiducial uncertainty or percentage operating uncertainty, by dividing the operating uncertainty by the IEC 61557-1-defined fiducial value F and multiplying it by 100 %:

$$B_{\%}(F) = \frac{B}{F} \cdot 100\ \% \tag{2}$$

where

F is the fiducial value;

$B_{\%}(F)$ is the fiducial uncertainty or percentage operating uncertainty (in percent)[2].

Further background information is given in IEC 61557-1:2019, Annex A.

5.2 Calculation

IEC 61557-2:2019, Table 1, gives all relevant contributions to determine the operating uncertainty when measuring the insulation resistance. The following calculation presents example values for the intrinsic uncertainty and the variations.

2 For consistency reasons and in order to show the dependency on the fiducial value F, the variable was renamed to $B_{\%}(F)$ and the "±" was removed from the formula.

Table 2 – Example calculation for the percentage operating uncertainty for the fiducial value F = 8 MΩ

Intrinsic uncertainty or influence quantity	Variable	Example value
Intrinsic uncertainty	A	0,050 MΩ
Position	E_1	0,10 MΩ
Supply voltage	E_2	0,50 MΩ
Temperature	E_3	0,50 MΩ

With the example values from Table 2, we obtain the following for Formula (3):

$$\begin{aligned} B &= \pm\sqrt{(0{,}050\ \text{M}\Omega)^2 + \frac{4}{3}\left((0{,}10\ \text{M}\Omega)^2 + (0{,}50\ \text{M}\Omega)^2 + (0{,}50\ \text{M}\Omega)^2\right)} \\ &= \pm\sqrt{0{,}002\,5\ \text{M}\Omega^2 + \frac{4}{3}\left(0{,}01\ \text{M}\Omega^2 + 0{,}25\ \text{M}\Omega^2 + 0{,}25\ \text{M}\Omega^2\right)} \\ &= \pm\sqrt{0{,}002\,5\ \text{M}\Omega^2 + \frac{4}{3}\left(0{,}51\ \text{M}\Omega^2\right)} \\ &= \pm\sqrt{0{,}002\,5\ \text{M}\Omega^2 + 0{,}68\ \text{M}\Omega^2} \\ &= \pm\sqrt{0{,}682\,5\ \text{M}\Omega^2} \approx \pm\,0{,}826\ \text{M}\Omega \end{aligned} \qquad (3)$$

This unrounded[3] result is then used in Formula (4) to calculate the percentage operating uncertainty relative to the fiducial value F = 8 MΩ:

$$B_{\%}\left(F = 8\ \text{M}\Omega\right) = \frac{\pm\sqrt{0{,}682\,5\ \text{M}\Omega^2}}{8\ \text{M}\Omega}\cdot 100\ \% \approx \frac{\pm 0{,}826\ \text{M}\Omega}{8\ \text{M}\Omega}\cdot 100\ \% = \pm\,10{,}325\ \% \qquad (4)$$

Usually, the final result of the measurement uncertainty is rounded to a limited number of digits. According to GUM a number of two significant digits is the best way to do so. Following this rule the percentage operating uncertainty for the fiducial value F = 8 MΩ is ±10 % as shown in Formula (5):

$$B_{\%}\ (F = 8\ \text{M}\Omega) = \pm 10\ \% \qquad (5)$$

5.3 Conclusions

The concept and the calculation method described in IEC 61557-1 and used in IEC 61557-2 give a framework that provides an operating uncertainty that has all necessary characteristics of a measurement uncertainty for comparison (see 4.2 and 4.3), metrological traceability (see 4.4) and improvement (see 4.5).

3 Rounding is only considered for the final result. Rounding in intermediate steps can cause additional errors in the final result.

It is important to note that the underlying assumptions about the PDF and coverage factor for the intrinsic uncertainty A and the variations E_i are decisive as to whether the final result is also a measurement uncertainty that conforms to the GUM. This includes the requirement for an intrinsic uncertainty A, which is provided by a traceable calibration together with the consideration of all relevant variations E_i given in IEC 61557-2.

6 Further examples

IEC Guide 115:2023 gives further examples in its Clause A.3 together with general background information on the determination of the measurement uncertainty. In particular, examples with influence quantities described by PDF other than rectangular assumed distributions.

ISO/IEC Guide 98-3:2008, Annex H contains more advanced examples on the determination of the measurement uncertainty.