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The Role of Measurement Uncertainty in the Decision Making for Testing and Inspection

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***Abstract* – In this paper is analysed the influence of the expanded uncertainty in the conformity assessment based on the international standards and documents. The different approaches for the calculation of combined standard uncertainties are given, based both on the worst possible consideration up to the implementation of corrections as appropriate. Furthermore, the influence of the effective degrees of freedom and *t*-distribution is pointed as well. The calculations are presented on the example of the testing and/or inspection of the current instrument transformers test for accuracy.**

Keywords* – *Measurement uncertainty, Decision Making, Testing, Inspection, Instrument Transformers

I. INTRODUCTION

The role of testing and inspection, generally speaking, is to measure one or more properties of the object of interest (such as, for instance, instrument transformer, energy meter or some other measuring instrument or system), to give measurement result associated to the measurand (for instance, the ratio error and phase displacement for a current instrument transformer), and to make a judgment about whether this measuring system meets relevant standards and fulfill specified requirements. That is to say, we are talking about conformity assessment [1].

In VIM [2], the measurement result is defined as "set of quantity values being attributed to a measurand together with any other available relevant information", and is generally expressed as a single measured quantity value and a measurement uncertainty [3, 4]. Furthermore, the measurement uncertainty is defined as "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used". It is easy to conclude that the measurement result without expressed measurement uncertainty is incomplete and, as such, cannot fulfill the basic requirement: to be a reference on which decision-making processes should be based.

Although this first conclusion was easy and obvious, the question arises when measurement uncertainty has to be determined and expressed. GUM [4] is the reference international document covering this field, and gives the common principles, guidelines, formulas, and examples about the calculation of measurement uncertainty. However, in the implementation of principles into the routine laboratory practise, many laboratories involved in the accreditation scheme according to the standard ISO/IEC 17025:2017 [5] for testing and calibration laboratories, or ISO/IEC 17020:2012 [6] for inspection bodies, will be faced with the same problems: (i) how to calculate this parameter for "my problem"? (ii) is the calculated uncertainty appropriate? and (iii) how this influences the decision making process [7, 8].

This paper aiming to emphasize the role of the determination of the measurement uncertainty, based on the definition of measurand, selection of the measurement method, limits of the used equipment and its calibration, and verification of the uncertainty contributions. By following such approach the testing laboratories or inspection bodies can assure that they are doing correct measurements and making correct decisions.

II. GUARD BANDS AND DECISION RULES

In conformity assessment a measurement result is used to decide if an item or object of interest conforms to a specified requirement. Although such requirement could be given in different forms, here the frequent case will be considered when it is in the form of a Tolerance Interval (TI), which "defines interval of permissible values of a property". The tolerance interval is defined by the Tolerance Limit (TL), called also Specification Limit, which are "specified upper or lower bound of permissible values of a property" [7]. Frequently TI is defined by tolerance limits specified as symmetrical (±) bounds around the nominal value.

Therefore, if the true value of the property lies within the tolerance interval, one may say for particular property that conforms to a specified requirement so an item or object can be accepted, or non-conforms if otherwise, having the rejection of an item or object as a consequence. The problem lies in our inability to make perfect measurements and to determine *the true value of the property* (i.e. measured quantity or measurand), marked with Y. All we can do is to determine y, the measured quantity value which denotes ***the best estimate*** of Y, and to determine ***the interval*** in which the true value lies with high probability P, defined by the expanded uncertainty U_P. In that case the following can be written:

$$y - U_P \leq Y \leq y + U_P. \tag{1}$$

The existence of uncertainty in measurement could lead to incorrect decisions, which could be of two types: the first one is that an item accepted as conforming may actually be non-conforming, while the second one is that an item rejected as non-conforming may actually be conforming. From the risk assessment it could be considered that incorrect decisions have probabilities which can differ for the supplier (α) and for the consumer (β) in the same case. The problem is that both incorrect decisions imply costs and risks, so the decisions have to be taken carefully.

This lead to the definition of Acceptance Interval (AI), which is "interval of permissible measured quantity values", defined by Acceptance Limit (AL), which are "specified upper or lower bound of permissible measured quantity values" [7]. To define AI there are both lower and upper bound marking the acceptance limits, and frequently they are defined as symmetrical (±) bounds around the nominal value. If there is no additional explanation or exclusion, the acceptance limits belong to the acceptance interval.

Taking into consideration TL and AL, the Guard Band (w) is defined as interval between a tolerance limit and a corresponding acceptance limit:

$$w = |TL - AL|. \tag{2}$$

Guard bands are used to reduce the probability of making an incorrect conformance decision by reducing the acceptance limit below that of the tolerance limit to account for measurement uncertainty.

In the clause 3.7 of the standard ISO/IEC 17025 [5] a decision rule is defined as "a rule that describes how measurement uncertainty will be accounted for when stating conformity with a specified requirement". These decision rules are different and can be based on different requirements (or cases); in EUROLAB documents [9, 10] decision rules, applied to conformity assessment, are defined and divided as follows:

1. With a single tolerance without guard band
2. With single tolerance and guard band
3. With a tolerance interval without guard band
4. With a tolerance interval and guard band

In the above mentioned documents the decision rule is a binary one, which means that the result is limited to two choices: *pass* or *fail*. Due to the fact that in ILAC document [7] are pointed some similar decision rules, a common analysis for both of them will be given. A common case and our interest as well, is the decision rule based on the tolerance interval, so the further analysis has been done only for these cases. In ILAC document [7] it can be found the following:

1. Binary Statement for Simple Acceptance Rule (w = 0) – the same as no. 3 of EUROLAB documents.

Statements of conformity are reported as:

Pass	The measured value is below the acceptance limit, $AL = TL$
Fail	The measured value is above the acceptance limit, $AL = TL$

2. Binary Statement with Guard Band ($w = U_{95}$)* – the same as no. 4 of EUROLAB documents.

Statements of conformity are reported as:

Pass	Acceptance based on guard band; the measurement result being below the acceptance limit, $AL = TL - w$
Fail	Rejection based on guard band; if the measurement result is above the acceptance limit, $AL = TL - w$

*Note: index "95" point out the probability of 95 %.

3. Non-binary Statement with Guard Band ($w = U_{95}$) – this rule is not given in EUROLAB documents; it is graphically presented in Fig. 1.

Statements of conformity are reported as:

Pass	The measured result is below the acceptance limit, $AL = TL - w$
Conditional Pass	The measured result is inside the guard band and below the tolerance limit, in the interval $[TL - w, TL]$
Conditional Fail	The measured result is above the tolerance limit but below the tolerance limit added to the guard band, in the interval $[TL, TL + w]$
Fail	The measured result is above the tolerance limit added to the guard band, $TL + w$

In Fig. 1 a non-binary statement with a guard band is presented, where the tolerance limits (TLs) are given as symmetrical (±) bounds around the nominal value, they are marked as upper specification and lower specification limit, and this forms the tolerance interval (TI). Similarly, the acceptance interval (AI) is defined by upper acceptance limit and lower acceptance limit. What is important for our analysis is the definition of the guard band w equal to the expanded uncertainty, $w = U_{95}$, where index "95" point out the probability of 95 %. If one assume that the distribution of values that reasonably could be attributed to Y (i.e. the probability density function – PDF) is the normal (Gauss) distribution, which is discussed further in section III, the probability for a random value to be outside of the interval $y \pm U_{95}$ is 5 %, and this random value could be *the true value of the property* (i.e. measurand). For instance, if y is equal to the upper AL, then the value of $y + U_{95}$ is equal to the upper TL, the condition $AL = TL - w$ would be fulfilled and the associated statement of conformity would be "Pass". However, there is still a chance that measured quantity lies above the TL and the probability of such scenario is 2.5 %; actually, this is the associated value of the PFA (Probability of False Accept) parameter for such case. In other words, the item is accepted but should not be accepted.

From the previous analysis it can be concluded that the calculation of the expanded uncertainty has an important part in the decision making process and that the careful attention has to be paid to its calculation.

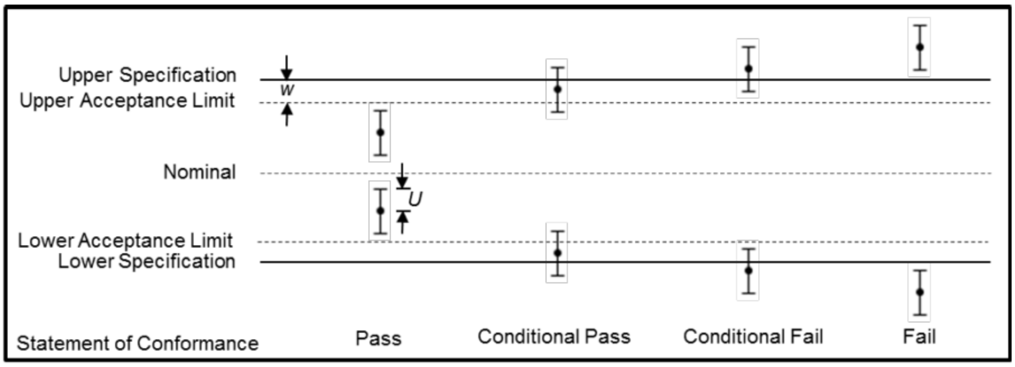

Fig. 1. Graphical representation of a non-binary statement with a guard band (shown for w = U, where U = U_{95}); further explanations are given in the text – the picture is taken from [7]

III. DETERMINATION OF EXPANDED UNCERTAINTY

A common procedure used for conformity assessment should have the following steps for a tested item:

1. Definition of a measurand Y
2. Determination of y (as the best estimate of Y)
3. Calculation of the combined standard uncertainty $u_c(y)$
4. Calculation of the expanded uncertainty U_P for a calculated $u_c(y)$ and a chosen probability P
5. Specification of the tolerance interval, acceptance interval and guard zone
6. Application of the chosen decision rule
7. Reporting of the statements of conformity

The attention in the following sections will be on the points 3 and 4 listed above, applying the approach defined and given in GUM [3].

A. Calculation of the combined standard uncertainty $u_c(y)$

The best estimate of the measurand, y, is based on the best estimates x_i of the input quantities $X_i \dots X_N$:

$$y = f(x_1, x_2, \dots, x_N), \tag{3}$$

where the function f represent the mathematical model of the measurand, which rarely can be explicitly (completely) known The $u_c(y)$ is estimated standard deviation associated to y, called the combined standard uncertainty, and determined on the basis of the estimated standard uncertainties $u(x_i)$ of the input quantities x_i. For independent input quantities (here we would not take into the consideration possible correlation between them, for simplicity) the **combined standard uncertainty** $u_c(y)$ is the positive square root of the combined variance $u_c^2(y)$:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)}. \tag{4}$$

The partial derivatives $\partial f/\partial x_i = c_i$ are called sensitivity coefficients and describe how the output estimate y varies with changes in the values of the input estimates.

B. Calculation of the expanded uncertainty U_P

The **expanded uncertainty** is calculated as follows:

$$U_P = k_P \cdot u_c(y), \tag{5}$$

where k_P is the coverage factor and "P" in index refers to the associated level of confidence (probability P). The factor k_P depends on the distribution of the output quantity y, and when the approximation with the normal distribution is justifiably (a common case) $k_P \in [2, 3]$; i.e. for $k_P = 2$ a level of confidence is approximately 95 % (exactly for $k_P = 1.96$), while for $k_P = 3$ it is approximately 99 %. This is valid and can be taken as first approximation if $u_c(y)$ is not dominated by a component of type A, based on only a few observations, or a component of type B with rectangular distribution.

Suggested better approach is based on the fact that the distribution of the variable $(y - Y) / u_c(y)$ can be approximated by the t-distribution for the effective degree of freedom ν_{eff}, which is calculated by the Welch-

Satterthwaite's formula:

$$\nu_{\text{eff}} = \frac{u_c^4(y)}{\sum_{i=1}^{N}\left[\frac{u_i^4(y)}{\nu_i}\right]} \tag{6}$$

Here is denoted $u_i(y) = c_i\, u(x_i)$. Expanded uncertainty, instead by (5), is then calculated using the formula:

$$U_P = t_P(\nu_{\text{eff}}) \cdot u_c(y), \tag{7}$$

where t_P is the parameter of t-distribution. The given equations will be used in the example of calculations presented in the following section.

IV. EXAMPLE OF THE TESTING (AND INSPECTION) OF CURRENT INSTRUMENT TRANSFORMERS

The routine tests in testing of Current instrument transformers (CITs) have to be done according to the standard IEC 61869-1:2007 [11] and IEC 61869-2:2012 [12], both clause *7.3 Routine tests*, while the inspection of CIT have to be done according to the same standards, but limited only to the clause *7.3.5 Test for accuracy*.

Determination of the accuracy of CIT generally is based on the calibration of the ratio error ε and phase displacement $\Delta\varphi$. Calibration is based on the comparison of the tested transformer (TCIT) to the reference current instrument transformer (RCIT) by means of the measuring bridge (MB), as shown in Fig. 2. The primary winding of RCIT must be connected in series with the primary winding of TCIT, and both transformers should be set on the same ratio. The secondary currents of RCIT and TCIT are compared by MB on which direct reading of the ratio error (ε_{MB}) and phase displacement ($\Delta\varphi_{\text{MB}}$) are obtained. In this example in further text we will concentrate only on the ratio error.

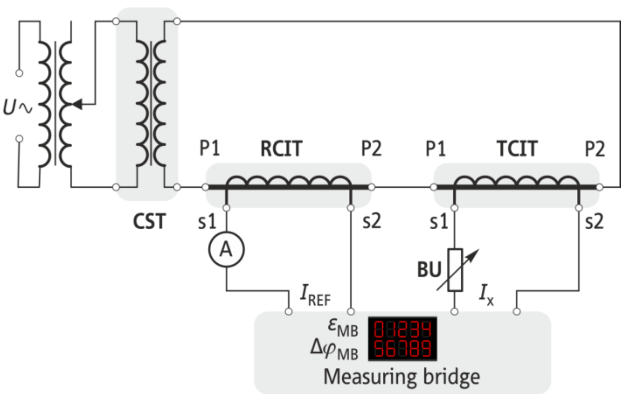

Fig. 2. The method and measurement set-up for the test for accuracy of a current instrument transformer

The nominal current ratio is equal to $K_n = I_{1n} / I_{2n}$, where I_{1n} and I_{2n} stands for nominal primary and secondary current, respectively. The ratio error, usually expressed in percentage, is defined as:

$$\varepsilon = \frac{K_n I_2 - I_1}{I_1} 100\ \%. \tag{8}$$

Mathematical model should emphasize all possible input quantities which have an influence on the measurement result, and is given as follows:

$$\varepsilon_X = \varepsilon_{\text{MB}} + \delta\varepsilon_{\text{MB}} + \delta\varepsilon_{\text{MBCAL}} + \delta\varepsilon_{\text{REF}} + \delta\varepsilon_{\text{REFCAL}} + \delta\varepsilon_{\text{BU}} + \delta\varepsilon_{\text{I}} + \delta\varepsilon_{\text{E}}. \tag{9}$$

They are given in percentage, and their meaning is:

ε_X … the measurand - the ratio error of the tested current instrument transformer (TCIT);

ε_{MB} … direct reading of the ratio error on MB, defined as arithmetic mean of n readings;

$\delta\varepsilon_{\text{MB}}$ … correction due to the specifications of MB;

$\delta\varepsilon_{\text{MBCAL}}$ … correction due to the calibration of MB;

$\delta\varepsilon_{\text{REF}}$ … correction due to the specifications of RCIT;

$\delta\varepsilon_{\text{REFCAL}}$ … correction due to the calibration of RCIT;

$\delta\varepsilon_{\text{BU}}$ … correction due to the influence of the used burden (which includes the accuracy of the burden, its change with the load, etc.);

$\delta\varepsilon_{\text{I}}$ … correction due to the settings of the set-up (includes the repeatability of the current setting in measuring points, influence of the connecting cables, distortion of the current source, parasitic elements, etc.);

$\delta\varepsilon_{\text{E}}$ … correction due to the environmental influences (influence of the changes of temperature and humidity on measurement set-up, assumptions taken into account about the correct measurement of these influences, etc.).

The associated standard uncertainties are:

$u(\varepsilon_{\text{MB}})$ … standard deviation of the arithmetic mean of n readings, taken for particular measurement (0.0003 %);

$u(\delta\varepsilon_{\text{MB}})$ … defined by MB specifications, which are given as the limits of errors $G = \pm 0.007$ %;

$u(\delta\varepsilon_{\text{MBCAL}})$ … taken from the calibration certificate, with $U(\varepsilon) = 0.005$ % for $k = 2$;

$u(\delta\varepsilon_{\text{REF}})$ … defined by RCIT specifications, which are given as the limits of errors $G = \pm 0.01$ %;

$u(\delta\varepsilon_{\text{REFCAL}})$ … taken from the calibration certificate, with $U(\varepsilon) = 0.009$ % for $k = 2$;

$u(\delta\varepsilon_{\text{BU}})$ … estimated from the limits $G = \pm 0.0003$ %;

$u(\delta\varepsilon_{\text{I}})$ … estimated from the limits $G = \pm 0.0004$ %;

$u(\delta\varepsilon_{\text{E}})$ … estimated from the limits $G = \pm 0.0002$ %.

Note that the estimation of the $u(\delta\varepsilon_{\text{BU}})$, $u(\delta\varepsilon_{\text{I}})$ and $u(\delta\varepsilon_{\text{E}})$ are based on the verification, which can be done separately from the actual measurement and is the expertise of the testing laboratory (or inspection body).

Summarised presentations are given in the table form according to the document EA-4/02 M: 2013 [13]; the combined standard uncertainty $u_c(y)$ is calculated by (10). Although the numbers are not taken from one real experiment, they have the representative values.

In Table 1 the basic (conservative) approach is given - all corrections are equal to 0 (nevertheless if they are known or not known), while for the MB and RCIT both manufacturer's specifications and uncertainty of calibration are taken into account for the estimation of their accuracy (corrections are zero, but their respective uncertainty contribution are taken into account). We may consider that this is the worst possible case, and that $u_c(y)$ calculated in that way could be overestimated. However, the advantage is that we should not take care about the correctness of the applied corrections, which reduces the possibility of error propagations in calculation and data processing, simplifying the routine work and saving the time. For this example $k_P = 2$ is used for calculation of U_P for $P = 95$ %. In Table 2 somewhat improved approach is presented, by introducing the application of corrections. The main difference to the calculation presented in Table 1 is the different estimation of the contribution of MB and RCIT. It this case the influence of the manufacturer's specifications on the accuracy of MB and RCIT are omitted (both corrections and associated standard uncertainties are set to 0), while for particular measuring point the correction is applied, taken from the calibration certificate. For this example $k_P = 2$ is used again for the calculation of U_P for $P = 95$ %; it is reduced by a factor of 1.7, from 0.0175 % (Table 1) to 0.0103 %. It can be seen as the important value reduction, which is certainly the positive thing. The negative aspect of such approach is necessity of careful determination and implementation of the used corrections for each measuring point, which requires additional time and could lead to the errors in calculation and/or expression of the results.

$$u_c(\varepsilon_X) = \sqrt{u^2(\varepsilon_{MB}) + u^2(\delta\varepsilon_{MB}) + u^2(\delta\varepsilon_{MBCAL}) + u^2(\delta\varepsilon_{REF}) + u^2(\delta\varepsilon_{REFCAL}) + u^2(\delta\varepsilon_{BU}) + u^2(\delta\varepsilon_{I}) + u^2(\delta\varepsilon_{E})} \tag{10}$$

Table 1. Basic (conservative but easiest) approach to the calculation of expanded uncertainty where all corrections are equal to zero, but their uncertainties are taken into account; $k_P = 2$ - further explanations are given in the text.

Quantity	Estimate		Input data		Probability distribution	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution	
X_i	x_i		$a(x_i)$ or $U_p(x_i)$			$u(x_i)$		c_i	$u_i(y)$	
ε_{MB}	-0.0357	%	/	%	normal	0.0003	%	1	0.0003	%
$\delta\varepsilon_{MB}$	0.0000	%	0.0070	%	rectangular	0.0040	%	1	0.0040	%
$\delta\varepsilon_{MBCAL}$	0.0000	%	0.0050	%	normal	0.0025	%	1	0.0025	%
$\delta\varepsilon_{REF}$	0.0000	%	0.0100	%	rectangular	0.0058	%	1	0.0058	%
$\delta\varepsilon_{REFCAL}$	0.0000	%	0.0090	%	normal	0.0045	%	1	0.0045	%
$\delta\varepsilon_{BU}$	0.0000	%	0.0003	%	rectangular	0.0002	%	1	0.0002	%
$\delta\varepsilon_{I}$	0.0000	%	0.0004	%	rectangular	0.0002	%	1	0.0002	%
$\delta\varepsilon_{E}$	0.0000	%	0.0002	%	rectangular	0.0001	%	1	0.0001	%
ε_X	**-0.0357**	**%**							0.0087	%
			Combined standard uncertainty					$u_c(\varepsilon_X)$	**0.0087**	**%**
			Expanded uncertainty, $k = 2$					$U_{95}(\varepsilon_X)$	**0.0175**	**%**

Table 2. Application of the known corrections and reduction of the influence of the manufacturer's specifications for MB and RCIT – the differences to the data in Table I are given with blue colour in the second and third column; $k_P = 2$.

Quantity	Estimate		Input data		Probability distribution	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution	
X_i	x_i		$a(x_i)$ or $U_p(x_i)$			$u(x_i)$		c_i	$u_i(y)$	
ε_{MB}	-0.0357	%	/	%	normal	0.0003	%	1	0.0003	%
$\delta\varepsilon_{MB}$	0.0000	%	**0.0000**	%	rectangular	0.0000	%	1	0.0000	%
$\delta\varepsilon_{MBCAL}$	**0.0016**	%	0.0050	%	normal	0.0025	%	1	0.0025	%
$\delta\varepsilon_{REF}$	0.0000	%	**0.0000**	%	rectangular	0.0000	%	1	0.0000	%
$\delta\varepsilon_{REFCAL}$	**-0.0002**	%	0.0090	%	normal	0.0045	%	1	0.0045	%
$\delta\varepsilon_{BU}$	0.0000	%	0.0003	%	rectangular	0.0002	%	1	0.0002	%
$\delta\varepsilon_{I}$	0.0000	%	0.0004	%	rectangular	0.0002	%	1	0.0002	%
$\delta\varepsilon_{E}$	0.0000	%	0.0002	%	rectangular	0.0001	%	1	0.0001	%
ε_X	**-0.0343**	**%**							0.0052	%
			Combined standard uncertainty					$u_c(\varepsilon_X)$	**0.0052**	**%**
			Expanded uncertainty, $k = 2$					$U_{95}(\varepsilon_X)$	**0.0103**	**%**

Table 3. Application of the known corrections and reduction of the influence of the manufacturer's specifications for MB and RCIT (the same as given in Table 2), but with the calculation of expanded uncertainty based on t-distribution; ν_{eff} is set to 1000 (instead of ∞) for quantities with rectangular distribution to enable calculation; $t_P(\nu_{eff})$ = 2.074 - further explanations are given in the text.

Quantity	Estimate		Input data		Probability distribution	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution		Eff. degrees of freedom
X_i	x_i		$a(x_i)$ or $U_p(x_i)$			$u(x_i)$		c_i	$u_i(y)$		$\nu_{eff}(x_i)$
ε_{MB}	-0.0357	%	/	%	normal	0.0003	%	1	0.0003	%	7
$\delta\varepsilon_{MB}$	0.0000	%	**0.0000**	%	rectangular	0.0000	%	1	0.0000	%	1000
$\delta\varepsilon_{MBCAL}$	**0.0016**	%	0.0050	%	normal	0.0025	%	1	0.0025	%	13
$\delta\varepsilon_{REF}$	0.0000	%	**0.0000**	%	rectangular	0.0000	%	1	0.0000	%	1000
$\delta\varepsilon_{REFCAL}$	**-0.0002**	%	0.0090	%	normal	0.0045	%	1	0.0045	%	14
$\delta\varepsilon_{BU}$	0.0000	%	0.0003	%	rectangular	0.0002	%	1	0.0002	%	1000
$\delta\varepsilon_{I}$	0.0000	%	0.0004	%	rectangular	0.0002	%	1	0.0002	%	1000
$\delta\varepsilon_{E}$	0.0000	%	0.0002	%	rectangular	0.0001	%	1	0.0001	%	1000
ε_X	**-0.0343**	**%**							0.0052	%	22.07
			Combined standard uncertainty					$u_c(\varepsilon_X)$	**0.0052**	**%**	**22**
			Expanded uncertainty, $t_P(\nu_{eff})$ = 2.074					$U_{95}(\varepsilon_X)$	**0.0107**	**%**	**2.074**

In Table 3 is presented the same approach as given in Table 2, but with the addition of calculation of expanded uncertainty by (7), based on the calculated effective degrees of freedom ($\nu_{eff} = 22$) and associated parameter $t_P = 2.074$ for $P = 95$ %. In this case the calculated expanded uncertainty U_P is *slightly higher* than the value given in Table 2 (for approximately 3.9 %), which means that without such additional analyses the expanded uncertainty could be slightly underestimated. It is not significant, but could make a difference in the critical cases. Although this approach could be considered as the best and more accurate, it requires additional calculations, efforts and time. Such, or similar analysis, could be used as a guidance when the requirements on the measuring equipment (such as their calibration intervals), used in testing and/or inspection, are considered [14].

V. CONCLUSIONS AND OUTLOOK

The expanded uncertainty U_P has the important role in the conformity assessment because in the relevant international documents it is used for the definition of the guard band w, and consequently determines the outcome of the testing and/or inspection. Different approaches were shown for the calculation of combined standard uncertainty and expanded uncertainty. The most practical approach is taking the specifications of the used measuring equipment in full, but this could lead to somewhat overestimated combined standard uncertainty. The most accurate approach is based on the application of known corrections for input quantities in actual measurement, which can be taken from the calibration certificates, or determined by thorough analysis of the history data. Determination of the expanded uncertainty based on $t_P(\nu_{eff})$ probably gives the most accurate value. At the end, it is on the testing laboratory (or inspection body) to define the most appropriate way on its own to perform measurement procedure, related calculations and data processing, expression of the measurement results and decision makings.

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