

Measurement uncertainty evaluation of automatic Tan Delta and resistivity test set for transformer oil

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Abstract. Quality of transformer oil plays vital role in the performance of transformer in electrical appliances. Measurement uncertainty is a general concept associated with any measurement and can be used in professional decision processes as well as judging attributes in many domains, both theoretical and experimental. As the tolerances applied in industrial production become more demanding, the role of measurement uncertainty becomes more important when assessing conformity to these tolerances. Measurement uncertainty plays a central role in quality assessment and quality standards. In an effort to meet national, international and commercial accreditation requirements, users of transformer oil testing machines must establish adequate methods of determining calibration and test measurement uncertainties. Determining measurement uncertainty for transformer oil testing equipments and test data can be a very complex process. Many factors affect the uncertainty of test data produced by testing machines. In this paper, the concepts associated with the procedure for estimation of uncertainty is discussed and the application of these for the determination of uncertainty in transformer oil testing equipments in government testing labs is illustrated. The objective of this study is to develop a methodology for determining the result of measurement concerning electrical properties of transformer oil and their respective uncertainties.

Keywords: Resistivity; Tan Delta; transformer oil; accuracy; uncertainty of measurement

1 Introduction

In dealing with the various firms that perform laboratory testing of transformer oil samples, there are different recommended tests and different threshold levels associated with the results. Therefore, it might be useful to discuss what is consider to be the more useful tests that need to be performed and the acceptable results associated with those tests. It is highly recommended that transformer oil sample tests to be performed at least on an annual basis with results compared from year to year. Transformer oil sample tests can be separated into two general categories, those that assess the immediate acceptability of the insulation system and those that assess the degree of aging or degradation of the insulation system. Electrical properties of the insulating system change due to age and continuous electrical stress [1]. The principal contributor to the unexpected breakdown of the high voltage equipment is the insulation failure. As compared to the magnetic, conducting and insulating materials which form the basics of any electrical equipment, the insulating material is more prone to service stresses like thermal stress, electrical stress, mechanical stress, environmental stress, etc.

By measuring the electrical properties such as capacitance and Tan-Delta regularly on periodical basis, it is possible to ensure the operational unexpected breakdown. Dissipation factor (Tan-Delta) is one of the most powerful off-line non destructive diagnostic tools to monitor the condition of solid insulation of various high voltage equipment. There are several reasons due to which Tan Delta value may be affected-moisture, dissolving of some of the transformer varnish, insulating material deteriorating, etc.

1.1 Description

The automatic Tan Delta and resistivity test set has been specially designed to determine the Tan Delta and resistivity of transformer oil and other electrical insulating liquids using a guarded three terminal test cell. This may also be used for measurement of the above parameters of solid insulating materials using a guarded three terminal solid test cell. There are built-in safety features which include zero start on voltage adjustment, auto trip with LED indication if two grounds are not connected; auto trip with LED indication if safeties interlock is opened [2, 3].

The ϵ (epsilon) – DF portion of the instrument operates as a manually balanced capacitance bridge. Since ϵ is

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Table 1. Specification of Tan Delta and resistivity set.

Ranges	
Tan Delta	10^{-5} to 10
Resistivity	From 10^9 to 10^{15} Ω cm
Accuracy	
Tan Delta	$\pm 0.01\%$
Resistivity	$\pm 2\%$
Resolution	
Tan Delta	0.00001 in 10^{-5} range 0.0001 in 10^{-4} range 0.001 in 10^{-3} range 0.01 in 10^{-2} range
Resistivity	0.01 of each range
Cell constant (cm)	3 digit adjustment for Tan Delta zero and capacitance. Any cell or test fixture between 50–70 pF can be used.
Test voltage	Internally generated with accuracy $\pm 1\%$
Tan Delta	(0–1000 V and 0–3000 V)
Resistivity	+500 V DC-Fixed
Power supply	230 V AC $\pm 10\%$, 50 Hz, or 110 V AC $\pm 10\%$, 60 Hz, 150 VA
Temperature range	-10 $^{\circ}\text{C}$ to 50 $^{\circ}\text{C}$
Humidity	Ambient to 90% RH
Dimension	19 standard racks mount chassis
Weight	Approx. 17 kg

**Fig. 1.** Tan Delta test cell.

ratio of the full cell capacitance to the empty cell capacitance (in cm) must be dialed in or be balanced out by using the balancing procedure. The cell constant (in cm) equals $3.6 \times \pi \times 1 \times C$, where C is the cell capacitance in pF. The bridge balance is accomplished with the aid of synchronous and phase sensitive null detector which allows easy and independent balancing of the ϵ and DF components. The ϵ -DF tests are carried out with respect to line frequency [2].

The resistivity meter is auto ranging with the reading displayed on $3^{1/2}$ digits DPM. Once the cell constant is balanced with the cm dial, the resistivity meter reads volume resistivity directly in ohm-centimeters. With the cm dial set to 1000, the resistivity meter reads resistance in ohms multiplied by a factor of 1000. The auto ranging feature eliminates the need for selecting the right range

Table 2. Specifications of Oil Test Cell Heater.

Power supply	230 V AC $\pm 10\%$, 50 Hz or 110 V 200 VA AC $\pm 10\%$, 60 Hz,
Temperature range	20–110 $^{\circ}\text{C}$
Accuracy of temperature control	± 2 $^{\circ}\text{C}$
Dimension	310 \times 190 \times 300 mm
Weight	Approx. 12 kg

manually. Refer Figure 1. The specifications of Tan Delta and resistivity set are as shown in Table 1.

1.2 Essential accessories

1.2.1 Oil Test Cell Heater

The Oil Test Cell Heater OCH-85 Figure 2 is a very compact unit and is used to heat the oil in the cell to the required temperature. This uses high frequency induction heating which raises the temperature to 90 $^{\circ}\text{C}$ in 15 min approximately. A knob and a dial are provided to set the temperature at required level. A temperature sensing probe is supplied and this senses the temperature and stops heating the oil once the set temperature is reached. Two LEDs are provided to indicate 'heating on' and 'heating off'. To ensure safety the built-in micro switch interlock automatically trips out the high voltage when the plexi cover of the heater is raised. Refer Figures 2 and 3. The specification of oil test cell heater is as shown in Table 2.



Fig. 2. (Color online) Oil Test Cell Heater.

Table 3. Specification of Oil Test Cell.

Construction	3 terminal configurations
Material	Stainless Steel Body (SS 316) with Teflon spacers
Capacitance	50–70 pF
Electrode spacing	2 mm
Volume	45 ml
Dimension	90 × 185 mm
Weight	Approx. 2.5 kg



Fig. 3. (Color online) Solid test cell.



Fig. 4. Oil Test Cell.

1.2.2 Oil Test Cell

This three Terminal Oil Test Cell Figure 4 is designed for routine and laboratory Tan Delta tests on transformer oils and other electrical insulating liquids. The electrode of the cell is designed with a spherical bottom which offers more uniform stress on the oil as compared to electrode with tapered end. The specification of oil test cell is as shown in Table 3.

1.2.3 C-Df and resistivity calibrator

This calibration box Figure 5 is used to routinely check and inspect the test set. The portable calibrator offers one capacitance, three Tan Delta and four resistivity values. The maximum operating voltage is 500 v AC/DC.

1.2.4 Principle of working

Automatic Tan Delta and resistivity test set is an automated instrument for measuring the electrical characteristics of transformer oil, insulating liquids and other insulating material samples. The Tan Delta test works on

the principle that any insulation in its pure state acts as a capacitor. The test involves applying a very low frequency AC voltage. A low frequency causes a higher value of capacitive reactance which leads to lesser power requirement during the test. Besides, the currents will be limited enabling easier measurement. In a pure capacitor, the current is ahead of the voltage by 90 degrees. The insulation, in a pure condition, will behave similarly. However, if the insulation has deteriorated due to the entry of dirt and moisture, the current which flows through the insulation will also have a resistive component. This will cause the angle of the current to be less than 90 degrees. This difference in the angle is known as the loss angle. The tangent of the angle which is I_r/I_c (opposite/adjacent) gives us an indication of the condition of the insulation. A higher value for the loss angle indicates a high degree of contamination of the insulation references [2, 3] Figure 6.

2 Evaluation of uncertainty

In case of transformer oil testing, we have performed number of test for each parameter. Two types of uncertainties are associated with each measuring parameters.



Fig. 5. (Color online) Calibrator.

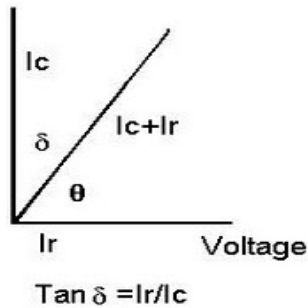


Fig. 6. Principle of working.

To calculate uncertainty following steps are to be followed [4, 5]:

- Step 1. Specify measurand, express mathematically the equation relating measurand and input quantities. Identify all uncertainty sources.
- Step 2. Determine the input quantities.
- Step 3. Quantify the standard uncertainties of all single components.
- Step 4. Identify the covariance (of correlated input quantities).
- Step 5. Calculate the result of the measurement from the input quantities.
- Step 6. Calculate the combined uncertainty.
- Step 7. Calculate the expanded uncertainty.
- Step 8. Give the result together with the uncertainty as estimated.

The combined uncertainty is given by equation (1).

$$U_c = \sqrt{U_A^2 + U_{B1}^2 + U_{B2}^2 + \dots + U_{Bn}^2} \quad (1)$$

where:

- U_A = type-A standard uncertainty;
- U_B = type-B standard uncertainty.

2.1 Methodology of selecting factors

The factors are selected based on analytical data, calibration certificates, past experience and results at interlab testing as below [6, 7].

2.1.1 Repeatability

It is included in type-A uncertainty. It is an analytical method including the calculation of standard deviation and type-A standard uncertainty. Standard deviation indicates the spread of values which tells us something about the uncertainty of measurement [2].

2.1.2 Accuracy of reading

Least count of scale, slight fluctuations of reading are considered in type-B uncertainty. The uncertainty contributed by this factor affects the final result. So their considerations are must.

Table 4. Reading of Tan Delta.

Sr. No.	1	2	3	4	5	6	7	8	9	10
X_i value	0.00733	0.00740	0.00773	0.00766	0.00792	0.00792	0.00748	0.00733	0.00740	0.00773

Table 5. Uncertainty budget.

Sources	Probability type A or type B	Std uncertainty MPa	Sensitivity coefficient	Uncertainty contribution	DOF
$U_1 =$ Repeatability	Normal, type A	0.000073	1	0.000073	9
$U_2 =$ Accuracy of reading	Rectangular type B	0.000057	1	0.000057	∞
$U_3 =$ Accuracy of test voltage	Rectangular type B	0.00577	1	0.00577	∞
$U_4 =$ Calibration of capacitor	Rectangular type B	0.00076	1	0.00076	∞
Expanded uncertainty	$K = 1.96$			± 0.01140	

Table 6. Resistivity value.

Sr. No.	1	2	3	4	5	6	7	8	9	10
$X_i \times 10^{12}$	20.46	21.72	18.61	19.06	18.18	16.66	21.55	20.46	21.72	18.61

2.1.3 Accuracy of test voltage

In both the tests, proper test voltage is set. The test voltage has its accuracy mentioned in technical specification. Using this value standard uncertainty is calculated. This uncertainty value has a major contribution in final result.

2.1.4 Calibration of capacitor and resistor

Calibration of instrument and its components play an important role in calculating uncertainty of measurement. Calibration of instrument has an uncertainty which is consider into the uncertainty of the measurement.

3 Result

The test is performed with same operator and same equipment for testing the quality parameters of transformer oil in term of Tan Delta value and resistivity for ten times and observations are as shown below.

3.1 Uncertainty of measurement of Tan Delta

Observation – Refer Table 4

Mean = $x = 0.00759$.

Standard deviation = 2.31×10^{-4} .

Standard uncertainty = $U_1 = 0.000073$.

DOF = $n - 1$ (n = number of readings).

Accuracy of reading = $\pm 0.01\% = 0.0001$ (mentioned in technical specification).

Standard uncertainty = $U_2 = 5.7 \times 10^{-5}$.

Accuracy of test voltage = $\pm 1\% = 0.01$ (mentioned in technical specification).

Standard uncertainty = $U_3 = 0.00577$.

Calibration uncertainty of capacitor = $\pm 0.15\% = 0.0015$, at $K = 1.96$ (mentioned on calibration certificate).

Standard uncertainty = $U_4 = 0.0015 \div 1.96 = 0.00076$.

Combined uncertainty = U_C

$$= \sqrt{0.000073^2 + 0.000057^2 + 0.00577^2 + 0.00076^2} \\ = 0.00582.$$

Effective degree of freedom,

$$V_{eff} = \frac{U_C^4}{\frac{U_1^4}{9} + \frac{U_2^4}{\infty} + \frac{U_3^4}{\infty} + \frac{U_4^4}{\infty}} = \infty.$$

Then coverage factor (K) for $U_{eff} = \infty$ at level of confidence of approximately 95%, $K = 1.96$.

Expanded uncertainty = $0.00582 \times 1.96 = \pm 0.01140$.

Final result -0.00759 ± 0.01140 .

Uncertainty Budget – Refer Table 5.

Uncertainty contribution – Refer Figure 7.

3.2 Uncertainty of measurement of resistivity

Observation – Refer Table 6

Mean = $x = 19.703 \times 10^{12}$.

Standard deviation = 1.734×10^{12} .

Standard uncertainty = $U_1 = 0.5483 \times 10^{12}$.

DOF = $n - 1 = 9$ (n = number of readings).

Accuracy of reading = $\pm 2\% = 0.02$ (mentioned in technical specification).

Standard uncertainty $U_2 = 0.01154$.

Accuracy of test voltage = $\pm 1\% = 0.01$ (mentioned in technical specification).

Standard uncertainty = $U_3 = 0.00577$.

Calibration uncertainty of resistor = $\pm 0.02\% = 0.0002$.

Standard uncertainty = $U_4 = 0.00010$. ($K = 1.96$),

DOF = ∞ .

Combined uncertainty = U_C

$$= \sqrt{(0.5483 \times 10^{12})^2 + 0.01154^2 + 0.00577^2 + 0.00010^2}.$$

$$\text{Effective degree of freedom} = \frac{U_C^4}{\frac{U_1^4}{9} + \frac{U_2^4}{\infty} + \frac{U_3^4}{\infty} + \frac{U_4^4}{\infty}} = \infty.$$

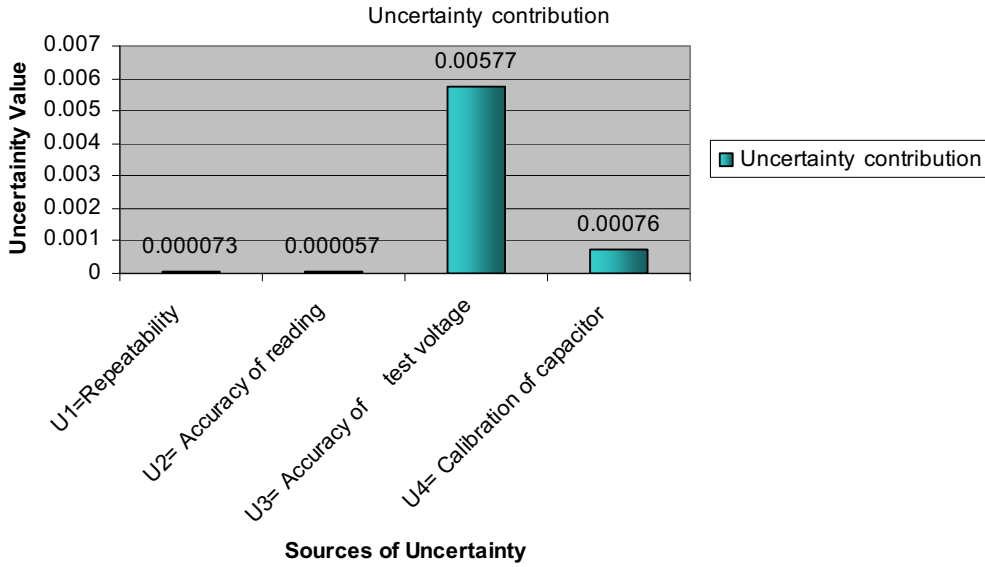


Fig. 7. (Color online) Effects of various factors for Tan Delta.

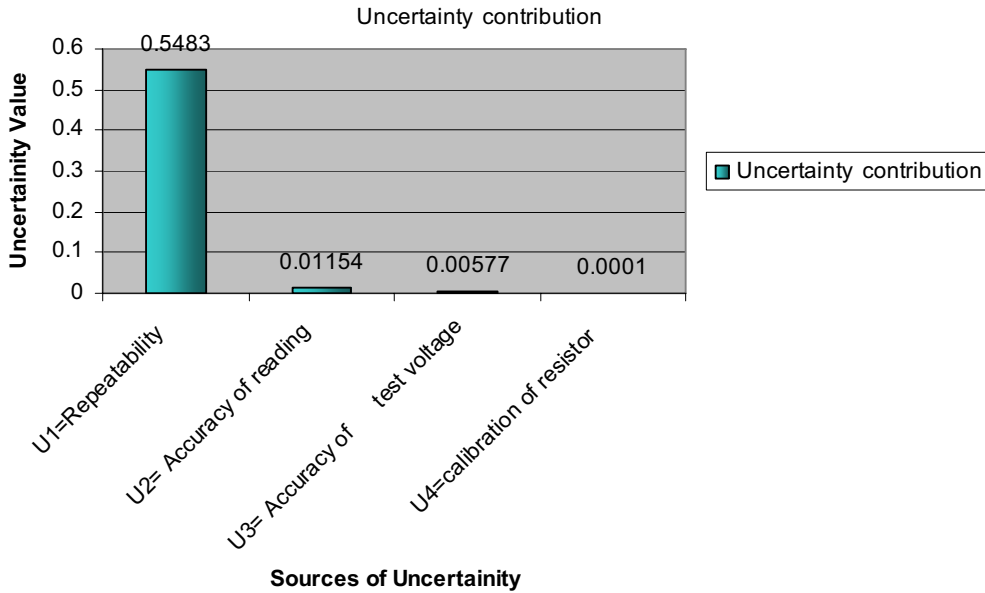


Fig. 8. (Color online) Effects of various factors for resistivity.

Then coverage factor (K) for $U_{eff} = \infty$ at level of confidence of approximately 95%, $K = 1.96$.

Expanded uncertainty = $0.5483 \times 10^{12} \times 1.96 = \pm 1.0966 \times 10^{12}$.

Considering coverage factor $K = 1.96$ at 95% confidence level.

Final result = $19.703 \times 10^{12} \pm 1.0966 \times 10^{12}$.

Uncertainty Budget – Refer Table 7.

Uncertainty Contribution – Refer Figure 8.

3.3 Combine effect analysis of test set up

Two quality parameters i.e. Tan Delta and resistivity of transformer oil are checked on single equipment setup. The

effects of individual parameters on combined uncertainty of measurement is case of resistivity is more as compare to Tan Delta as represented in Table 8.

4 Conclusion

Uncertainty of measurement plays vital role for deciding the quality of transformer oil. Selection of improper oil affects the performance of electrical appliances. In case of Tan Delta test uncertainty factor arising from test voltages is affecting more, so proper care should be taken for calibration of instrument and setting of test voltage so that the uncertainty value should get reduced. The main

Table 7. Uncertainty budget.

Sources	Probability type A or type B	Std uncertainty MPa	Sensitivity coefficient	Uncertainty contribution	DOF
$U_1 =$ Repeatability	Normal, type A	0.5483×10^{12}	1	0.5483×10^{12}	9
$U_2 =$ Accuracy of reading	Rectangular type B	0.01154	1	0.01154	∞
$U_3 =$ Accuracy of test voltage	Rectangular type B	0.00577	1	0.00577	∞
$U_4 =$ calibration of resistor	Rectangular type B	0.00010	1	0.00010	∞
Expanded uncertainty	$K = 1.96$			$\pm 1.0966 \times 10^{12}$	

Table 8. Effects of individual factors for two tests.

Test	Type-A		Type-B		
	Repeatability	Accuracy of reading	Accuracy of test voltage	calibration of capacitor	calibration of resistor
Tan Delta	0.000073	0.000057	0.00577	0.00076	–
Resistivity	0.5483×10^{12}	0.01154	0.00577	–	0.00010

influence factor in the determination of the uncertainty of measurement in case of resistivity is the variation attributed to the measurand that is the repeatability obtained in the measurements of the studied properties. The operator error which affects repeatability should be minimizing by following the proper procedure of the test. Even if the result of the measurement is not perfect, it is possible to obtain reliable information, since the result of the measurement is associated with its respective uncertainty. This study involves the development of a methodology for determining the result of measurement concerning electrical properties and their respective uncertainties. Such methodology, which has a possible systematic application, is associated with guaranteeing of reliability to the results of the electrical properties, as well as the possibility of Implementation in transformer oil testing laboratories.

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