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RESEARCH ARTICLE

Evaluation of Uncertainty in Partial Discharge Measurement: A Case Study

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ABSTRACT ISO/IEC 17025:2017 recommends all accredited laboratories under this standard, performing testing and calibration, shall identify and evaluate the contributions to the uncertainty of their measurements. This paper represents the results of the 'measurement uncertainty' assessment carried out on a partial discharge (PD) test set in our laboratory. The major sources of uncertainty include sampling error, calibrator inaccuracy, the resolution limit of display panels, temperature and humidity factors, etc. The uncertainty for each factor was calculated by the principles outlined in NIST-1297:1994 and JCGM-100:2008. The test PD levels were 1, 5, 10, 20, 50 and 100 pC. The combined uncertainty was calculated based on all uncertainty contributions, and the expanded uncertainties were expressed with 68%, 95% and 99% confidence level. Apparently, the measurement uncertainty was highest for the lowest test PD which decreased with the increase in PD level. The uncertainty was around 18% at 1 pC PD whereas it dropped to 2.84% at 100 pC PD. Within the whole test range of 5 to 100 pC, the maximum uncertainty was equal to 5.81%.

INDEX TERMS Degree of freedom, high voltage testing, ISO 17025, partial discharge, level of confidence, measurement uncertainty, instrumentation and control.

NOMENCLATURE

S or σ	Standard deviation.
N	Number of samples.
x_i	i-th sample.
$\bar{x}$	Arithmetic mean.
u_i	Standard uncertainty.
u_c	Combined uncertainty.
U	Expanded uncertainty.
k	Coverage factor.
a_i	Sensitivity coefficient.
p	Level of confidence.
t_p	t-factor for the required level of confidence.
a_+, a_-	Upper and lower limit of a rectangular or triangular probability distribution.
v_{eff}	Effective degree of freedom.
LSD	Least significant digit.

I. INTRODUCTION

The growth of renewable energy integration into the distribution grid is facilitating the necessity of developing smart switching devices [1], [2], [3], [4], and medium voltage switchgear manufacturers all over the globe are investing in new interrupter design. As a part of this endeavor, the demand for type testing of new prototypes is growing and many type test laboratories are getting accredited under the

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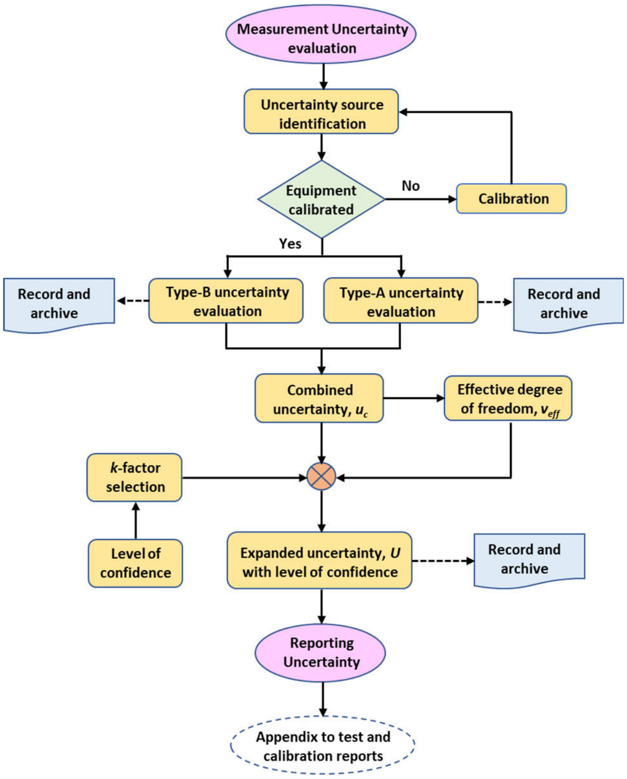
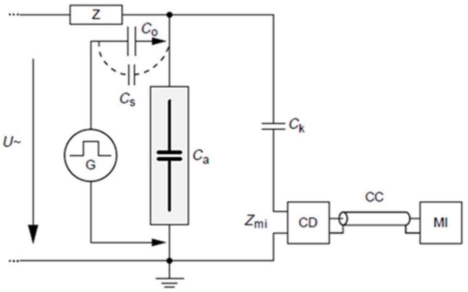
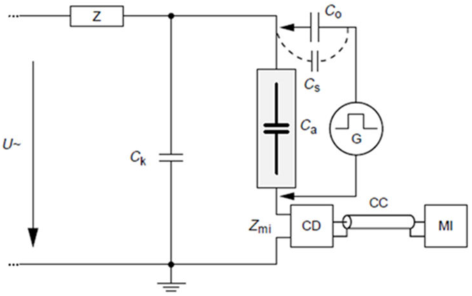


FIGURE 1. Step-by-step procedure to calculate uncertainty in PD measurement.



(a) Coupling device CD in series with the coupling capacitor



(b) Coupling device CD in series with the test object

Components

$U_{\sim}$	high-voltage supply	C_k	coupling capacitor
G	step voltage generator	CD	coupling device
C_0	calibration capacitor	C_s	stray capacitance
Z_{mi}	input impedance of measuring system	MI	measuring instrument
CC	connecting cable	Z	filter
C_a	test object		

FIGURE 2. Connections for the calibration of PD test (source: IEC 60270).

ISO 17025 standard. ISO/IEC 17025 [5] outlines the general requirements for the competence of testing and calibration laboratories. Among the three releases of this standard, the 1999 [6] and 2005 [7] versions emphasized the quality management system and communication with the customer. These two releases aligned closely with the 2000 edition/version of the ISO 9001 standard [8]. The 2017 version highlighted the process and resource requirements more than the previous releases.

Under the process requirement of ISO 17025:2017, subsection 7.6 demonstrates that any laboratory performing type testing and calibration (including its own equipment) shall identify and evaluate the contributions to measurement uncertainty. The standard further refers to ISO/IEC Guide 98-3, ISO 21748 and the ISO 5725 series in assessing uncertainty. Moreover, while reporting a test result, the measurement uncertainties of the related test equipment shall be included with an appropriate level of confidence in the report. Literature reveals the widespread implementation of measurement uncertainty in high voltage testing [9], [10], [11], [12], [13], [14], medical diagnosis [15], food processing industries [16], telecommunication [17], [18], [19], [20], analog/digital data acquisition [20], [21], [22], [23] etc. Nevertheless, the existing literature provides very limited information on assessing uncertainty in partial discharge measurement in an atmospheric environment.

As a part of the ISO 17025 application of our laboratory, it is a prerequisite to evaluate the overall uncertainty related to the partial discharge test set of our facility. This paper demonstrates a step-by-step procedure (fig. 1) to estimate the uncertainty of a partial discharge measurement setup in a high voltage test laboratory. Section II gives a brief description of the PD measurement test set and its calibration procedure at our laboratory. Section III focuses on the significant sources of uncertainty in PD measurement. The uncertainty contributions from sampling error, calibrator inaccuracy, resolution limit and environmental factors are analyzed and calculated in section IV. Finally, in section V, the combined and expanded uncertainty of measurement of the PD detector under consideration has been evaluated and reported with three different confidence levels.

II. PD TEST SET AND CALIBRATION

The PD test set under consideration in this work is an ICM*compact* model PD detector [24] manufactured by Power Diagnostix Systems. It is a compact stand-alone instrument for monitoring the condition of MV and HV insulation. It is often used for quality assurance purpose and quality control tests in manufacturing industries. The standard configuration of ICM*compact* comes with five main display modes namely: (1) Scope Sine mode, (2) Scope Norm mode, (3) Meter, (4) HVM and (5) DSO display mode, among which the HVM display has been used in this work.

Under the in-house equipment calibration program of our laboratory, the PD measurement set is calibrated yearly according to clause 5 of IEC 60270 [25]. The calibration of a measuring system in the complete test circuit is carried out by injecting short-duration current pulses (by means of a calibrator) of known charge magnitude, into the terminals of the test object (see fig. 2). PD calibrator model CAL1A of Power Diagnostix Systems is utilized for this purpose. This standard calibration impulse generator offers a charge range of 1, 2, 5, 10, 20, 50 and 100 pC.

As shown in fig. 2, the calibration of the PD measuring system, intended for the measurement of apparent charge q, was done by injecting current pulses from a calibrator across the terminals of the test object. To avoid the distortion of the injected voltage step, the connection cable between the step voltage generator and capacitor C_o was equipped with appropriate terminations. The relevant range of voltage magnitude was within 50% to 200% of the specified PD magnitude as per the requirement of IEC 60270 [25]. The calibration capacitor C_o is a low-voltage capacitor; therefore, the complete test arrangement was calibrated with the test object de-energized. As per standard guidelines, the calibration capacitor C_o was selected lower than $0.1C_a$ to maintain the sustainability of calibration. Since a test object can be of several meters in height, the injection capacitor C_o was placed close to the high-voltage terminal of the test object so that the stray capacitance C_s could not cause unacceptable errors. Finally, the C_o was removed after calibration before energizing the test circuit.

III. SOURCES OF UNCERTAINTY

Generally, the result of a measurement is only an estimate or approximation of the value of the specific quantity subject to measurement, and thus the result is considered complete only when it is accompanied by a quantitative statement of its uncertainty. No matter the sources of uncertainties, they can be grouped into two categories according to the method used to estimate their numerical values. Those which are evaluated by statistical methods are classified as *Type A* uncertainties and those which are evaluated by other means are classified as *Type B* uncertainties. These two classes are also known as 'Random' (*Type A*) and 'Systematic' (*Type B*) uncertainty [26], [27], [28].

In our laboratory, the major *Type A* uncertainty for PD measurement is 'Sampling Error' and it can be estimated by any valid statistical method used for creating random data. One of the potential sources of this error is the skill and judgment capacity of the operator. Moreover, measuring instruments suffer from errors like bias, changes due to aging, different kinds of drift, poor readability, external background noise, etc. Another substantial reason is the unstable behavior of the measurand e.g. the partial discharge. In this case, repeating the PD measurement gives a randomly different result within the calibrated accuracy of the test set. Therefore, taking more samples and then averaging gives a better estimate.

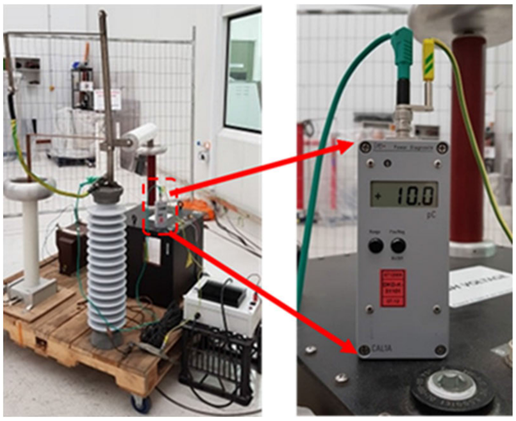


FIGURE 3. Injection of 10 pC current pulse at the HV terminal of PD test set from PD calibrator CAL1A. The figure on the right shows the zoomed view of the calibrator where the current pulse applied through the green wire and the yellow-green stripe wire used for earth connection.

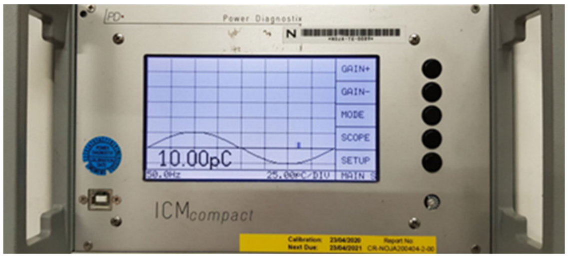


FIGURE 4. Measurement of the applied 10 pC current pulse on the display panel of the PD test set (ICM$_{compact}$ - Power diagnostix systems). The yellow calibration sticker shows that the test was calibrated on 23/04/2020 and the next calibration is due on 23/04/2021. The data was collected in the mid of June 2020.

There are several sources of *Type B* uncertainties in our test case. The first one is the inaccuracy of the calibrator used in the calibration of the PD measurement set. The second and third sources are the resolution limits of the display panel of the PD test set and the PD calibrator. Environmental factors like temperature, humidity, air pressure, etc. need to be considered in overall uncertainty calculation.

IV. UNCERTAINTY EVALUATION

Upon identification of the uncertainty sources in partial discharge measurement, in this section, we will evaluate the individual uncertainty contributions from these sources. Here we will demonstrate the step-by-step procedure to evaluate the uncertainty at 10 pC discharge level and the summary of calculation for 1, 5, 10, 20, 50 and 100 pC will be tabulated in section V.

A. SAMPLING ERROR, u_1

To evaluate the uncertainty contribution from sampling error u_1 at 10pC, a positive polarity discharge current pulse of 10pC was injected from the PD calibrator (CAL1A) at the HV terminal of the partial discharge test set (ICM*compact*). See fig. 3 for the experimental setup. The PD measurement was taken from the display panel of ICM*compact*(fig. 4) located in the control room of the HV test laboratory. The pulse injection was done at the HV testing area where other tests like lightning impulse withstand, power frequency voltage withstand, simulated surge arrester test, etc. are done.

According to GUM [26], [27], 10 samples are enough to calculate the uncertainty of an ordinary distribution given that more samples will improve the measurement. As per the laboratory procedure for uncertainty measurement [29], which is developed based on NIST-1297:1994 [28] and JCGM-100:2008 [26] guidelines, we have taken 15 samples at 10pC (see Table-1). The arithmetic mean or average $\bar{x}$ of n (equals 15 in this case) independent samples will be calculated using equation (1).

$$\bar{x} = \frac{1}{n} \sum\nolimits_{i=1}^{n} x_i \tag{1}$$

The formula to calculate the experimental standard deviation (S) is

$$S = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{2}$$

The standard uncertainty u_1 to be associated with xi is the estimated standard deviation of the mean [28].

$$u_1 = \frac{S}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n(n-1)}} \tag{3}$$

Using equation (1) to (3), the *Type A* uncertainty u_1 for fifteen samples (Table-1) at 10pC was calculated equal to 0.015pC. A few more parameters associated with this uncertainty contribution are: probability distribution type, sensitivity coefficient and degrees of freedom.

The scatter of the samples can be Gaussian or Normal type, Rectangular or Uniform type, Triangular or Bi-modal type [26]. In case of our PD samples, the distribution was of Normal or Gaussian type. The sensitivity coefficient (a) relates the individual uncertainty component to the standard deviation (S) of the reported value for a test item. It is the ratio of the change in measurement response and the corresponding change in stimulus. The sensitivity coefficient of a variable $x(t,\lambda_0)$ with respect to a parameter λ is given by the partial derivative of that variable with respect to that parameter i.e. by $\partial x/\partial \lambda$. Usually the value of the sensitivity coefficient is equal to 1 for the *Type A* uncertainty case we are considering [28].

The degree of freedom is a value related to the amount of information that was utilized in making an estimate. The calculation of the degree of freedom is important as it determines the critical value at which a hypothesis can be accepted or rejected. Therefore, it helps to achieve the desired confidence level in a test. Usually the degree of freedom is equal to the sample size minus one *(n-1)* for *Type A* uncertainties, and thus it is 14 in our sampling error uncertainty estimation.

TABLE 1. Sampling of PD measurement injecting current pulse from calibrator CAL1A.

Measurement	Injected value [pC] *(from PD calibrator)*	Measured value [pC] *(from PD detector panel)*	Deviation from average
Sample 1	10	10.00	-87×10^{-4}
Sample 2	10	10.00	-87×10^{-4}
Sample 3	10	10.00	-87×10^{-4}
Sample 4	10	10.00	-87×10^{-4}
Sample 5	10	10.00	-87×10^{-4}
Sample 6	10	10.07	$+61\times10^{-3}$
Sample 7	10	10.00	-87×10^{-4}
Sample 8	10	9.86	-15×10^{-2}
Sample 9	10	10.14	$+13\times10^{-2}$
Sample 10	10	10.00	-87×10^{-4}
Sample 11	10	10.06	$+51\times10^{-3}$
Sample 12	10	10.00	-87×10^{-4}
Sample 13	10	9.99	-87×10^{-4}
Sample 14	10	10.00	-87×10^{-4}
Sample 15	10	10.01	-87×10^{-4}

B. CALIBRATOR INACCURACY, u_2

The uncertainty contribution u_2 due to the inaccuracy of the calibrator (CAL1A) is a *Type B* uncertainty and it cannot be determined statistically during the measurement process. This parameter is typically extracted from the experience of measurements or manufacturer's specifications or calibration certificates/reports. As per the requirements of standards [5], [8], the PD calibrator was calibrated from an external laboratory which has NATA accreditation to ISO-17025. The standards used for the calibration measurements of CAL1A are traceable to the National Measurement Institute (NMI), Australia, or the National Metrology Institute, UK which is a signatory to the Comité International des Poids et Mesures (CIPM).

The values of u_2 at different positive and negative current pulse discharges, extracted from the calibration certificate of CAL1A issued by the external laboratory, are summarized in Table 2. The measurements were made across a capacitor with a nominal value of 105pF. According to [30], the reported uncertainties in Table 2 are calculated following the principles outlined in the ISO Guide to the Expression of Uncertainty in Measurement [27] and are given as an interval estimate at approximately 95% confidence level. A coverage factor $k = 2$ was used to calculate these uncertainties with a degree of freedom of 30. An infinite (∞) degree of freedom and unity sensitivity coefficient is often considered for the parameters taken from manufacturer specifications or calibration certificates.

C. RESOLUTION LIMIT of PD TEST SET, u_3

Measurements include error due to the resolution limit of the display panel of a measuring instrument. The error is considered as one half of the least significant digit (LSD) of the panel (fig. 5) and the resulting uncertainty is a *Type B* uncertainty. The formula used to calculate u_3 depends on the type of probability distribution. u_3 equals to $1.48a$ for normal distribution, equals to $a/\sqrt{3}$ for uniform or rectangular distribution and equals to $a/\sqrt{6}$ for triangular distribution where $a = (a+ - a-)/2$, $a-$ and $a+$ is the lower and upper limit of the quantity value.

TABLE 2. Measurement uncertainty of PD calibrator CAL1A [30].

Function Tested	Nominal Value [pC]	Measured Value [pC]	Uncertainty [pC]
Pulse output charge: Positive			
Setting: +1 pC	1.0	1.0	0.3
Setting: +2 pC	2.0	1.9	0.3
Setting: +5 pC	5.0	4.8	0.5
Setting: +10 pC	10.0	9.6	0.6
Setting: +20 pC	20.0	19.1	1.1
Setting: +50 pC	50.0	47.5	2.5
Setting: +100 pC	100.0	95.5	4.9
Pulse output charge: Negative			
Setting: –1 pC	– 1.0	– 0.9	0.3
Setting: –2 pC	– 2.0	– 1.9	0.3
Setting: –5 pC	– 5.0	– 4.7	0.5
Setting: –10 pC	– 10.0	– 9.4	0.6
Setting: –20 pC	– 20.0	– 18.7	1.1
Setting: –50 pC	– 50.0	– 46.7	2.5
Setting: –100 pC	– 100.0	– 93.8	4.8

* *The measured values were taken after calibration*

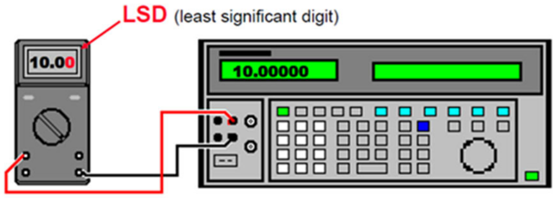


FIGURE 5. Illustration of LSD fact while measurement. Example: a fluke multimeter is measuring 10V d.c. applied from a multiproduct calibrator. Here LSD is 0.01V.

In our case of PD measurement, the probability distribution is of rectangular type and the LSD of the PD test set (ICM*compact*) display panel is 0.01pC. Therefore, the uncertainty contribution u_3 for the resolution limit of the PD measurement panel is 0.0028pC which is ignorable compared to u_1 and u_2.

D. RESOLUTION LIMIT of CALIBRATOR, u_4

The uncertainty evaluation for the resolution limit of PD calibrator CAL1A is similar to u_3. The LSD of this device is 0.1pC and uncertainty probability distribution is the rectangular type. As a result, the u_4 is equal to 0.029pC.

E. ENVIRONMENTAL FACTORS, u_5

Although the standard for high-voltage testing [31] and the standards for high-voltage switchgear [32] have specific guidelines to evaluate atmospheric correction factors e.g. air density and humidity correction factor for dielectric tests like impulse voltage withstand and power frequency voltage withstand, the PD measurement standard [25] did not include any environmental correction factor for partial discharge test. Therefore, the value of u_5 is zero in our consideration.

V. REPORTING UNCERTAINTY

As per JCGM-100 [26], the uncertainty of a measurement result shall be reported by the expanded uncertainty together with the coverage factor k used to obtain it, or by the combined uncertainty. In this section, we will focus on evaluating combined and expanded uncertainties.

A. COMBINED UNCERTAINTY, u_c

The combined uncertainty (u_c) of a measurement result is taken to represent the estimated standard deviation of the result. u_c is obtained by combining the individual uncertainties whether arising from a *Type A* or *Type B* evaluation, using the traditional method for combining standard deviations. This method is frequently known as the *law of propagation of uncertainty* and in common phrasing the *root-sum-of-squares* (RSS) method [27] of combining uncertainty components calculated as standard deviations.

In many cases a measurand Y is determined from N other quantities $X_1, X_2, X_3, \ldots X_N$ through a first-order Taylor series approximation:

$$Y = f(X_1, X_2, \ldots X_N) \tag{4}$$

According to the *law of propagation of uncertainty*, the positive square root of the estimated variance $u_c^2(y)$ is expressed by the following equation [28]

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, x_j)$$

Here, the partial derivatives $\partial f/\partial x_i$ are the sensitivity coefficients, $u(x_i)$ is the standard uncertainty associated with the input estimate x_i and $u(x_i, x_j)$ is the estimated covariance associated with x_i and x_j. The simplest case of this equation is where the combined uncertainty u_c is the square root of the total summation of the squares of all contributing uncertainty components [26] i.e.

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + \ldots\ldots + u_n^2} \tag{5}$$

The aforementioned formula gives a combined uncertainty of 0.348pC for our test case of 10pC PD measurement; the evaluation of u_1 to u_4 is described in section IV. The effective degrees of freedom (v_{eff}) of u_c is calculated by the *Welch-Satterthwaite* formula [28]. This formula considers each uncertainty, and their sensitivity coefficient and degrees of freedom to calculate v_{eff}.

$$v_{eff} = \frac{u_c^4}{\sum_{i=1}^{N}\frac{c_i^4 u_i^4}{v_i}} \tag{6}$$

Here c_i is $\partial f/\partial x_i$ which is the sensitivity coefficient of the standard uncertainty u_i and v_i is the degree of freedom of u_i. Considering the values of u_1 to u_4, and their corresponding sensitivity coefficient and degree of freedom, the effective degree of freedom v_{eff} for the combined uncertainty 0.348pC at 10pC PD level of our partial discharge test set is 4.2×10^6 which is plausibly considered at infinity.

TABLE 3. Uncertainty budget at 10pC test PD.

Source of Uncertainty	Type	u_i	Uncertainty value *(pC)*	Sensitivity coefficient	Probability distribution	Coverage factor	Standard uncertainty *(pC)*	Degrees of freedom
Repeatability	A	u_1	0.015	1	Normal	1	0.015	14
Calibrator	B	u_2	0.600	1	Normal	1.73	0.347	∞
Resolution (PD display)	B	u_3	0.010	1	Rectangular	√3	0.003	∞
Resolution (Calibrator)	B	u_4	0.100	1	Rectangular	√3	0.029	∞
Environmental factors	B	u_5	NA	–	–	–	–	–
Parameter Measurement	Combined	u_c	0.348	–	Assumed Normal	–	–	4.2×10^6
Parameter Measurement	Expanded	U	0.683	–	Assumed Normal	1.96	–	4.2×10^6

TABLE 4. Combined and expanded uncertainty at six test levels of the PD measurement set.

Test PD (pC)	Combined Uncertainty, uc (pC)	Degree of Freedom, v	Expanded Uncertainty, Um (pC)	Coverage Factor, k	Level of Confidence	% Uncertainty of Measurement
1	0.177	2.09×10^5	0.177 0.346 0.454	1 1.96 2.57	68% 95% 99%	17.65%
5	0.291	3.82×10^6	0.291 0.570 0.747	1 1.96 2.57	68% 95% 99%	5.81%
10	0.348	4.19×10^6	0.348 0.683 0.895	1 1.96 2.57	68% 95% 99%	3.48%
20	0.637	8.43×10^6	0.637 1.248 1.637	1 1.96 2.57	68% 95% 99%	3.18%
50	1.448	1.41×10^6	1.448 2.837 3.720	1 1.96 2.57	68% 95% 99%	2.90%
100	2.837	1.37×10^6	2.837 5.561 7.291	1 1.96 2.57	68% 95% 99%	2.84%

B. EXPANDED UNCERTAINTY, U

Although u_c is used to express the uncertainty of many results, it is often required for some industrial, commercial and regulatory applications as a measure of uncertainty that defines an interval about the measured result within which the value of the measurand is confidently believed to lie. It is termed as expanded uncertainty (U) and is obtained by multiplying the combined uncertainty (u_c) by a coverage factor (k) [26].

Generally, the value of k is chosen based on the desired level of confidence. Typically, it is in the range of 2 to 3. When the Gaussian or normal distribution is applied and the u_c value is negligible then $k = 2$ (i.e. $U = 2u_c$) defines an interval having level of confidence of 95%, and $k = 3$ (i.e. $U = 3u_c$) defines an interval having the level of confidence of 99%. To calculate U, the t-factor $t_p(v_{eff})$ shall first be obtained from the t-distribution table (see Table 5 in the appendix) for the required level of confidence. In most cases, v_{eff} is not an integer. In such cases, the v_{eff} shall be either interpolated or truncated to the next lower integer. Then $k = t_p(v_{eff})$ and U shall be equal to the k times u_c.

The calculation done in the previous subsection demonstrated that our partial discharge test set has a combined uncertainty of 0.348pC with 4.2×10^6 (i.e. infinity) effective degree of freedom at 10pC test PD. Therefore, the value of k is 1.960 for a 95% confidence level (see Table 5) and the corresponding expanded uncertainty is 0.683pC. Most of the type testing laboratories include a common note in their issued reports that the results are expressed with a 95% confidence level and k is equal to 2 unless otherwise stated.

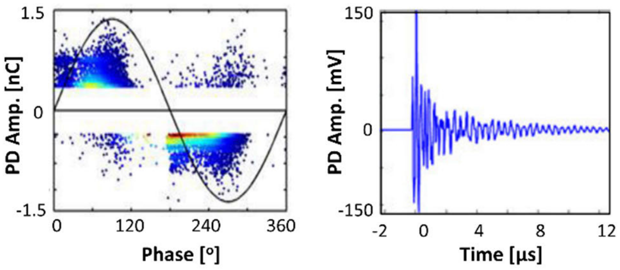
VI. DISCUSSIONS

Table 4 shows the overall uncertainty budget calculated for the 10pC test PD. Such tables are substantial in the

TABLE 5. Value of $t_p(v)$ from the t-distribution for degrees of freedom v that defines an interval $-t_p(v)$ to $+t_p(v)$ that encompasses the fraction p of the distribution. [28].

Degrees of freedom v	Fraction p in percent					
	68.27(a)	90	95	95.45(a)	99	99.73(a)
1	1.84	6.31	12.71	13.97	63.66	235.80
2	1.32	2.92	4.30	4.53	9.92	19.21
3	1.20	2.35	3.18	3.31	5.84	9.22
4	1.14	2.13	2.78	2.87	4.60	6.62
5	1.11	2.02	2.57	2.65	4.03	5.51
6	1.09	1.94	2.45	2.52	3.71	4.90
7	1.08	1.89	2.36	2.49	3.50	4.53
8	1.07	1.86	2.31	2.37	3.36	4.28
9	1.06	1.83	2.26	2.32	3.25	4.09
10	1.05	1.81	2.23	2.28	3.17	3.96
11	1.05	1.80	2.20	2.25	3.11	3.85
12	1.04	1.78	2.18	2.23	3.05	3.76
13	1.04	1.77	2.16	2.21	3.01	3.69
14	1.04	1.76	2.14	2.20	2.98	3.64
15	1.03	1.75	2.13	2.18	2.95	3.59
16	1.03	1.75	2.12	2.17	2.92	3.54
17	1.03	1.74	2.11	2.16	2.90	3.51
18	1.03	1.73	2.10	2.15	2.88	3.48
19	1.03	1.73	2.09	2.14	2.86	3.45
20	1.03	1.72	2.09	2.13	2.85	3.42
25	1.02	1.71	2.06	2.11	2.79	3.33
30	1.02	1.70	2.04	2.09	2.75	3.27
35	1.01	1.70	2.03	2.07	2.72	3.23
40	1.01	1.68	2.02	2.06	2.70	3.20
45	1.01	1.68	2.01	2.06	2.69	3.18
50	1.01	1.68	2.01	2.05	2.68	3.16
100	1.005	1.660	1.984	2.025	2.626	3.077
∞	1.000	1.645	1.960	2.000	2.576	3.000

(a)For a quantity z described by a normal distribution with expectation μ_z and standard deviation s, the interval $\mu_z \pm k\sigma$ encompasses p = 68.27, 95.45, and 99.73 percent of the distribution for k = 1, 2 and 3, respectively.



(a)

(b)

FIGURE 6. PD pattern waveform (a) phase-resolved; (b) time-resolved.

uncertainty calculation database (more specifically calibration database) of laboratories seeking for testing and calibration accreditation because the auditors of accreditation bodies ask for uncertainty budgets at several test values to evaluate the uncertainty calculation technique of the laboratory. Table 3 summarizes the uncertainty sources, type of uncertainties, probability distribution functions used to evaluate the uncertainties, and sensitivity coefficient, coverage factor and degree of freedom of uncertainty.

Generally, the uncertainty of test equipment is evaluated at several test points. Thus, we have estimated the combined measurement uncertainty of our partial discharge test set at 1, 5, 10, 20, 50 and 100 pC, and expressed the expanded uncertainty with 68%, 95% and 99% confidence level. The results are summarized in Table 4. The column of an effective degree of freedom (v) shows the calculated numerical values, but they can be mentioned as infinity (∞) while including in calibration/uncertainty reports. Table 4 shows that the combined uncertainty increases with the increase of the discharge level. While u_c is 0.177pC at 1pC discharge, it raises to 2.837pC at 100pC discharge. The reason is quite understandable, both the contribution of sampling error (u_1) and calibrator inaccuracy (u_2) increases at higher discharge levels although the resolution errors remain the same. A similar behaviour is observed for expanded uncertainties, the value of U increases at higher test PD.

On the other hand, while expressing the uncertainty in percentage, the scenario is the opposite. The lowest test PD 1 pC shows the maximum percentage of uncertainty and the highest test PD 100 pC results in the minimum percentage of uncertainty. The fluctuation of test discharge is significantly higher at low test points; therefore the percentage of uncertainty increases at low discharges compared to the higher discharges. For this reason, laboratories like KEMA (now CESI) express their PD measurement uncertainty in pC unit at lower test PD and in percentage at higher test PD [33], [34].

An appropriate display pattern of PD pulse is important to interpret the partial discharge signal properly. Several techniques like phase and time resolved PD (see fig. 6) and three-phase amplitude relation diagram (3 PARD) are used to visualize PD patterns [36], [37], [38], [39], [40], [41]. In this work, the uncertainty in PD measurement was evaluated based on the individual signals. However, the phase resolved partial discharge (PRPD) pattern is commonly used to evaluate the condition of an equipment in the commercial site measurements. In a PRPD pattern, the two significant parameters are the discharge rate and magnitude, both in reference to the phase angle. It represents a bivariate distribution $H_n(\phi,q)$ correlating the discharge magnitude (q), power frequency phase angle (ϕ) and discharge rate (n) of the PD pulse [36]. The uncertainty evaluation procedure outlined in this paper is also applicable to the test equipment utilizing PRPD pattern. While these instruments mostly have higher resolution e.g. express three or more digits after the decimal point, the u_3 contribution to overall uncertainty decreases. The evaluation criteria of u_2(calibrator inaccuracy), u_4 (resolution limit of calibrator) and u_5 (environmental effect) remains unchanged. Moreover, the Gaussian or Normal distribution should be used to estimate the sampling error uncertainty u_1.

VII. CONCLUSION

Accreditation bodies outlined several criteria for uncertainty measurement based on the type of test and accreditation scope. For the laboratories performing qualitative or semi-quantitative tests, a measurement uncertainty budget is not essential [35]. There is also a flexible prerequisite for the laboratories using well-recognized standard test methods that specify limits to the values of the major sources of uncertainty.

In such cases, the laboratories are considered to have satisfied the uncertainty requirement by following the test method [35]. Nevertheless, the evaluation of the uncertainty budget is mandatory for the laboratories providing calibration service to the external customer. To achieve and maintain type testing accreditations, laboratories calibrate their test equipment externally or conduct in-house calibration. In both cases, the laboratories have to estimate the uncertainty contribution after an equipment calibration and demonstrate to the auditing authorities.

This paper explains the uncertainty sources related to a partial discharge measurement and demonstrates the uncertainty evaluation techniques leading to combined and expanded uncertainty. A detailed calculation was described at 10 pC discharge level in the context of conventional standards and supplementary results were represented for different test points within 1 to 100 pC PD. The expanded uncertainties were expressed with three different confidence levels. The results showed that the maximum uncertainty was found at the lowest test discharge and it decreased with the increase in discharge level. The uncertainty was around 18% at 1 pC PD and it decreased to 2.84% at 100 pC PD. This paper would be a useful reference for evaluating uncertainties related to partial discharge measurement at high voltage test laboratories.

APPENDIX

See Table - 5.

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