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मानक

IS 16086 (2013): Insulating Liquids--Determination of the Dielectric Dissipation Factor by Measurement of the Conductance and Capacitance--Test Method [ETD 3:



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Indian Standard

INSULATING LIQUIDS — DETERMINATION OF THE DIELECTRIC DISSIPATION FACTOR BY MEASUREMENT OF THE CONDUCTANCE AND CAPACITANCE — TEST METHOD

ICS 17.220.99; 29.040.01

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Price Group 8

NATIONAL FOREWORD

This Indian Standard which is identical with IEC 61620 : 1998 'Insulating liquids — Determination of the dielectric dissipation factor by measurement of the conductance and capacitance — Test method' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Fluids for Electrotechnical Applications Sectional Committee and approval of the Electrotechnical Division Council.

The text of IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain terminology and conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

- a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
- b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

International Standard	Corresponding Indian Standard	Degree of Equivalence
IEC 60475 : 1974 Method of sampling liquid dielectrics	IS 6855 : 2003 Method of sampling for liquid dielectrics (<i>first revision</i>)	Technically Equivalent
ISO 5725-1 : 1994 Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions	IS 15393 (Part 1) : 2003 Accuracy (trueness and precision) of measurement methods and results: Part 1 General principles and definitions	Identical
ISO 5725-2 : 1994 Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method	IS 15393 (Part 2) : 2003 Accuracy (trueness and precision) of measurement methods and results: Part 2 Basic method for the determination of repeatability and reproducibility of a standard measurement method	do
ISO 5725-3 : 1994 Accuracy (trueness and precision) of measurement methods and results — Part 3: Intermediate measures of the precision of a standard measurement method	IS 15393 (Part 3) : 2003 Accuracy (trueness and precision) of measurement methods and results: Part 3 Intermediate measures of the precision of a standard measurement method	do
ISO 5725-4 : 1994 Accuracy (trueness and precision) of measurement methods and results — Part 4: Basic methods for the determination of the trueness of a standard measurement method	IS 15393 (Part 4) : 2003 Accuracy (trueness and precision) of measurement methods and results: Part 4 Basic methods for the determination of the trueness of a standard measurement method	do

INTRODUCTION

The conductivity σ is a characteristic of a liquid only if it is measured at thermodynamic equilibrium.

To fulfil this requirement high electric stress and/or prolonged voltage application is to be avoided, this is not the case in IEC 60247 for the d.c. resistivity measurement (electric stress up to 250 Vmm⁻¹, conventional arbitrary time of electrification 1 min).

There is a simple relationship between the dielectric dissipation factor tan δ , the conductivity σ and the permittivity ε of the liquid with no (or negligible) dipolar losses, which is the case of most liquids for electrotechnical applications:

$$\tan \delta = \frac{\sigma}{\varepsilon \omega}$$

where $\omega = 2 \pi f$ and *f* is the frequency of the voltage.

Therefore, the measurement of either tan δ or σ gives the same information on the conduction properties of the liquid. In fact, very often in practice, there are large discrepancies between the resistivity calculated from the measurement of tan δ with conventional apparatus and the d.c. resistivity measured following the recommendation of IEC 60247.

New devices for the measurement of the conductivity σ at thermodynamic equilibrium are currently available. They are able to measure easily and with precision very low values of σ . The capabilities of this new equipment allow measurements of σ of unused insulating liquids even at room temperature.

Indian Standard

INSULATING LIQUIDS — DETERMINATION OF THE DIELECTRIC DISSIPATION FACTOR BY MEASUREMENT OF THE CONDUCTANCE AND CAPACITANCE — TEST METHOD

1 Scope

This International Standard describes a method for the simultaneous measurement of conductance G and capacitance C enabling the calculation of the dielectric dissipation factor tan δ of insulating liquids. The proposed method applies both to unused insulating liquids and insulating liquids in service in transformers and in other electrical equipment.

The standard is no substitute for IEC 60247; rather it complements it insofar as it is particularly suited to highly insulating liquids and it recommends a method of measurement for these liquids. This method allows values of the dielectric dissipation factor as low as 10^{-6} at power frequency to be determined with certainty. Moreover, the range of measurements of tan δ lies between 10^{-6} and 1 and can be extended up to 200 in particular conditions.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60247:1978, Measurement of relative permittivity, dielectric dissipation factor and d.c. resistivity of insulating liquids

IEC 60475:1974, Method of sampling liquid dielectrics

ISO 5725-1:1994, Accuracy (trueness and precision) of measurement methods and results – Part 1: General principles and definitions

ISO 5725-2:1994, Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method

ISO 5725-3:1994, Accuracy (trueness and precision) of measurement methods and results – Part 3: Intermediate measures of the precision of a standard measurement method

ISO 5725-4:1994, Accuracy (trueness and precision) of measurement methods and results – Part 4: Basic methods for the determination of the trueness of a standard measurement method

IS 16086 : 2013 IEC 61620 : 1998

3 Definitions

For the purpose of this International Standard, the following definitions apply

3.1

conductivity (σ)

quantity related to the electric field strength *E* and to the conduction current density *j* by

 $j = \sigma E$

3.2

resistivity (*ρ*)

reciprocal of the conductivity σ , given by

$$\rho = \frac{1}{\sigma}$$

3.3

resistance (R)

the resistance of the liquid-filled test cell is the ratio of the voltage V applied to the cell to the direct or in-phase current I_R , and is given by

$$R = \frac{V}{I_R}$$

In the simplest case of plane parallel electrodes of area A and with a gap distance L,

$$R = \frac{\rho L}{A}$$

3.4

conductance (G)

reciprocal of the resistance, given by

$$G=\frac{1}{R}$$

3.5

capacitance (C)

the capacitance of the liquid-filled test cell is the ratio of the charge Q of the electrodes to the voltage V applied to the test cell. For a plane capacitor,

$$C = \frac{\varepsilon A}{L}$$

where ε is the permittivity of the liquid.

3.6

dielectric dissipation factor (dielectric loss tangent tan δ)

for a material subjected to a sinusoidal voltage, tan δ is the ratio of the value of the absorbed active power to the value of the reactive power. In the simple case of a capacitance *C* shunted by a resistance *R*,

$$\tan \delta = \frac{G}{C\omega}$$

where $\omega = 2\pi f$ and *f* is the frequency of the voltage.

Details about the factors influencing the conduction of liquids can be found in annex C.

4 Principle of operation

The principle of operation is to measure both the capacitive current and the conduction current by applying an alternate square wave voltage to the test cell. The capacitive current is measured during the rise time and the conduction current is measured during the stable period of the voltage, but prior to any possible disturbance of the electric field due to ion accumulation. The currents can be measured at both positive and negative half-waves of the alternate square wave voltage for a number of cycles to increase the accuracy of the measurement (see figure 1 and [6] to [12]*).



Figure 1 – Principle of operation using the square wave method

The square wave voltage V(t) of amplitude $\pm V$, is periodically reversed with a slope dV/dt. The current *I* during the rise and fall of the voltage is the sum of the capacitive current (displacement current) and the conduction current, i.e.

$$I = C \times \left(\frac{\mathrm{d}V}{\mathrm{d}t}\right) + \frac{V}{R}$$

The capacitive current I_C is measured during the rising and falling periods of V(t).

The conduction current I_R is measured at the flat parts of V(t), since $V/R << I_C$, after the system has settled for a time at the beginning of each flat period. The capacitance C, the resistance R (or conductance G) and tan δ at a given angular frequency ω can be determined from the following relations:

$$C = \frac{I_{C}}{\left(\frac{dV}{dt}\right)}$$
$$R = \frac{V}{I_{R}} \text{ or } G = \frac{I_{R}}{V}$$
$$\tan \delta = \frac{1}{\omega CR}$$

^{*} Figures in square brackets refer to the bibliography in annex D.

IS 16086 : 2013 IEC 61620 : 1998

5 Apparatus

Apparatus specifically constructed or assembled from stand-alone instruments can be used to realize this measurement method. The block diagram shown in figure 2, and the following subclauses illustrate an appropriate equipment.



Key

- 1 Test cell
- 2 Heating device
- 3 Square wave generator
- 4 Measurement chain
- 5 Meter
- 6 Recorder

Figure 2 – Block diagram for the measuring apparatus

5.1 Test cell

Three terminal test cells designed according to the recommendations given in IEC 60247 are generally suitable for this measurement.

An additional type of cell in which there is no bridge made by any solid insulating material between the measurement electrodes, as shown in figure 3, can be used. This type of cell often proves more accurate on highly insulating liquids.



Key

- 1 Cover
- 2 Inner electrode
- 3 Outer electrode
- 4 Stainless steel vessel
- 5 Sheath for temperature measurement
- 6 BNC plugs for electrical connection

Figure 3 – Example of a test cell designed for highly insulating liquids

The distance between the outer and the inner electrode is typically 4 mm; the minimum distance should not be lower than 1 mm. The material recommended for the electrodes is stainless steel. As an example, the diameter of the inner electrode is 43 mm, that of the outer electrode is 51 mm; the height of the electrodes is 60 mm; the diameter of the stainless steel vessel is 65 mm.

This type of test cell was designed to minimise the effects of contamination from the surfaces in contact with the liquid: although the surface in contact is large, the ratio χ = "electrode surfaces" / "liquid volume" is rather small (χ = 2,6 cm⁻¹) due to the large volume of liquid (ν = 200 cm³).

NOTE – It is recommended to restrict the use of a given cell to a particular type of liquid.

5.2 Heating device

The heating device shall be adequate to maintain the temperature of the measurement cell within ± 1 °C of the prescribed value. It may consist of a forced draught air oven or an oil-filled thermostatically controlled bath fitted with a shelf to support the cell.

The heating device shall provide screened electrical connections to the cell.

5.3 Square wave generator

The square wave generator shall deliver a highly stable quasi-rectangular voltage. The following characteristics are suitable:

- amplitude: 10 V to 100 V;
- frequency: 0,1 Hz to 1 Hz;
- ripple: <1 %;</p>
- rise time: 1 ms to 100 ms.

5.4 Measurement chain

The conduction current I_R through the test cell is measured during the second part of each half-wave and averaged over a number of periods depending on the range of measurement. The measuring chain gives the conductance *G* of the test cell.

$$G = \frac{I_R}{V}$$

As an example, the range of measurable conductance values is 2×10^{-6} S to 2×10^{-14} S with a margin of error of less than 2 %.

The capacitance C of the test cell is deduced from the current measured during the rise of the voltage. The measurable capacitance values are between 10 pF and 1 000 pF with an uncertainty of less than 1 %.

As an example, for a liquid of relative permittivity $\varepsilon_r = 2$, a conductance value of 2×10^{-14} S gives tan $\delta = 0.8 \times 10^{-6}$ at 50 Hz.

6 Sampling

The insulating liquid samples shall be taken in accordance with IEC 60475 by qualified personnel. During transportation and storage the samples shall be protected from direct light.

7 Labelling

Insulating liquid samples shall be properly labelled before being dispatched to the laboratory.

The following information is necessary:

- customer or plant;
- identification of the liquid (type and grade);
- identification of equipment;
- date and time of sampling;
- temperature when sampling;
- point of sampling;
- other pertinent information.

8 Procedure

In order to get a significant measurement of dissipation factor tan δ , it is essential to follow precise rules concerning

- the careful cleaning of the test cell;
- the careful filling of the test cell and handling of the liquid samples and of the test cell itself.

8.1 Cleaning of the test cell

8.1.1 Operating procedure

According to the state of cleanliness of the test cell and the level of conductivity of the liquid to be measured, the cleaning procedure of the test cell can be more or less sophisticated and take more or less time.

If the cleanliness of the test cell is unknown or if there is any doubt, a cleaning procedure shall be applied.

Many different types of cleaning procedure can be used provided they have proved to be efficient.

In annex A, a reference procedure is given. It shall be used in case of dispute between two laboratories.

In annex B, an appropriate simplified cleaning procedure is given as an example.

NOTE – For routine testing and when a number of samples of the same type of unused liquid are to be tested consecutively, the same test cell may be used without intermediate cleaning, provided that the value of the property for the sample previously tested is better than the specified value. If such is not the case, the test cell must be cleaned before being used for further tests.

8.1.2 Checking the cleanliness of the empty cell

To obtain a significant measurement it is necessary that the electrical losses of the empty cell be much lower than those of the liquid to be measured.

NOTE - Nevertheless, the walls of the vessel and the electrodes may retain impurities liable to dissolve eventually in the liquid.

8.1.3 Checking the cleanliness of the filled cell for measurement at room temperature

If the test cell is perfectly clean and if the temperature of the liquid is constant, σ and tan δ are independent of time. The measurement can thus be taken as soon as it is practically possible. In fact, this can be done within 1 min. Moreover, one measurement on a single sample is enough to obtain the right value.

It may happen that, at constant temperature, the conductivity σ (or tan δ) increases or decreases with time, but not by more than 2 % at two minutes after filling. In this case the test cell is considered sufficiently clean and the first measured value, i.e. at one minute or less after filling, may be recorded.

If not, it is recommended, after having cleaned the test cell again, to take a second sample of the same liquid and to carry out a second measurement. The lowest of the two values shall be retained as already recommended in IEC 60247.

8.1.4 Checking the filled cell for measurement at temperature above room temperature

Before making any measurement at high temperature, ensure that the temperature of the liquid throughout the cell is constant. Except for cases where the test cell is perfectly clean, the result of the measurement will depend on the way in which the test cell and the liquid are brought to high temperature.

If the test cell is perfectly clean and if the temperature of the liquid is constant, the conductivity σ and tan δ are independent of time. The measurement can thus be taken immediately. Practically, the measurement can be taken as soon as the temperature can be considered constant. Moreover, one measurement on a single sample is enough to obtain the correct value.

It may happen that, even though the liquid in the test cell is at constant temperature, the conductivity σ (or tan δ) increases or decreases with time. This can be due to different causes: e.g. heating at elevated temperatures may alter the composition of certain insulating liquids, or modify the moisture content of particles. In practice, temperature is not perfectly constant and its variations naturally influence the possible variations of σ (or tan δ). The conductivity σ (or tan δ) of liquids more or less varies with the temperature according to the nature of the liquid, typically up to 5 % per degree Celsius. Therefore, the origin of the variations of σ (or tan δ) can only be determined if the temperature fluctuations are small enough. Then, if the drift of σ (or tan δ) is less than 2 % over 2 min, the test cell is considered sufficiently clean, and the value measured one minute or less after temperature is considered as constant can be recorded.

If the test cell is not perfectly clean, the heating time will influence the values measured, even the first one, because the impurities coming from the test cell dissolve into the liquid. The first value measured shall therefore be rejected, and the test cell cleaned again.

8.2 Precautions to be taken when filling the test cell

When filling the cell with the sample, ensure that the environmental atmosphere is, as far as possible, free of any vapours or gases liable to dissolve in the liquid.

The electrodes shall be entirely immersed in the liquid.

NOTE – When not in use, the cell must be stored in a desiccator.

8.3 Test temperature

Measurement of the conductivity and of the dissipation factor of a liquid can be performed at any temperature.

Ambient temperature is recommended for its simplicity of operation and time-saving qualities. The ambient temperature being essentially variable, a fixed value shall be agreed (for instance 25 °C \pm 1 °C).

There is nothing to prevent carrying out the test at a higher test temperature (for instance 40 °C \pm 1 °C, 90 °C \pm 1 °C or more).

8.4 Heating methods

To perform a measurement at high temperature several heating methods can be used. The time required to reach the test temperature will depend on the heating method and may typically vary from 10 min to 60 min. If the test cell is not perfectly clean, the increase in conductivity due to the progressive dissolution of impurities will depend on the duration of the heating period, and the measured conductivity will therefore depend on the method of heating.

Thus it is recommended to heat the test cell as fast as possible.

A suitable way to achieve this is to heat separately the test cell and the liquid contained in a clean vessel. Another method consists in rapidly heating the liquid in the test cell itself.

NOTE – Rapidly heating the liquid and cell together may result in a significant thermal gradient. Before using such a method the uniformity of temperature should be verified for type of fluid being tested.

8.5 Measurement

Fill the cell with the sample avoiding any pollution of the liquid or of the cell (see 8.2).

Check cleanliness according to 8.1.3 and 8.1.4. If the cell is sufficiently clean (see 8.1), note the values of G and C.

9 Expression of results

Results may be calculated using the following equation:

$$\tan \delta = \frac{G}{C\omega}$$

where

G is the conductance, in siemens (S);

C is the capacitance, in farad (F);

 ω is the angular frequency, in radian/second (rad/s), $\omega = 2\pi f$;

f is the chosen frequency, in Hertz (Hz).

NOTE – Provided that the relative permittivity \mathcal{E}_r at the measuring temperature is known the conductivity of the liquid can be calculated by the following equation:

$$\sigma = \frac{\varepsilon G}{C}$$

where $\varepsilon = \varepsilon_0 \varepsilon_r$

10 Test report

The report shall include the following:

- sample identification;
- temperature of test;
- measured values of G and C;
- calculated values of tan δ .

11 Precision

11.1 General

The precision of a test method is the closeness of several experimental results obtained on identical samples. Assessment of the precision is given by the repeatability r and reproducibility R, both defined in ISO 5725-1. Calculation methods are given in ISO 5725-2, ISO 5725-3 and ISO 5725-4.

The values of r and R for the dielectric dissipation factor of an insulating liquid depend on the nature of the liquid under test, whether it is unused or used, and that of the temperature; these values are impaired when tan δ is very low (less than 10⁻⁴), as found in highly insulating liquids which are readily affected by impurities, handling, cleaning of the test cell, etc.

11.2 Repeatability (x)

If two measurements A and B are obtained in one laboratory at room temperature, they can be considered acceptable if the absolute difference |A - B| satisfies the following relation:

$$|A - B| < \alpha Min (A,B)$$

where Min (A,B) is the lowest of the two values A and B.

For unused insulating liquids: $\alpha = 0.2$

For used insulating liquids: $\alpha = 0,1$

11.3 Reproducibility (R)

If two measurements A and B are obtained in two different laboratories at room temperature, the above relation is still valid with the following values for α :

For unused insulating liquids: $\alpha = 0.35$

For used insulating liquids: $\alpha = 0,20$

11.4 Examples of r and R

Examples of r and R values are given in the table below and are deduced from inter-laboratory tests carried out at room temperature on mineral insulating oils.

Table 1 – Values of r	and R according to	the condition of the	e mineral insulating oil
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	tan δ	R	r
Unused mineral oil	2×10^{-6}	$1,2 \times 10^{-6}$	$0,4 imes 10^{-6}$
Used mineral oil	$1,5 \times 10^{-4}$	$3,5 imes 10^{-5}$	$1,2 \times 10^{-5}$
Used mineral oil	1 × 10 ⁻³	$1,2 \times 10^{-4}$	$0,8 imes 10^{-4}$

Annex A

(normative)

Exhaustive cleaning procedure for the test cells

- a) Empty the test cell and drain off the liquid which remains on the different parts of the cell.
- b) Boil the different parts of the cell (without dismantling them) for at least 5 min in a solution of about 5 % trisodium phosphate diluted in de-ionized water, followed by several rinses with de-ionized water.
- c) Rinse for 5 min under running tap water.
- d) Boil in de-ionized water for at least half an hour.
- e) Dry the different parts of the cell in a clean oven at 105 °C for 2 h.
- f) Let the parts of the cell cool down to room temperature in a desiccator without touching the electrode surface with bare hands.
- g) Assemble the parts of the cell, still without touching the electrode surface.
- h) Fill the cell with the insulating liquid to be measured.
- i) Empty the first filling and perform the measurement on the second filling.

NOTE - If the cleaned cell is not used immediately, keep it dry in a desiccator in order to protect it against any contaminants.

Annex B

(normative)

Simplified cleaning procedure for test cells devoted to only one type of liquid

As stated in IEC 60247 it may be desirable to restrict the use of a cell to a particular class of liquids. In this case, a simplified cleaning procedure is often sufficient. In fact, the required degree of cleanliness of the test cell depends on the loss level of the liquid previously contained with respect to the expected loss level of the liquid to be measured. For this reason, as stated in IEC 60247, cleaning need not precede a routine measurement which is carried out following a measurement in which the property measured was within the limiting value specified. In this case, the test cell shall be stored filled with the previously measured liquid, preferably in a desiccator.

If it appears that the cell should be cleaned, the following procedure shall be applied:

- a) empty the test cell and drain off the liquid which remains on the different parts of the cell;
- b) rinse for 5 min the different parts with an analytical grade solvent appropriate to the previously tested liquid (the recommended solvents for the different insulating liquids are listed in the note);
- c) rinse the different parts with analytical grade ethanol;
- d) dry them in a clean oven at 80 °C for 3 h and let them cool down to room temperature in a desiccator;
- e) fill the cell with the insulating liquid to be measured;
- f) empty the first filling and perform measurement on the second filling.

NOTE - Recommended analytical grade solvents:

Cyclohexane for

- hydrocarbon liquids like mineral oil (IEC 60296) [1];
- polybutenes (IEC 60963) [4];
- alkylbenzene, mono/dibenzyltoluene, phenylxylylethane and isopropylnaphthalene (IEC 60867) [3];

Ethanol for

- organic esters like dioctylphthalate, tetrahydricalcohol esters (IEC 61099) [5];

Toluene for

- silicone liquids (IEC 60836) [2].

Annex C

(informative)

General considerations on the factors influencing the conduction of liquids

C.1 Volume conductivity

The conductivity σ is a scalar quantity which is related to the electric field strength *E* and to the conduction current density *j* by the relationship

 $j = \sigma E$

This is a local relationship, known as Ohm's law. It applies at any location of a material.

Conductivity σ depends on the properties of the material itself and on those of the foreign substances that it may contain; σ may also depend on the action of the electric field upon the material.

For an homogeneous material, particularly for a liquid subjected to a low field, σ is constant throughout its volume and the volume conductivity is therefore a characteristic of the liquid.

The electrical conduction at low field of most of the insulating liquids is due to the dissociation and recombination of ions from one (or several) ionizable substance(s).

At thermodynamic equilibrium (with no field applied, or with a very small field), the volume conductivity (expressed in S m^{-1}) is

$$\sigma = \sum_{i} k_{i} q_{i}$$

where

 k_i represents the mobilities of positive and negative charge carriers (ions), in m²/V × s;

 q_i represents the volume charge densities, in C m⁻³

As an example, for a single ionizable substance

$$\sigma = k_+ q_+ + k_- q_-$$

 σ is a characteristic of the ionic purity of the liquid.

To obtain σ , it is necessary to apply a voltage V and measure a current I_R in well-specified conditions using a convenient test cell. Practically, the test cell is designed to ensure a uniform or quasi-uniform field.

If the electrode gap distance is L and the surface area of the electrodes is A, the useful relations are

$$E = \frac{V}{L}$$

$$\rightarrow \sigma = \frac{j}{E} = \frac{I_R L}{VA}$$

$$j = \frac{I_R}{A}$$

where

 $\frac{V}{I_{R}}$ is the resistance *R* of the liquid-filled test cell, in ohms;

 $G = \frac{1}{R}$ is the conductance.

The volume resistivity is the reciprocal of the volume conductivity: $\rho = \frac{1}{\sigma}$

C.2 Dielectric dissipation factor (tan δ)

For a material subjected to a sinusoidal voltage, tan δ is the numerical value of the ratio of the imaginary to the real part of the complex permittivity.

For a capacitance *C* with no losses, the capacitive current I_C is in advance on the voltage *V* by $\pi/2$ and its amplitude is

$$I_C = C\omega V$$

where $\omega = 2\pi f$ and f is the frequency of the voltage.

For a capacitance shunted by a resistance *R* there is an in-phase component $I_R = \frac{V}{R}$ and the total current *I** is now in advance on *V* by an angle φ

$$\varphi = \frac{\pi}{2} - \delta$$

where

 $\delta~$ is the loss angle, the angle between I^* and the capacitive component I_C (see figure 4), and

$$\tan \delta = \frac{1}{RC\omega}$$
, or $\tan \delta = \frac{G}{C\omega}$



Figure 4 – Vectorial representation of voltage and currents with angles δ and φ

A liquid of absolute permittivity $\varepsilon = \varepsilon_0 \varepsilon_r$ (where ε_r is the relative permittivity) and of conductivity σ , with no dipolar losses at the considered frequency, admits as an equivalent circuit a capacitance *C* shunted by a resistance *R* with

$$R = \frac{L}{\sigma A}$$
 and $C = \frac{\varepsilon A}{L}$

then

$$\tan \delta = \frac{\sigma}{\varepsilon \omega} = \frac{1}{\varepsilon \rho \omega}$$

This shows that tan δ can be obtained from the sole measurement of σ and vice versa.

C.3 Nature and mobility of charge carriers

In well-filtered liquids, charge carriers are ions or ionic associations of higher order (multipoles) which result from the spontaneous dissociation of tiny amounts of ionizable substances or from the action of natural radiations. Electron or hole conduction will never occur in the situations considered in this standard.

lons draw neutral molecules to themselves (solvation phenomena), especially ions of small size. This is the reason why, in a given liquid, ionic mobilities are not very different, whatever the nature and the polarity of the ions. If a solvated ion carrying a charge e is modelled as a sphere of radius a, in a liquid of dynamic viscosity η , then equating the Coulomb force to the viscous force leads to the following expression of the ionic mobility k:

$$k = \frac{e}{6\pi\eta a}$$

This expression generally gives the correct order of magnitude, e.g.

$$k = 10^{-9} \, \frac{m^2}{Vs}$$

for $\eta = 10^{-2}$ Pa × s (typical value for a transformer oil at room temperature) and a = 0.8 nm.

The relation ηk = constant, known as Walden's rule, is commonly obeyed when the temperature varies, which allows us to evaluate the ion drift velocity by

$$v = kE$$

and the ion transit time *t* in a uniform field across the gap *L* by

$$t = \frac{L}{kE} = \frac{L^2}{kV}$$

C.4 Relation between the conductivity and some properties of dissociable products

With the simplifying hypothesis of a single electrolyte dissolved in a perfectly insulating liquid, the equilibrium reaction between the undissociated molecules AB of this electrolyte in concentration v and its ions A^+ and B^- is given by:

$$AB \leftrightarrow A^+ + B^-$$

At thermodynamic equilibrium, the number of ions generated by dissociation is equal to the number of those which recombine. If K_D is the dissociation constant, K_R the recombination constant, n_{\pm} the ionic densities, this equilibrium may be written

$$K_D v = K_R n_+ n_-$$

and hence

$$n_+ = n_- = \sqrt{\frac{K_D v}{K_R}}$$

The volume charge densities being $q_{\pm} = n_{\pm}e$, the conductivity is

$$\sigma = (k_+ + k_-)e\sqrt{\frac{K_D v}{K_R}}$$

C.5 Influence of the electric field and of the voltage on liquid conduction

As regards bulk conduction due to dissociation / recombination processes, the thermodynamic equilibrium will not significantly be displaced if the applied voltage is low enough or if the duration of this voltage (with the same polarity) is much shorter than the transit time of ions from one electrode to the other.

The recombination constant K_R is independent of the applied field, whereas the dissociation constant K_D increases when the field increases. The field-enhanced dissociation, according to Onsager's theory, is negligible whatever the liquid if $E < 1 \text{ kVcm}^{-1}$, but the conduction may increase noticeably when $E > 5 \text{ kVcm}^{-1}$ (an increase of 50 % can be expected for $E = 10 \text{ kVcm}^{-1}$ if $\varepsilon_r = 2,2$).

The ideal behaviour of ion neutralisation when the ions reach the electrode is generally not observed in practical situations for the following reasons:

- on the one hand, they can be blocked, as their discharge is not instantaneous, and hence accumulate to build a unipolar charged layer, which can be released when the field is reversed;
- on the other hand, either at the anode or at the cathode, or both, ions of the same sign as that of the electrode can be generated by various injection mechanisms (either in polar or non-polar liquids).

These ion injections depend on the nature of the liquid, its impurities and the metal of the electrodes. These phenomena are generally only noticeable at fields above say 1 kVcm⁻¹.

Charge injection, charge depletion, motion of unipolar charged layers, may produce electrohydrodynamic (EHD) liquid motion favouring charge transport and thus increasing the apparent conductivity, especially in viscous liquids.

The contribution of EHD motion in insulating liquids is usually negligible up to voltages of several hundred volts.

C.6 Influence of the temperature on liquid conduction

An increase in temperature will produce an increase in the conductivity depending both on the properties of the liquid (permittivity, viscosity) and on those of the dissolved substances (dissociation constant).

lon mobility, according to Walden's rule, increases due to viscosity decreasing when the temperature rises.

The increase of the dissociation constant when the temperature is raised may vary widely from one substance to another, but is generally quasi-exponential.

Annex D

(informative)

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(Continued from second cover)

The technical committee has reviewed the provision of the following International Standard referred in this adopted standard and has decided that it is acceptable for use in conjunction with this standard:

International Standard

Title

IEC 60247 : 1978

Measurement of relative permittivity, dielectric dissipation factor and d.c. resistivity of insulating liquids

Only the English language text has been retained while adopting it in this Indian Standard and as such the page numbers given here are not the same as in the IEC Publication.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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This Indian Standard has been developed from Doc No.: ETD 03 (6358).

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