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Significance of measurement uncertainty on digital multi-meters

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Abstract
This paper presents the calibration results with uncertainties of three digital multi-meters namely A, B & C that are used in various localized conditions to understand the calibration performance of the meters in both in ac and dc potentials. The uncertainty (Ue) values are calculated for both ac and dc potentials at defined tolerance at set points 3.8, 38 & 380V respectively. The variations in the Ue values are found to be 0.007 to 0.108V, 0.010 to 0.193Vand 0.007 to 0.374V for the ac potentials. Further, the Ue values are also measured in the dc voltages are 0.0007 to 0.0151V, 0.0007 to 0.0156V and 0.0007 to 0.0189V respectively. The calibration performance of the meters A, B & C are found to be in the order of A>B>C. The significance of uncertainty values are correlated by accounting the calibration history, usage pattern and the localized conditions.

Keywords: calibration, potentials, uncertainty value, tolerance, digital multi-meters, localized conditions.

1. Introduction
Metrology is the science that encompasses both theoretical and practical aspects of measurement which are made to understand the product quality from manufacturing equipment and product testing devices [1-3].In all measurements, deviations are inevitable which may occur due to various factors such as resolution, wear factor, localized condition, usage pattern etc. Therefore, all measuring instruments have to be calibrated with known standard reference source. Most of the measuring instruments are calibrated at a defined frequency interval so as to ensure that the instruments are within the tolerance limits leading to better accuracy of the measuring parameters ensuring product quality. Thus, the calibration of the measuring devices has become increasingly important in each and every manufacturing field in order to meet product quality and customer's satisfaction. Therefore, calibration is an essential part of the quality system.

The calibration with uncertainty values are worth presenting and the errors in uncertainty values (Ue) may be due to contribution of several unpredictable factors such as temperature, thermal emf's loading, power line conditions, also electrical interfaces like electrical drift, bias, noise etc. apart from usage and operating environments. The uncertainty of the Digital multimeter depends upon the uncertainty of the Multiproduct Calibrator used to calibrate it. Therefore, overall factors contributing to the measurement uncertainty of the instruments are described effectively through cause and effect diagram as shown in the Fig.1.

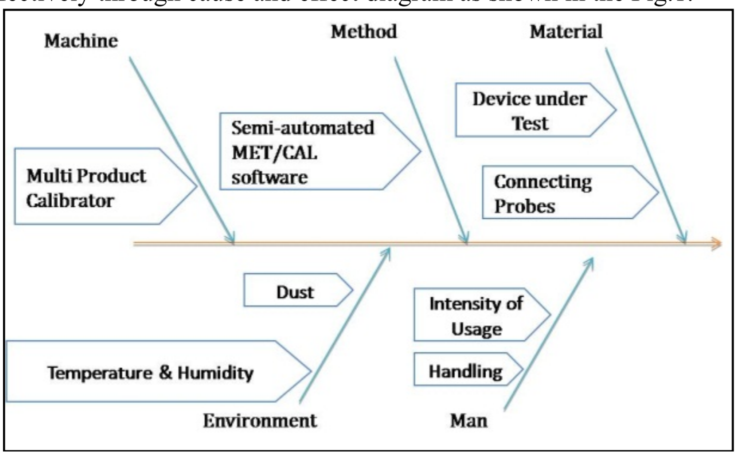

Fig 1: Cause and Effect diagram

In order to compute such measurements; the Ue value should be minimized as much as possible by smearing necessary corrections to nullify specific errors in the measurement of the test device subjected to recalibration after adjustment. Therefore, higher precedence is given to measurements and its traceability to the National Standards like National Accreditation Board for Testing and Calibration laboratories (NABL).

There are two approaches to estimate uncertainty namely (i) Type A and Type B evaluations and (ii) Expanded uncertainty where Type A and B evaluations are performed using GUM (Guide to the expression of Uncertainty in Measurement). There is also a need to estimate the expanded uncertainty which in turn gives better understanding of calibration error. The possible sources of uncertainty associated with the input parameters contribute to the final results of the Device Under Test (DUT) and are commonly evaluated by Type A & B evaluations which were analyzed by statistical distribution tools namely Normal, Lognormal, Quadratic, Cosine, Rectangular, Triangular and U-shaped distributions [4].Since Type A and Type B evaluations are contributed from Gaussian (normal) and rectangular distributions , these two distributions are discussed in detail in the Results and Discussions.

In this paper, an attempt has been made to understand the calibration performance of digital multimeter based on three years calibration performance history. The calibration data were analyzed by accounting the accuracies, uncertainty of the Calibrator and the resolution of the DUT to estimate U_e values for both ac and dc potentials. The change in the U_e values w.r.t. to the set values of each multimeter were explained by correlating the calibration results with calibration records of the manufacturer. The calibration performance of the digital multi-meters and their influence on the quality of measuring parameters were presented by correlating results of U_e and discussed.

2. Experimental:

All the measurable devices have to be calibrated with known standard reference preferably with an accuracy ratio 1:4 of test and reference source respectively subjected to traceability of the standard. In the present study ,all the multimeters are calibrated using Multi product calibrator (Fluke 5500A).The Multi product calibrator (MPC) has several functional parameters such as capacitance, resistance, temperature, voltage and current characteristics and also integrated with MET/CAL software(version 8.1.2).The software is flexible to perform calibration activity either manually, semi-automatically or automated to customize the data. The additional benefits of the software are to store the information for future reference. The calibration of the test instrument is performed in ac and dc potentials in the range 3.8V to 380V.The uncertainty (Ue) values are obtained by deploying the statistical tools mainly normal &rectangular distributions where the accuracy of each digital multimeter was analyzed and the error associated with the instrumental error (%) and in terms of ppm (parts per million).Type A and Type B evaluations are calculated as stipulated below.

2.1 Evaluation of Uncertainty:

Uncertainty values are evaluated by Type A associated with calculation of Ua & Ub that are associated with the experimental data and manufacturer's calibration results [5].The factors considered for type A evaluations are repeatability from the measured calibration data readings and the standard deviation (**σ**);and these results are used to calculate Ua values**.**The type B evaluations are associated with rectangular distributions where the calibrator's uncertainty is taken into account and Ub value is calculated.The uncertainty evaluations are presented in the following section .

2.1.1 Type A evaluations: [U_a]

The Type A evaluation of standard uncertainty can be applied when several independent observations are made for one of the input quantities under the same conditions of measurement. If there is sufficient resolution in the measurement process there will be an observable scatter or spread in the values obtained [6] .

The uncertainty is calculated using the arithmetic mean or average of 'n' readings are represented by

$$\overline{x} = \frac{1}{n\sum_{k=1}^{n} x_k} \quad (2.1)$$

Where x_k is the individual measurement and k= 1 to n.

$\overline{x}$ is the mean

'n' is the number of repeated measurements.

The sigma (Σ) is mathematical notation for algebraic sum of all the n readings.

The repeatability is calculated by substituting the mean value.

$$\text{Repeatability} = \sum (xi-\overline{x})^2 \quad (2.2)$$

where, 'xi' is the individual measurements.

The Standard deviation is the measure of spread of repeated measurements outward from the mean. This measure of spread is the basis of uncertainty specification. The spread of each individual observation around their mean is referred as the Experimental standard deviation(S) which is determined from the following equation.

$$\text{Standard Deviation}(\sigma) = \sqrt{1/n \sum_{k=1}^{n} (x_k - \bar{x})^2} \quad (2.3)$$

The Uncertainty calculated for Type A (Ua) is defined as the ratio of Standard deviation (σ) to the Number of repeated measurements n.

$$U_a=\sigma/\sqrt{n} \quad (2.4)$$

Where, 'U_a' is Type A Uncertainty

'n' is number of measurements

2.1.2 Type B evaluations:[U_b]

The uncertainty component is evaluated by deploying the possible variability of the measurand. These values may be derived from: (i) Previous measurement data (ii) Manufacturer's specification (iii) Experience with the behavior and properties of relevant instruments associated with the measurement. (iv) Data provided in calibration and other certificates (v) Uncertainty assigned to reference data [7]. Factors contributing for Type B evaluation are; Uncertainty due to Standard source and resolution of measuring instrument. Further the sources of uncertaintiesU_{b1}, $U_{b2}$are calculated:

The Uncertainty due to resolution of the instrument (U_{b1}) is ratio of resolution to (2*Rectangular distribution (√3) whereas Uncertainty due to Master (Ub_2) is ratio of Uncertainty of Standard source to the Coverage factor (k).

Combination of U_{b1}&U_{b2} gives the Type B evaluation (U_b) as calculated in eqn. (2.5).

$$U_b=\sqrt{(U^2_{b1} + U^2_{b2})} \quad (2.5)$$

Where, 'U_b' is Type B Uncertainty
'U_{b1}' is the Uncertainty due to resolution
'U_{b2}' is the Uncertainty due to Master
Root square sum the eqns. 2.4 & eqn. 2.5 i.e., Type A and Type B uncertainty respectively to obtain the total combined Uncertainty (U_c).
In order to represent uncertainty values of U_a and U_b in a simplified form, the combined uncertainty (U_c) is calculated and represented as below.
Combined Uncertainty (U_c): The Type A uncertainty (U_a) and Type B uncertainty (U_b) together produce Combined Uncertainty (U_c) in the following equation.

$$U_c=\sqrt{(U^2_a+U^2_b)} \quad (2.6)$$

Where, 'U_c' is Combined Uncertainty
'U_a' is the Type A Uncertainty
'U_b' is the Type B Uncertainty
In addition to combined uncertainty (U_c), to determine the uncertainty at 95% confidence level with a k value (coverage factor) of 1.96 ,the expanded uncertainty is obtained by the combined uncertainty U_c and the coverage factor k (=1.96) as given in eqn. (2.7) [1].

$$U_e=U_c*k \quad (2.7)$$

Where 'U_e' is Expanded Uncertainty.

The k value is chosen by considering a number of parameters with: (i) Knowledge of the probability distributions and (ii) Knowledge of the number of values used to estimate random effects. The commonly used k value at different confidence levels like 50%, 68.3% 95%, 99% and 100 % are 0.675 1.00 1.96 2.59 3.00 respectively. In general, the k value is chosen as1.96 for 95% confidence level. [1]

3. Results and discussions:

The calibration result with measurement uncertainty values was obtained for both ac and dc voltages of digital multi-meters. In order to understand measurement error and measurement uncertainty; the Probability error distributions namely normal and rectangular distributions which are applicable to our analysis are discussed in the following sections 3.1 and 3.2.

3.1 Normal distribution (U_a):

The Gaussian (normal) distributions of the multi-meters were obtained from the d.c potentials considering the repeatability of the meters and Standard deviation (σ).The Gaussian distribution for different set values of d.c voltages for digital multi-meters is shown in the Fig.2. The normal distribution (U_a) values are linear from 3.8 to 38V whereas the U_a value dramatically rises at 100V and has drifted down at 200V profile.

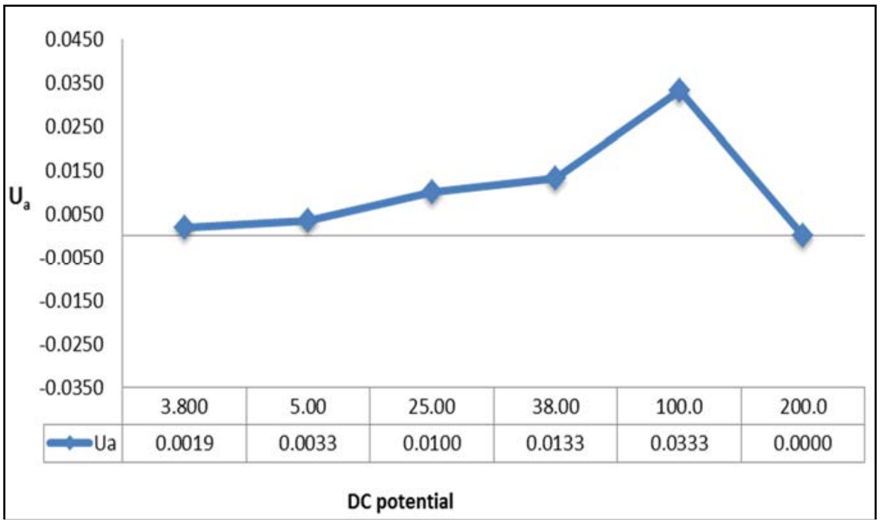

Fig 2: Normal distribution of Digital Multimeter

3.2 The rectangular distribution [U_b]:

The rectangular distribution is normally associated with Type B and it is applicable where an equal probability of measurement occurred within the boundary limits which are more frequently associated with manufacturer specification. To evaluate U_b value with rectangular distribution, the factors to be considered are (i)The resolution of the DUT and(ii)Uncertainty of the Master/Standard source and the coverage factor (k=1.96) are considered at 95% confidence level.

The U_b results with set voltages ranging from 3.8 V to 380V are presented in the Fig. 3 and it is seen that the values are evenly distributed throughout the studied voltage band. U_b values varied from 0.0004V at 3.8V and have drifted to 0.0038V at 100V which is maintained 200V and reached 0.0077V at 380V; so the values are distributed evenly within the range which describes the rectangular distribution.

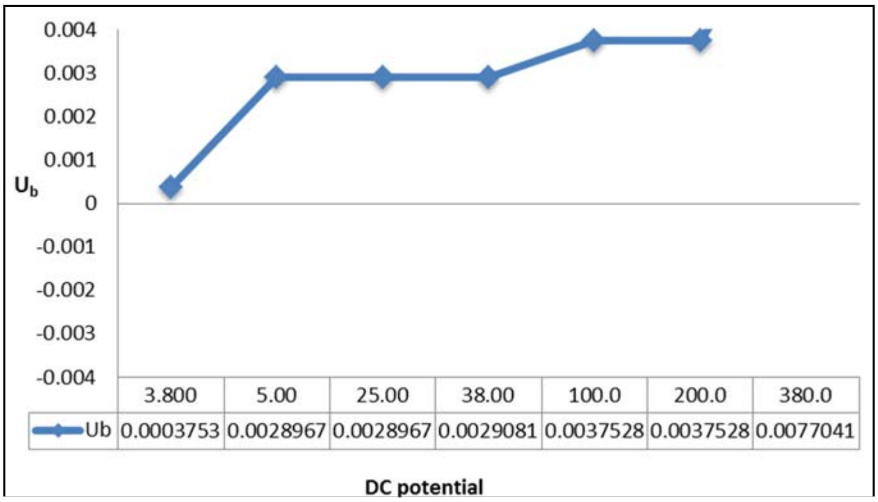

Fig 3: Rectangular distribution of Digital multimeter

3.3 AC Potential Measurements:
The uncertainty values (U_e) for ac voltage readings of A, B & C are calculated and shown in Fig 4. It was observed that the U_e values for different set values are found to be within tolerance for all multimeters.

The Uncertainty value of meter A is proportional to the input values and the U_e values increase with respect to the input value as shown in Fig 4. The possible contributing factors for U_e values may be (i) Intensity of usage [8](ii) Proper environment (iii) Handling.

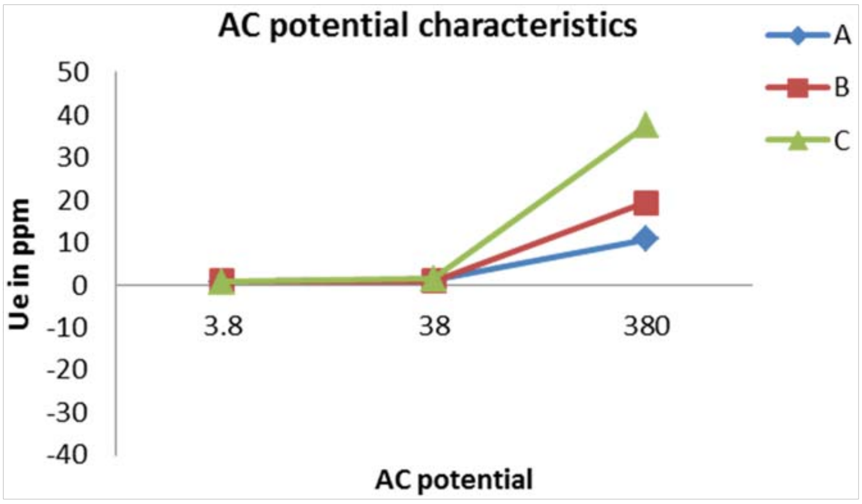

Fig. 4: Uncertainty of ac potentials of Multimeter

In contrast to the U_e value for meter A; considering the uncertainty value of meter B in Table 1, there is a drift to 0.95ppm at 38V.The reasons may be due to the (i) Ageing (ii) Delicate nature subjected to intensity of usage. [9]
Uncertainty values of meter C which is proportional to the input values as the U_e values increase with respect to the input values. The factors contributing to the U_e values of C may be due to (i)Frequent usage of meter (ii) The environmental impact and (iii)The handling of instrument is different when compared to meters A & B which is giving rise to higher voltage(in ppm) of U_e value of meter C.
From the analysis of meters A, B &C, meter A shows better stability and has good repeatability and the uncertainty results with the input values are found to be accurate when compared to meters B &C.

3.4 DC Potential Measurements:
The dc voltage measurements are of prime importance since voltage for automobile batteries is also 12V dc and other measurements related to Temperature, High frequency power wave & Microwave power are all related to dc measurements. Among all dc measurements; our analysis is based on the calibration studies of dc voltage characteristics with uncertainty of a Digital Multimeter.
The uncertainty results of dc voltage data are significant for the present analysis and are within the tolerance limits. The uncertainty profile of meters A, B and C at specific set ranges is given in Fig 5.

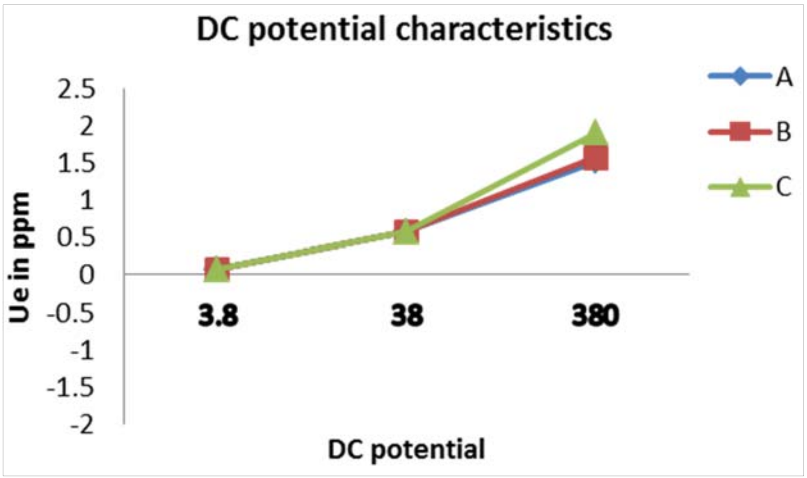

Fig 5: Uncertainty of dc potentials of Multimeter

From Fig 5 it is seen that the U_e values have varied with respect to the set values of dc voltage. The U_e value was found to be zero ppm at 3.80V and increased to 0.5ppm at 38V.A marginal drift in uncertainty was observed in the range 38V to 380V.The changes are significant at 380V as compared to 3.8& 38V.The U_e values have drifted to 1.8ppm approximately at 380V.

On Comparing the ac and dc voltages; the calibration results of d.c voltage are accurate than ac voltage. The uncertainty results of three meters studied in the range 3.8V and 38V are found to be reliable, stable even though the meters are operated at different environments. The drifts in a. voltages are significant; as most of the measuring meters are designed to operate at all environments. The normal and rectangular distributions have contributed to meter A's uncertainty and so it is very reliable and results have linearity compared to meters B&C. Comparing the performance of meters; the factors contributing to drift in ac & dc measurements in the studied potential ranges are:

Frequency of the operating multimeters varies with the uncertainty of the each multimeter when operated several cycles in a day, and then there is a possibility of occurrence of deviation in the measurements.

- The deviation may occur either due to mishandling or operation of the appraiser or due to storage in different environments.

The uncertainty results of other meters are found to be less accurate compared to A which may be due to the effects of temperature where temperature affects the performance of each and every component in the instrument –from the simplest resistor to the most elegant integrated circuit[10].

The ac and dc potential calculations are represented in ppm to get better visibility of the measurement results for A,B & C respectively and the variation is found to be same for both ac & dc potentials in Volts and ppm.

In order to abridge the uncertainty calculations of U_a, Ub, Uc and U_e are represented in the Uncertainty budget. The Uncertainty budget was calculated for both ac and dc potential results of ac & dc potentials at 3.8V of meter A are summarized in the Table 1.

Table 1: Uncertainty budget for ac and dc potentials

Uncertainty components			
Type A (Normal) (±U_a)	Type B (Rectangular) (±U_b)	Combined Uncertainty (±U_c)	Expanded Uncertainty (±U_e)
Uncertainty components in ac			
0.0012V	0.0036V	0.0038V	0.0074V
Uncertainty components in dc			
0.00001V	0.0004V	0.0004V	0.0007V

4. Conclusions:

The calibration performance of three digital multimeters in a.c & d.c potentials operated at different environments is studied. The uncertainty (U_e) is calculated based on the calibration performance results of last three years. The results are found to be within the tolerance limits though the U_e values vary marginally with multimeter to multimeter. Comparing the calibration performance of multimeters (A, B, & C) the U_e value of A is found to be lower as compared to B & C meters in both ac and dc potentials. The variation in the uncertainty value in the studied potential range may be due the intensity of usage and localized conditions as well.

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