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REDLINE VERSION

INTERNATIONAL STANDARD

Insulating liquids – Determination of the breakdown voltage at power frequency – Test method

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Insulating liquids – Determination of the breakdown voltage at power frequency – Test method

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INSULATING LIQUIDS – DETERMINATION OF THE BREAKDOWN VOLTAGE AT POWER FREQUENCY – TEST METHOD

FOREWORD

This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 60156:2018. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 60156 has been prepared by IEC technical committee 10: Fluids for electrotechnical applications. It is an International Standard.

This fourth edition cancels and replaces the third edition published in 2018. This edition constitutes a technical revision.

This edition constitutes a technical revision and, mainly, confirms the content of the previous edition even if some advances are included. The test method has not been changed for practical reasons, due to the very large number of instrumentations disseminated around the world.

The text of this International Standard is based on the following documents:

Draft	Report on voting
10/1241/FDIS	10/1256/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

INTRODUCTION

As normally applied, breakdown voltage of insulating liquids is not a basic material property but an empirical test procedure intended to indicate the presence of contaminants such as water and solid suspended matter and the advisability of carrying out drying and filtration treatment.

The AC breakdown voltage value of insulating liquids strongly depends on the particular set of conditions used in its measurement. Therefore, standardized testing procedures and equipment are essential for the unambiguous interpretation of test results.

The method described in this document applies to either acceptance tests on new deliveries of insulating liquids or testing of treated liquids prior to or during filling into electrical equipment, or to the monitoring and maintenance of ~~oil-filled~~ insulating liquid-filled apparatus in service. It specifies rigorous sample-handling procedures and temperature control that should be adhered to when certified results are required. For routine tests, especially in the field, less stringent procedures may be practicable, and it is the responsibility of the user to determine their effect on the results.

Annex A describes, for comparison, an alternative test method which could be introduced in the future. Annex B describes special test methods, using cells which may include low volume samples. Annex C describes a reference material for a performance test and check according to IEC 60060-3 [1][1].

1 Numbers in square brackets refer to the Bibliography.

INSULATING LIQUIDS – DETERMINATION OF THE BREAKDOWN VOLTAGE AT POWER FREQUENCY – TEST METHOD

1 Scope

This document specifies the method for determining the dielectric breakdown voltage of insulating liquids at power frequency. The test procedure is performed in a specified apparatus, where the oil sample is subjected to an increasing AC electrical field until breakdown occurs. The method applies to all types of insulating liquids of nominal viscosity up to 350 mm^2/s at 40 °C. It is appropriate both for acceptance testing on unused liquids at the time of their delivery and for establishing the condition of samples taken in monitoring and maintenance of equipment.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60475, *Method of sampling insulating liquids*

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

4 Electrical apparatus

4.1 General

The electrical apparatus consists of the following units:

1) voltage regulator,
2) step-up transformer,
3) switching system,
4) current-limiting resistors,
5) measuring device.

Two or more of these units may be integrated in any equipment system.

4.2 Voltage regulator

The test voltage shall be increased with an automatic control of the required uniform voltage rate of rise. The device should not introduce harmonics disturbances (< 3 %) and the AC source should be free from harmonics.

4.3 Step-up transformer

The test voltage is obtained by using a step-up or resonant transformer supplied from an AC source using 48 Hz to 62 Hz (sinusoidal waveform). The voltage source value is constantly increased. The controls of the variable low-voltage source shall be capable of varying the test voltage smoothly, uniformly and without overshoots or transients. Incremental increases (produced, for example, by a variable auto-transformer or an amplifier) shall not exceed 2 % of the expected breakdown voltage.

The centre-point of the secondary winding of the transformer should be connected to earth.

4.4 Switching system

The circuit shall be opened automatically if a sustained arc between the electrodes occurs and the voltage between the electrodes collapses ~~to a voltage less than 500 V~~.

NOTE Typically, voltage collapse is detected in the range of 500 V.

The primary circuit of the step-up transformer shall be fitted with a circuit-breaker operated by the current sensing device, resulting from the breakdown of the sample and shall break the voltage within 10 ms.

The sensitivity of the current or voltage sensing element depends on the energy-limiting device employed and only approximate guidance can be given.

A cut-off time of < 100 µs, as given in the previous edition of this document, is ~~needed~~ necessary to perform multiple breakdowns on silicone liquids.

4.5 Current-limiting resistors

To protect the equipment and to avoid excessive decomposition at the instant of breakdown of liquids, such as silicone or ester liquids, a resistance limiting the breakdown current shall be inserted in series with the test cell.

The short-circuit current of the transformer and associated circuits shall be within the range of 10 mA to 25 mA for all voltages higher than 15 kV. This may be achieved by a combination of resistors in either or both the primary and secondary circuits of the high-voltage transformer.

4.6 Measuring system

For the purpose of this document, the magnitude of the test voltage is defined as its peak value divided by $\sqrt{2}$.

The output voltage of the step-up transformer may be measured by means of a measuring system consisting of a voltage divider or a measuring winding of the step-up transformer coupled with a peak-voltmeter. The measuring system shall be calibrated up to the upper scale voltage to be measured. A method of calibration which has been found satisfactory is the use of a transfer standard. This is an auxiliary measuring device which is connected in place of the test cell between the high-voltage terminals to which it presents an impedance similar to the one of the sample liquids. The auxiliary device is separately calibrated against a primary standard [2], [3].

5 Test assembly

5.1 General

The breakdown voltage test is performed following the method described herewith as a routine test.

5.2 Test cell

The volume of the cell shall be between 350 ml and 600 ml.

The cell shall be made from electrically insulating materials that are not hygroscopic. The cell shall be transparent and chemically inert, resistant to the insulating liquid and to the cleaning agent that shall be used. ~~A glass cell is the preferred option.~~ Whilst glass is a commonly used material, other suitable materials such as plastics or polymers are appropriate, provided they have high chemical resistance to the insulating liquids (including mineral oils, ester liquids, etc.).

The cell shall be provided with a cover and shall be designed to permit easy removal of the electrodes for cleaning and maintenance. To improve homogenization of the test liquid, a rounded bottom shape of the cell is recommended. Containers and covers shall be cleaned by washing with a suitable solvent or clean insulating liquid to remove residues of an earlier sample. After cleaning, containers shall be immediately capped and kept closed until used again. Electrodes shall be stored in clean insulating liquids.

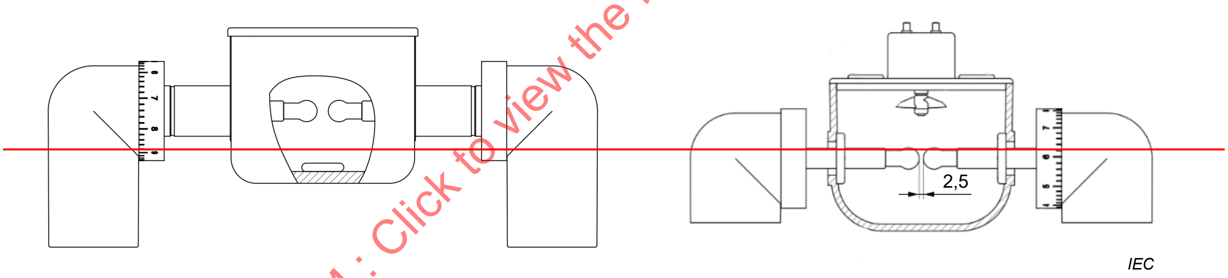
NOTE 1 It is preferable, in the case of esters to use a similar liquid to store the electrodes.

Different shapes of electrodes give different results. The partially hemispherical electrode shall be used, unless otherwise stated.

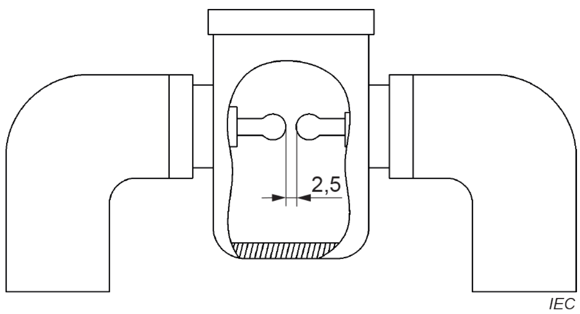
NOTE 2 If the difference in the shape of electrodes is minimal, the results difference is also minimal.

Examples of suitable cell designs are given in Figure 1 and Figure 2.

Dimensions in millimetres



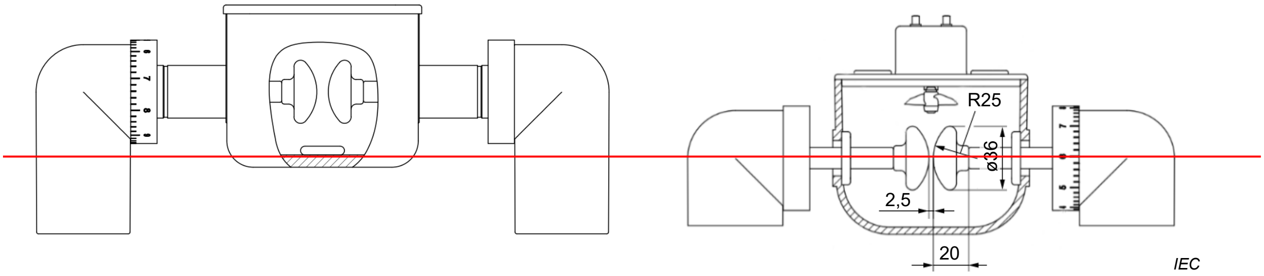
~~NOTE The stirring device can be mounted on the top (right side figure) or on the bottom (left side figure). The stirring device position and Vernier shifter are reported only as reference.~~



NOTE The stirring device can be mounted on the top or on the bottom.

Figure 1 – Example of test cell with spherical electrodes 12,5 mm to 13,0 mm diameter

Dimensions in millimetres



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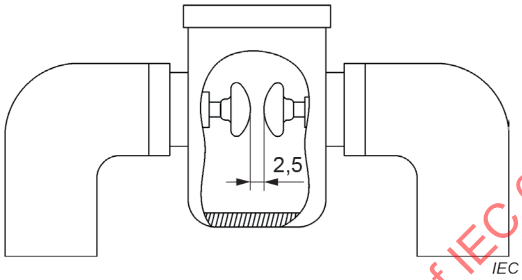


NOTE The stirring device can be mounted on the top or on the bottom.

Figure 2 – Example of test cell with partially hemispherical electrodes with 25 mm radius and 36 mm diameter

5.3 Electrodes

The electrodes shall be made either of brass, bronze or austenitic stainless steel. They shall be polished and, in shape, either spherical (12,5 mm to 13,0 mm diameter) as shown in Figure 1 or in partially hemispherical shape (25 mm ± 0,25 mm radius) as shown in Figure 2. The axis of the electrode system shall be horizontal and shall be at least 40 mm below the surface of the test liquid. No part of the cell or stirrer shall influence the electric field between the electrodes. The gap between the electrodes shall be 2,50 mm ± 0,05 mm.

The electrodes shall be examined frequently for pitting or other damage and shall be maintained or replaced as soon as such damage is observed.

NOTE The electrodes can be replaced or refurbished typically after 5 000 single breakdowns. The surface of the electrodes can be polished with a maximum grain diameter of 10 µm. The limit of the arithmetical mean deviation of the roughness profile of the electrodes can be Ra ~~≤~~ = < 0,5 µm, according to ~~ISO 4287~~ ISO 21290-2 [4].

5.4 Stirring device

The use of an automatic stirring device is recommended, to be used at all times during the test.

The stirrer shall be mounted in the test cell ~~in order to maximize the homogenization of the liquid~~. It shall be designed so that it is easily cleaned. Stirring shall be achieved by means of a two-bladed or appropriate stirrer of effective diameter 25 mm to 35 mm, axial depth 5 mm to 10 mm, rotating at a speed of 200 r/min to 300 r/min. The stirrer shall not produce air bubbles. It shall be fully immersed in the liquid sample. ~~Examples of stirring systems mounted in test cells are reported in Figures 1 and 2.~~

NOTE 1 To avoid bubbles between the electrodes, the stirrer can rotate preferably in such a direction that bubbles can be removed [5].

NOTE 2 The stirring device can be mounted on the top or on the bottom. ~~In Figures 1 and 2, the stirring device position is reported only as reference.~~

NOTE 3 ~~A magnetic stirring device can be also used.~~ Stirring by means of a magnetic bar (20 mm to 25 mm in length and 5 mm to 10 mm in diameter) is an acceptable solution, taking into consideration the collecting of magnetic particles from the fluid on the magnetic bar.

6 Preparation of electrodes

New electrodes shall be cleaned and fulfil the requirements of 5.3. Preparation of the electrodes shall follow the following procedure:

– clean all surfaces with a suitable volatile solvent and allow the solvent to evaporate;
– polish with fine abrasive powder (for example, jeweller's rouge) or abrasive paper or cloth, for example crocus cloth (see 5.3);
– after polishing, clean with petroleum spirit (reagent quality: boiling range of about 40 °C to 80 °C) followed by acetone (reagent quality);
– assemble the electrodes in the cell, fill with a clean, unused insulating liquid of the type to be tested;
– before the first breakdown test, raise the voltage until breakdown 24 times.

This procedure shall be repeated after each cleaning or change of electrodes.

7 Test assembly preparation

It is recommended that a separate test cell assembly be reserved for different insulating liquid types.

Test assemblies shall be stored in a dry place, covered and filled with dry insulating liquid of the type in regular use in the cell.

On change of the type of liquid under test, remove all residues of the previous liquid with an appropriate solvent, rinse the assembly with a clean, dry liquid of the same type as the one to be tested, drain and refill.

8 Sampling

Sampling shall be carried out in accordance with IEC 60475.

NOTE Breakdown voltage is extremely sensitive to the slightest contamination of the sample by water and particulate matter. Special precautions can be implemented to avoid contamination of the sample and the need for trained personnel and experienced supervision. The sample is taken where the liquid is likely to be most contaminated, usually at the lowest point of the container holding it, unless otherwise specified.

The test is carried out on the sample as received without drying or degassing, unless otherwise specified.

9 Test procedure

9.1 Sample preparation

Immediately before filling the test cell, the sample container is gently agitated and turned over several times in such a way as to ensure, as far as possible, a homogeneous distribution of the impurities contained in the liquid without causing the formation of air bubbles.

A possible method is an automatic rotation of the sample container horizontally for 1 min with a recommended speed of 30 r/min.

Equilibrate the sample to room temperature. Unnecessary exposure to the ambient air of the sample shall be avoided. The sample liquid is exposed to ambient air only during pouring from the sampling vessel to the test cell.

9.2 Filling of the cell

Immediately before commencing the test, drain the test cell and rinse the walls, electrodes and other component parts, with the test liquid. Drain and slowly fill with the test liquid avoiding the formation of air bubbles.

Measure and record the temperature of the liquid.

Close the test cell directly after filling.

9.3 Application of the voltage

At the time of test, the temperatures shall be maintained at room temperature (~~20~~22 °C ± 5 °C).

~~Adjust the electrode gap distance to 2,5 mm ± 0,05 mm with a vernier or other system and start the stirrer. The stirrer, if used, shall run continuously throughout the test.~~

~~Metallic gauges can damage the surface of the electrodes; hence, they have to be avoided.~~

Adjust the electrode gap distance to 2,5 mm ± 0,05 mm using an adjustment device and start the stirrer. If the gauge is used to verify the gap distance, it must be ensured that no damage to the electrodes surface is introduced.

The first application of voltage is started approximately 5 min after completion of filling and checking that no air bubbles are visible in the electrode gap.

The stirrer, if used, shall run continuously throughout the test.

Apply voltage to the electrodes and uniformly increase voltage from zero at the rate of 2,0 kV/s ± 0,2 kV/s until breakdown occurs.

The breakdown voltage is the maximum voltage reached at the time the circuit is opened either automatically (established arc) or manually (visible or audible discharge detected).

Record the value in kV (kilovolts).

Carry out six breakdowns on the same cell filling, allowing a pause of at least 2 min after each breakdown before re-application of voltage. Check that no gas bubbles are present within the electrode gap.

Calculate the mean value of the six breakdowns, standard deviation and related coefficient of variation (ratio between standard deviation and mean breakdown voltage).

For insulating liquids having a nominal kinematic viscosity higher than 15 mm^2/s (40 °C), the resting time before application of the voltage shall be increased in the range of 15 min to ~~30~~ 60 min. In addition, the resting time between two consecutive shots shall ~~also~~ be increased ~~accordingly~~ to 6 min.

10 Report

The report shall include:

– sample identification, possibly including the type of insulating liquids;

– value of each individual breakdown in kV (kilovolts).
– mean breakdown value;
– ~~type~~shape of electrodes used;
– temperature of the liquid (in the test cell);
– coefficient of variation (%).

Other optional information includes:

– frequency of the test voltage (optional);
– stirring arrangement (optional).

In the case where the individual breakdown voltage is above the maximum equipment voltage capability, the result shall be reported as greater than the maximum voltage capability (example: > 80 kV).

11 Test data dispersion and reproducibility

11.1 Test data dispersion

The graphical representation of Figure 3 indicates the values of the coefficient of variation and its mean value which have been found in a large body of test data in several laboratories using transformer liquids. The solid line in the graph shows the distribution of the coefficient of variation as a function of the mean breakdown value. The dotted lines indicate the expected 2,5 % (0,025) to 97,5 % (0,975) range of values of coefficient of variation (i.e. relative standard deviation (SD) divided by mean, expressed in percentage) as a function of the value of the mean.

Typical coefficients of variation reported in Figure 3 are for information only and do not represent an acceptance criterion of the obtained results.

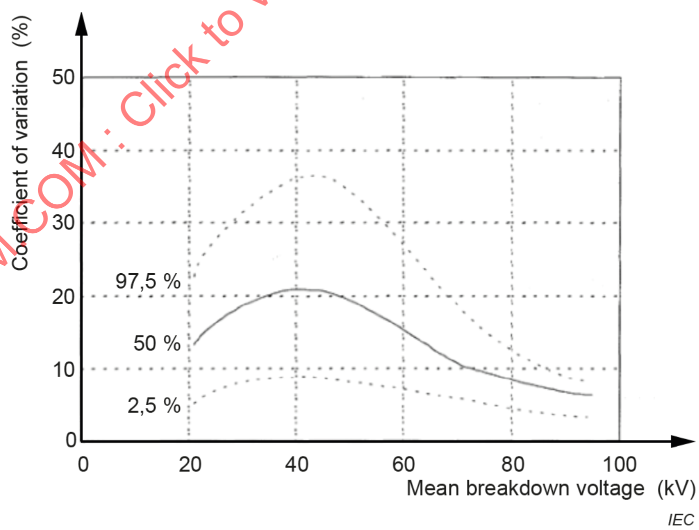


Figure 3 – Graphical representation of coefficient of variation versus mean breakdown voltage

11.2 Reproducibility

Experience has shown that the reproducibility of individual dielectric breakdown values is in the range of ±30 %.

Annex A
(informative)

Improved test method

A.1 Test procedure for improved test method

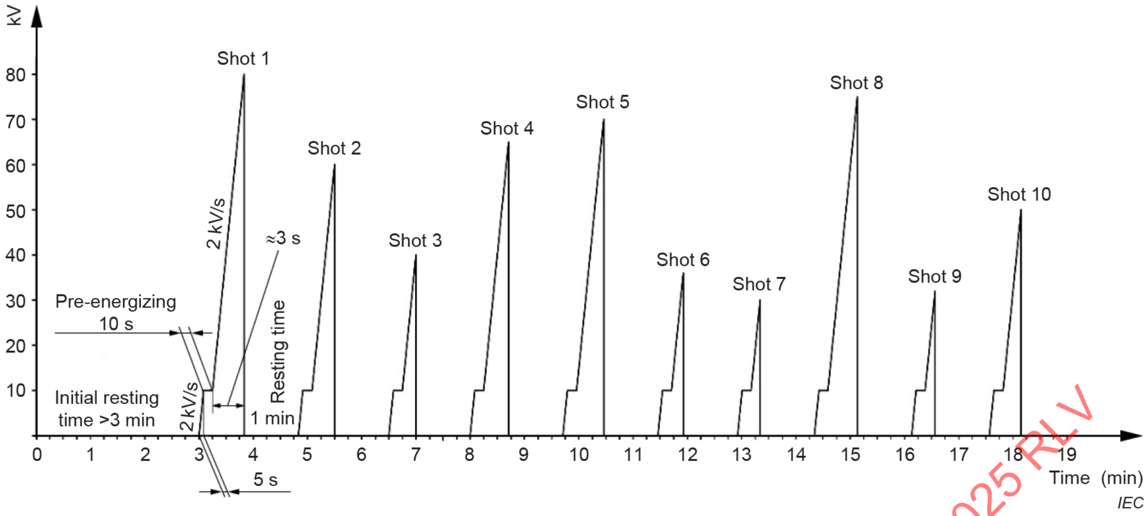
Annex A describes an improved test method, believed to be able to reduce the scatter of the results of breakdown voltage, which may be used [5], [6], [7]. The results obtained using both methods around the world in the years to come will assist in a future choice when this document is revised.

Use the same instrument and prepare the test according to Clause 4 to Clause 8. Instead of the procedure described in Clause 9, follow the procedure described hereafter (Figure A.1):

NOTE The software of the device can be aligned with the procedure described in this Annex A.

1) The first application of voltage is started at least 5 min after completion of filling and after checking that the liquid under test is free from air bubbles.
2) Apply voltage to the electrodes uniformly and increase the voltage from zero at the rate of 2 kV/s ± 0,2 kV/s until 10 kV is reached.
3) Maintain the 10 kV level for 10 s, then continue with a rate of voltage rise of 2 kV/s ± 0,2 kV/s until a breakdown occurs.
4) The breakdown voltage ~~shall~~ should be recorded at the maximum voltage reached.
5) Carry out 10 breakdowns on the same filling, allowing a pause of at least 1 min after each breakdown before re-application of the test voltage. Record each single breakdown. Calculate the test results as the average and coefficient of variation (ratio between standard deviation and mean breakdown voltage) of the remaining six results after disregarding the two highest and two lowest results.
6) When the coefficient of variation of the test result (mean breakdown voltage) exceeds the upper limit (Figure 3), the test procedure should proceed for another 10 breakdowns, repeating the procedure from 2) to 6) with the same sample liquid. Record also the results of these additional breakdowns. Calculate the test results as the average and coefficient of variation of the remaining 12 results after disregarding the four highest and four lowest results [7].

For insulating liquids having a nominal kinematic viscosity higher than 15 mm^2/s (40 °C), the resting time before application of the voltage shall be increased in the range of 15 min to ~~30~~ 60 min. In addition, the resting time between two consecutive shots shall also be increased accordingly.



In the average calculation, the results of four outliers (two highest and two lowest values) ~~have to~~ shall be discarded (in this example, shots 1 and 8 are the highest and shots 7 and 9 are the lowest).

Figure A.1 – Example of a sequence of breakdown shots for determination of the breakdown voltage

A.2 Report

See Clause 10.

Annex B
(informative)

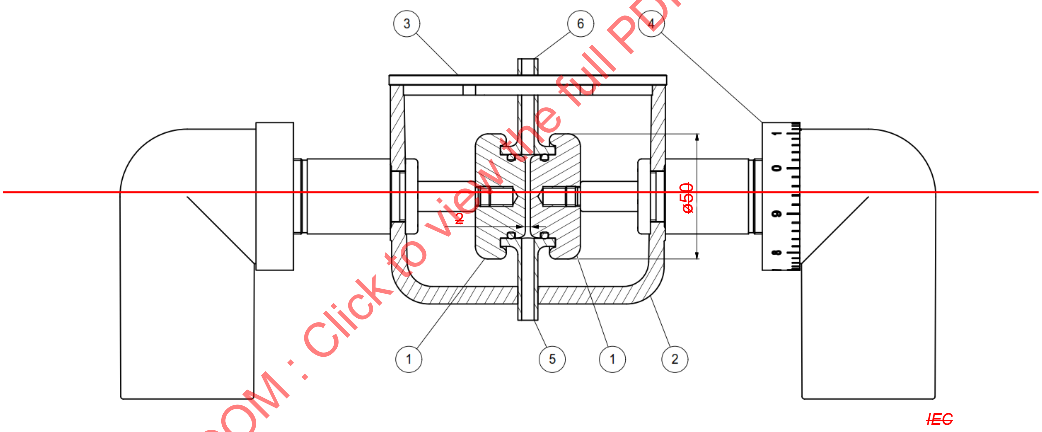
Special test method for low volume samples

~~B.1 Low volume sample test~~

~~The special test method reported in this annex is suggested for use with low sample volumes. A limited body of data has shown that The results obtained are comparable to the results obtained from the method described in the main body of this document. Examples of the reduced volume test cell are shown in Figures B.1 and B.2.~~

~~A fast test on-site may require small portable testers, able to measure the breakdown voltage of insulating liquids (in either direct current or alternating current). An example of such instruments is a Cockcroft-Walton generator, which utilizes a small electrode gap cell and measuring instrumentation. The cell in such an instrument also requires very small quantities of test liquid.~~

~~NOTE The results obtained with such portable instruments cannot be used for diagnostic purposes. Results can differ significantly unless comparability has been established.~~



~~**Key**~~

~~1 partially spherical electrodes, rounded disk electrode, 50 mm diameter, 2 mm gap~~

~~2 oil filled cup, test cell HV insulation~~

~~3 cover~~

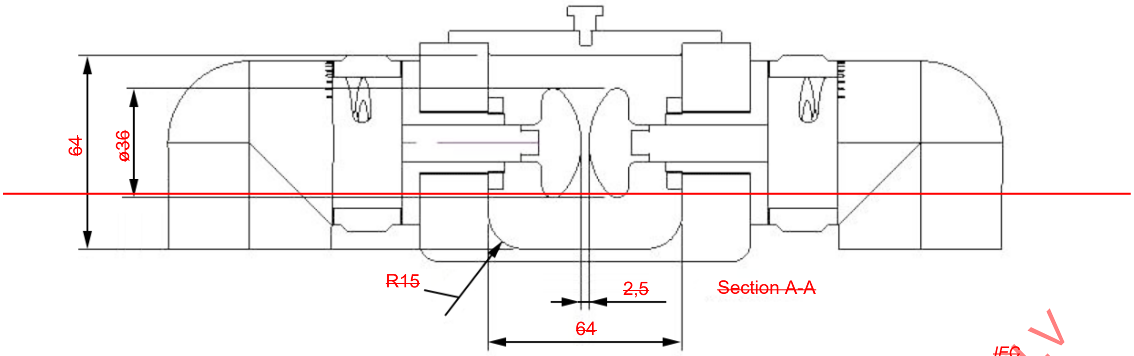
~~4 electrode distance control~~

~~5 sample inlet~~

~~6 sample outlet~~

~~**Figure B.1 – Example of low volume test cell, fixed electrode distance of 2 mm with 2 ml active volume under dielectric stress**~~

~~Dimensions in millimetres~~



~~**Figure B.2 – Example of low volume test cell, fixed electrode distance of 2,5 mm (150 ml to 200 ml)**~~

A special test method is suggested for use with low volume samples.

The results obtained with these low volume testers cannot be compared with the results obtained with the test procedure described in the main body of this document.

A fast test on-site can require small portable testers, able to measure the breakdown voltage of insulating liquids (in either direct current or alternating current). An example of such instruments is a Cockcroft-Walton generator, which utilizes a small electrode gap cell and measuring instrumentation. These testers should require very small quantities of test liquid.

NOTE The results obtained with such portable instruments cannot be used for diagnostic purposes. Results can differ significantly unless comparability has been established.

Annex C
(informative)

Representative material for a performance test

The reference analysis may be used as performance check to prove that the test system is fit for use according to IEC 60060-3.

The representative material shall be an unused, filtered and degassed mineral oil, silicone or ester liquid. The minimum quality requirement of the liquid shall be according to IEC relevant standards.

~~If the test result does not reach the required > 70 kV value, check the functionality of the equipment, or prepare a fresh representative material sample and carry out a new performance check.~~

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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Insulating liquids – Determination of the breakdown voltage at power frequency – Test method

Isolants liquides – Détermination de la tension de claquage à fréquence industrielle – Méthode d'essai

IEC 60156:2025-01(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

INSULATING LIQUIDS – DETERMINATION OF THE BREAKDOWN VOLTAGE AT POWER FREQUENCY – TEST METHOD

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

INTRODUCTION

As normally applied, breakdown voltage of insulating liquids is not a basic material property but an empirical test procedure intended to indicate the presence of contaminants such as water and solid suspended matter and the advisability of carrying out drying and filtration treatment.

The AC breakdown voltage value of insulating liquids strongly depends on the particular set of conditions used in its measurement. Therefore, standardized testing procedures and equipment are essential for the unambiguous interpretation of test results.

The method described in this document applies to either acceptance tests on new deliveries of insulating liquids or testing of treated liquids prior to or during filling into electrical equipment, or to the monitoring and maintenance of insulating liquid-filled apparatus in service. It specifies rigorous sample-handling procedures and temperature control that should be adhered to when certified results are required. For routine tests, especially in the field, less stringent procedures may be practicable, and it is the responsibility of the user to determine their effect on the results.

Annex A describes, for comparison, an alternative test method which could be introduced in the future. Annex B describes special test methods, using cells which may include low volume samples. Annex C describes a reference material for a performance test and check according to IEC 60060-3 [1][1].

1 Numbers in square brackets refer to the Bibliography.

INSULATING LIQUIDS – DETERMINATION OF THE BREAKDOWN VOLTAGE AT POWER FREQUENCY – TEST METHOD

1 Scope

This document specifies the method for determining the dielectric breakdown voltage of insulating liquids at power frequency. The test procedure is performed in a specified apparatus, where the oil sample is subjected to an increasing AC electrical field until breakdown occurs. The method applies to all types of insulating liquids of nominal viscosity up to 350 mm^2/s at 40 °C. It is appropriate both for acceptance testing on unused liquids at the time of their delivery and for establishing the condition of samples taken in monitoring and maintenance of equipment.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60475, *Method of sampling insulating liquids*

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

4 Electrical apparatus

4.1 General

The electrical apparatus consists of the following units:

1) voltage regulator,
2) step-up transformer,
3) switching system,
4) current-limiting resistors,
5) measuring device.

Two or more of these units may be integrated in any equipment system.

4.2 Voltage regulator

The test voltage shall be increased with an automatic control of the required uniform voltage rate of rise. The device should not introduce harmonics disturbances (< 3 %) and the AC source should be free from harmonics.

4.3 Step-up transformer

The test voltage is obtained by using a step-up or resonant transformer supplied from an AC source using 48 Hz to 62 Hz (sinusoidal waveform). The voltage source value is constantly increased. The controls of the variable low-voltage source shall be capable of varying the test voltage smoothly, uniformly and without overshoots or transients. Incremental increases (produced, for example, by a variable auto-transformer or an amplifier) shall not exceed 2 % of the expected breakdown voltage.

The centre-point of the secondary winding of the transformer should be connected to earth.

4.4 Switching system

The circuit shall be opened automatically if a sustained arc between the electrodes occurs and the voltage between the electrodes collapses.

NOTE Typically, voltage collapse is detected in the range of 500 V.

The primary circuit of the step-up transformer shall be fitted with a circuit-breaker operated by the current sensing device, resulting from the breakdown of the sample and shall break the voltage within 10 ms.

The sensitivity of the current or voltage sensing element depends on the energy-limiting device employed and only approximate guidance can be given.

A cut-off time of < 100 µs, as given in the previous edition of this document, is necessary to perform multiple breakdowns on silicone liquids.

4.5 Current-limiting resistors

To protect the equipment and to avoid excessive decomposition at the instant of breakdown of liquids, such as silicone or ester liquids, a resistance limiting the breakdown current shall be inserted in series with the test cell.

The short-circuit current of the transformer and associated circuits shall be within the range of 10 mA to 25 mA for all voltages higher than 15 kV. This may be achieved by a combination of resistors in either or both the primary and secondary circuits of the high-voltage transformer.

4.6 Measuring system

For the purpose of this document, the magnitude of the test voltage is defined as its peak value divided by $\sqrt{2}$.

The output voltage of the step-up transformer may be measured by means of a measuring system consisting of a voltage divider or a measuring winding of the step-up transformer coupled with a peak-voltmeter. The measuring system shall be calibrated up to the upper scale voltage to be measured. A method of calibration which has been found satisfactory is the use of a transfer standard. This is an auxiliary measuring device which is connected in place of the test cell between the high-voltage terminals to which it presents an impedance similar to the one of the sample liquids. The auxiliary device is separately calibrated against a primary standard [2], [3].

5 Test assembly

5.1 General

The breakdown voltage test is performed following the method described herewith as a routine test.

5.2 Test cell

The volume of the cell shall be between 350 ml and 600 ml.

The cell shall be made from electrically insulating materials that are not hygroscopic. The cell shall be transparent and chemically inert, resistant to the insulating liquid and to the cleaning agent that shall be used. Whilst glass is a commonly used material, other suitable materials such as plastics or polymers are appropriate, provided they have high chemical resistance to the insulating liquids (including mineral oils, ester liquids, etc.).

The cell shall be provided with a cover and shall be designed to permit easy removal of the electrodes for cleaning and maintenance. To improve homogenization of the test liquid, a rounded bottom shape of the cell is recommended. Containers and covers shall be cleaned by washing with a suitable solvent or clean insulating liquid to remove residues of an earlier sample. After cleaning, containers shall be immediately capped and kept closed until used again. Electrodes shall be stored in clean insulating liquids.

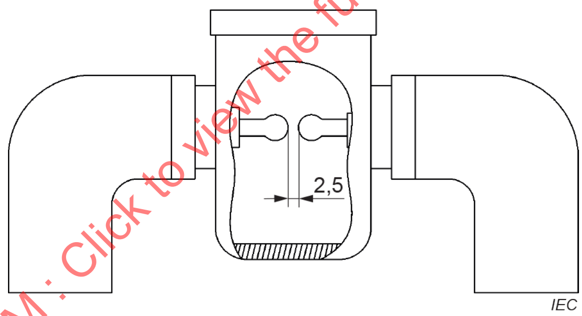
NOTE 1 It is preferable, in the case of esters to use a similar liquid to store the electrodes.

Different shapes of electrodes give different results. The partially hemispherical electrode shall be used, unless otherwise stated.

NOTE 2 If the difference in the shape of electrodes is minimal, the results difference is also minimal.

Examples of suitable cell designs are given in Figure 1 and Figure 2.

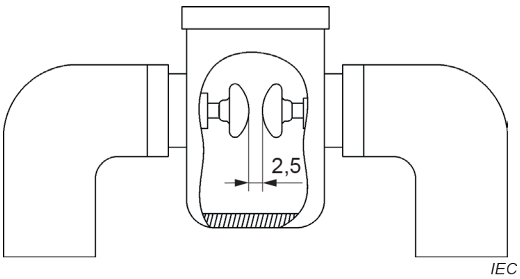
Dimensions in millimetres



NOTE The stirring device can be mounted on the top or on the bottom.

Figure 1 – Example of test cell with spherical electrodes 12,5 mm to 13,0 mm diameter

Dimensions in millimetres



NOTE The stirring device can be mounted on the top or on the bottom.

Figure 2 – Example of test cell with partially hemispherical electrodes with 25 mm radius and 36 mm diameter

5.3 Electrodes

The electrodes shall be made either of brass, bronze or austenitic stainless steel. They shall be polished and, in shape, either spherical (12,5 mm to 13,0 mm diameter) as shown in Figure 1 or in partially hemispherical shape (25 mm ± 0,25 mm radius) as shown in Figure 2. The axis of the electrode system shall be horizontal and shall be at least 40 mm below the surface of the test liquid. No part of the cell or stirrer shall influence the electric field between the electrodes. The gap between the electrodes shall be 2,50 mm ± 0,05 mm.

The electrodes shall be examined frequently for pitting or other damage and shall be maintained or replaced as soon as such damage is observed.

NOTE The electrodes can be replaced or refurbished typically after 5 000 single breakdowns. The surface of the electrodes can be polished with a maximum grain diameter of 10 µm. The limit of the arithmetical mean deviation of the roughness profile of the electrodes can be Ra = < 0,5 µm, according to ISO 21290-2 [4].

5.4 Stirring device

The use of an automatic stirring device is recommended, to be used at all times during the test.

The stirrer shall be mounted in the test cell. It shall be designed so that it is easily cleaned. Stirring shall be achieved by means of a two-bladed or appropriate stirrer of effective diameter 25 mm to 35 mm, axial depth 5 mm to 10 mm, rotating at a speed of 200 r/min to 300 r/min. The stirrer shall not produce air bubbles. It shall be fully immersed in the liquid sample.

NOTE 1 To avoid bubbles between the electrodes, the stirrer can rotate preferably in such a direction that bubbles can be removed [5].

NOTE 2 The stirring device can be mounted on the top or on the bottom.

NOTE 3 Stirring by means of a magnetic bar (20 mm to 25 mm in length and 5 mm to 10 mm in diameter) is an acceptable solution, taking into consideration the collecting of magnetic particles from the fluid on the magnetic bar.

6 Preparation of electrodes

New electrodes shall be cleaned and fulfil the requirements of 5.3. Preparation of the electrodes shall follow the following procedure:

– clean all surfaces with a suitable volatile solvent and allow the solvent to evaporate;
– polish with fine abrasive powder (for example, jeweller’s rouge) or abrasive paper or cloth, for example crocus cloth (see 5.3);
– after polishing, clean with petroleum spirit (reagent quality: boiling range of about 40 °C to 80 °C) followed by acetone (reagent quality);
– assemble the electrodes in the cell, fill with a clean, unused insulating liquid of the type to be tested;
– before the first breakdown test, raise the voltage until breakdown 24 times.

This procedure shall be repeated after each cleaning or change of electrodes.

7 Test assembly preparation

It is recommended that a separate test cell assembly be reserved for different insulating liquid types.

Test assemblies shall be stored in a dry place, covered and filled with dry insulating liquid of the type in regular use in the cell.

On change of the type of liquid under test, remove all residues of the previous liquid with an appropriate solvent, rinse the assembly with a clean, dry liquid of the same type as the one to be tested, drain and refill.

8 Sampling

Sampling shall be carried out in accordance with IEC 60475.

NOTE Breakdown voltage is extremely sensitive to the slightest contamination of the sample by water and particulate matter. Special precautions can be implemented to avoid contamination of the sample and the need for trained personnel and experienced supervision. The sample is taken where the liquid is likely to be most contaminated, usually at the lowest point of the container holding it, unless otherwise specified.

The test is carried out on the sample as received without drying or degassing, unless otherwise specified.

9 Test procedure

9.1 Sample preparation

Immediately before filling the test cell, the sample container is gently agitated and turned over several times in such a way as to ensure, as far as possible, a homogeneous distribution of the impurities contained in the liquid without causing the formation of air bubbles.

A possible method is an automatic rotation of the sample container horizontally for 1 min with a recommended speed of 30 r/min.

Equilibrate the sample to room temperature. Unnecessary exposure to the ambient air of the sample shall be avoided. The sample liquid is exposed to ambient air only during pouring from the sampling vessel to the test cell.

9.2 Filling of the cell

Immediately before commencing the test, drain the test cell and rinse the walls, electrodes and other component parts, with the test liquid. Drain and slowly fill with the test liquid avoiding the formation of air bubbles.

Measure and record the temperature of the liquid.

Close the test cell directly after filling.

9.3 Application of the voltage

At the time of test, the temperatures shall be maintained at room temperature (22 °C ± 5 °C).

Adjust the electrode gap distance to 2,5 mm ± 0,05 mm using an adjustment device and start the stirrer. If the gauge is used to verify the gap distance, it must be ensured that no damage to the electrodes surface is introduced.

The first application of voltage is started approximately 5 min after completion of filling and checking that no air bubbles are visible in the electrode gap.

The stirrer, if used, shall run continuously throughout the test.

Apply voltage to the electrodes and uniformly increase voltage from zero at the rate of 2,0 kV/s ± 0,2 kV/s until breakdown occurs.

The breakdown voltage is the maximum voltage reached at the time the circuit is opened either automatically (established arc) or manually (visible or audible discharge detected).

Record the value in kV (kilovolts).

Carry out six breakdowns on the same cell filling, allowing a pause of at least 2 min after each breakdown before re-application of voltage. Check that no gas bubbles are present within the electrode gap.

Calculate the mean value of the six breakdowns, standard deviation and related coefficient of variation (ratio between standard deviation and mean breakdown voltage).

For insulating liquids having a nominal kinematic viscosity higher than 15 mm^2/s (40 °C), the resting time before application of the voltage shall be increased in the range of 15 min to 60 min. In addition, the resting time between two consecutive shots shall be increased to 6 min.

10 Report

The report shall include:

– sample identification, possibly including the type of insulating liquids;
– value of each individual breakdown in kV (kilovolts).
– mean breakdown value;
– shape of electrodes used;
– temperature of the liquid (in the test cell);
– coefficient of variation (%).

Other optional information includes:

– frequency of the test voltage (optional);
– stirring arrangement (optional).

In the case where the individual breakdown voltage is above the maximum equipment voltage capability, the result shall be reported as greater than the maximum voltage capability (example: > 80 kV).

11 Test data dispersion and reproducibility

11.1 Test data dispersion

The graphical representation of Figure 3 indicates the values of the coefficient of variation and its mean value which have been found in a large body of test data in several laboratories using transformer liquids. The solid line in the graph shows the distribution of the coefficient of variation as a function of the mean breakdown value. The dotted lines indicate the expected 2,5 % (0,025) to 97,5 % (0,975) range of values of coefficient of variation (i.e. relative standard deviation (SD) divided by mean, expressed in percentage) as a function of the value of the mean.

Typical coefficients of variation reported in Figure 3 are for information only and do not represent an acceptance criterion of the obtained results.

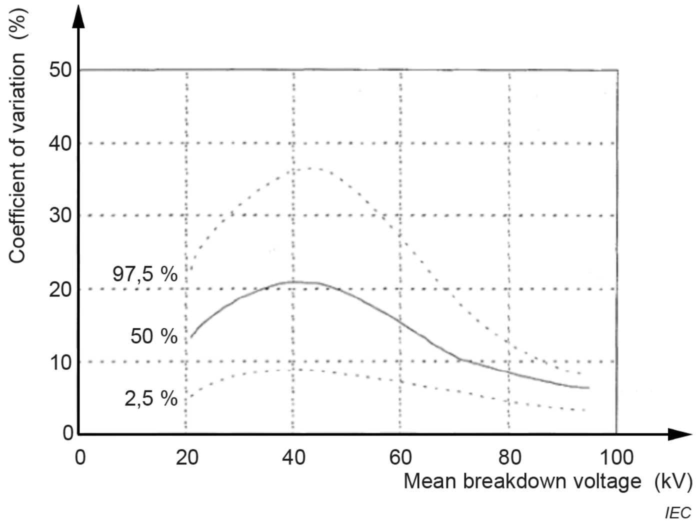


Figure 3 – Graphical representation of coefficient of variation versus mean breakdown voltage

11.2 Reproducibility

Experience has shown that the reproducibility of individual dielectric breakdown values is in the range of ±30 %.

Annex A
(informative)

Improved test method

A.1 Test procedure for improved test method

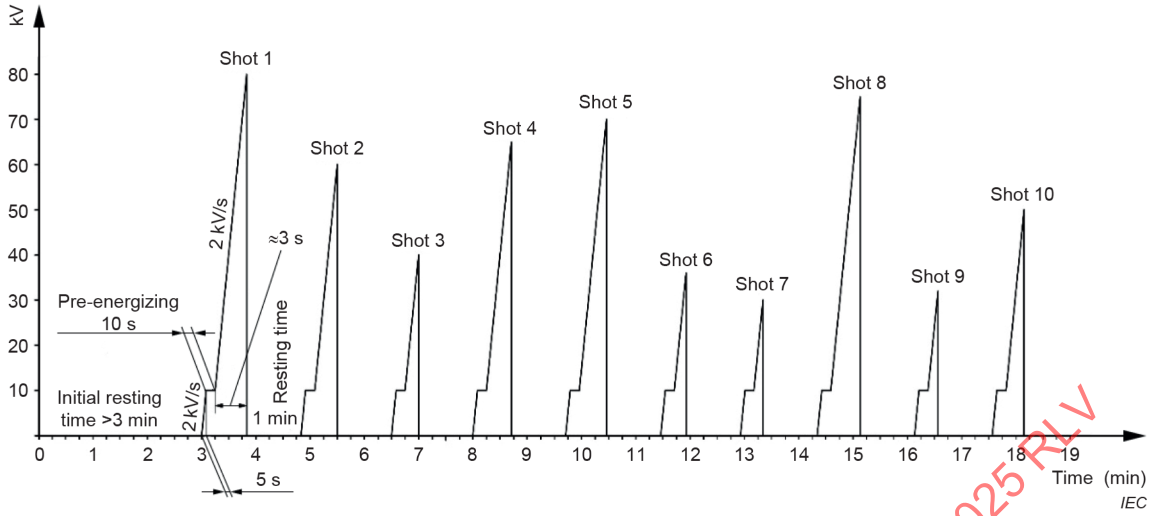
Annex A describes an improved test method, believed to be able to reduce the scatter of the results of breakdown voltage, which may be used [5], [6], [7]. The results obtained using both methods around the world in the years to come will assist in a future choice when this document is revised.

Use the same instrument and prepare the test according to Clause 4 to Clause 8. Instead of the procedure described in Clause 9, follow the procedure described hereafter (Figure A.1):

NOTE The software of the device can be aligned with the procedure described in this Annex A.

1) The first application of voltage is started at least 5 min after completion of filling and after checking that the liquid under test is free from air bubbles.
2) Apply voltage to the electrodes uniformly and increase the voltage from zero at the rate of 2 kV/s ± 0,2 kV/s until 10 kV is reached.
3) Maintain the 10 kV level for 10 s, then continue with a rate of voltage rise of 2 kV/s ± 0,2 kV/s until a breakdown occurs.
4) The breakdown voltage should be recorded at the maximum voltage reached.
5) Carry out 10 breakdowns on the same filling, allowing a pause of at least 1 min after each breakdown before re-application of the test voltage. Record each single breakdown. Calculate the test results as the average and coefficient of variation (ratio between standard deviation and mean breakdown voltage) of the remaining six results after disregarding the two highest and two lowest results.
6) When the coefficient of variation of the test result (mean breakdown voltage) exceeds the upper limit (Figure 3), the test procedure should proceed for another 10 breakdowns, repeating the procedure from 2) to 6) with the same sample liquid. Record also the results of these additional breakdowns. Calculate the test results as the average and coefficient of variation of the remaining 12 results after disregarding the four highest and four lowest results [7].

For insulating liquids having a nominal kinematic viscosity higher than 15 mm^2/s (40 °C), the resting time before application of the voltage shall be increased in the range of 15 min to 60 min. In addition, the resting time between two consecutive shots shall also be increased accordingly.



In the average calculation, the results of four outliers (two highest and two lowest values) shall be discarded (in this example, shots 1 and 8 are the highest and shots 7 and 9 are the lowest).

Figure A.1 – Example of a sequence of breakdown shots for determination of the breakdown voltage

A.2 Report

See Clause 10.

Annex B
(informative)

Special test method for low volume samples

A special test method is suggested for use with low volume samples.

The results obtained with these low volume testers cannot be compared with the results obtained with the test procedure described in the main body of this document.

A fast test on-site can require small portable testers, able to measure the breakdown voltage of insulating liquids (in either direct current or alternating current). An example of such instruments is a Cockcroft-Walton generator, which utilizes a small electrode gap cell and measuring instrumentation. These testers should require very small quantities of test liquid.

NOTE The results obtained with such portable instruments cannot be used for diagnostic purposes. Results can differ significantly unless comparability has been established.

Annex C
(informative)

Representative material for a performance test

The reference analysis may be used as performance check to prove that the test system is fit for use according to IEC 60060-3.

The representative material shall be an unused, filtered and degassed mineral oil, silicone or ester liquid. The minimum quality requirement of the liquid shall be according to IEC relevant standards.

Bibliography

[1] IEC 60060-3, *High-voltage test techniques – Part 3: Definitions and requirements for on-site testing*

[2] IEC 60052:2002, *Voltage measurement by means of standard air gaps*

[3] IEC 60060-2:2010, *High-voltage test techniques – Part 2: Measuring systems*

[4] ISO 21920-2:2021, *Geometrical product specifications (GPS) – Surface texture: Profile – Part 2: Terms, definitions and surface texture parameters*

[5] Elektrische Festigkeit von Isolieröl, Dissertation von G. J. Pukel TU Graz, 2004, ISBN 978-3-85133-060-1

[6] M. BAUR, M. POMPILI, R. BARTNIKAS, "A comment on the test methods for the breakdown voltage of dielectric liquids", IEEE Trans. Dielectric Electric Insulation, Vol. 19, pp. 1482-1484, 2012

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[8] T. J. LEWIS, "Mechanism of electrical breakdown in saturated hydrocarbon liquids", Journal of Applied Physics, Vol. 27, pp. 645-650, 1956

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[11] IEC 60296, *Fluids for electrotechnical applications – Mineral insulating oils for electrical equipment*

[12] IEC 60422, *Mineral insulating oils in electrical equipment – Supervision and maintenance guidance*

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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ISOLANTS LIQUIDES – DÉTERMINATION DE LA TENSION DE CLAQUAGE À FRÉQUENCE INDUSTRIELLE – MÉTHODE D'ESSAI

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L'IEC 60156 a été établie par le comité d'études 10 de l'IEC: Fluides pour applications électrotechniques. Il s'agit d'une Norme internationale.

Cette quatrième édition annule et remplace la troisième édition parue en 2018. Cette édition constitue une révision technique.

Cette édition constitue une révision technique et valide essentiellement le contenu de l'édition précédente même si elle comporte certaines améliorations. La méthode d'essai n'a pas été modifiée pour des raisons pratiques et du fait du très grand nombre de dispositifs de mesure utilisés au niveau international.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
10/1241/FDIS	10/1256/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/publications.

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INTRODUCTION

La tension de claquage des isolants liquides, telle qu'elle est généralement appliquée, n'est pas une propriété fondamentale du matériau, mais une procédure d'essai empirique destinée à révéler la présence de produits contaminants comme l'eau ou des matières solides en suspension, et permettre ainsi de décider de l'opportunité d'effectuer un traitement de séchage et de filtration.

La valeur de la tension de claquage sous courant alternatif des isolants liquides dépend beaucoup de l'ensemble des conditions particulières appliquées pour son mesurage. En conséquence, des procédures d'essai et un équipement normalisés sont essentiels pour interpréter sans ambiguïté les résultats d'essai.

La méthode décrite dans le présent document s'applique soit aux essais de réception de nouvelles livraisons d'isolants liquides, soit aux essais de liquides traités, avant ou pendant le remplissage de matériels électriques, soit à la surveillance et à la maintenance des appareils remplis d'isolant liquide en service. Elle spécifie des méthodes rigoureuses de manipulation des échantillons et de vérification des températures auxquelles il convient de se conformer quand des résultats certifiés sont exigés. Pour les essais individuels de série, notamment sur le terrain, des procédures moins rigoureuses peuvent être appliquées et il revient alors à l'utilisateur de déterminer leurs effets sur les résultats obtenus.

L'Annexe A décrit, à titre de comparaison, une autre méthode d'essai qui pourrait être adoptée à l'avenir. L'Annexe B décrit des méthodes d'essai spéciales utilisant des cellules qui peuvent contenir des échantillons de faible volume. L'Annexe C décrit un matériau de référence pour un essai de détermination des caractéristiques et un contrôle de caractéristiques conformément à l'IEC 60060-3 [1] [1].

1 Les chiffres entre crochets renvoient à la Bibliographie.

ISOLANTS LIQUIDES – DÉTERMINATION DE LA TENSION DE CLAQUAGE À FRÉQUENCE INDUSTRIELLE – MÉTHODE D'ESSAI

1 Domaine d'application

Le présent document spécifie la méthode de détermination de la tension de claquage diélectrique des isolants liquides à fréquence industrielle. La procédure d'essai est réalisée dans un appareil spécifié dans lequel l'échantillon d'huile est soumis à un champ électrique alternatif croissant jusqu'à l'obtention du claquage. La méthode est applicable à tous les types d'isolants liquides de viscosité nominale allant jusqu'à 350 mm^2/s à 40 °C. Elle convient aussi bien pour les essais de réception de liquides neufs à la livraison que pour définir l'état des échantillons prélevés lors de la surveillance et de la maintenance des matériels.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60475, *Méthode d'échantillonnage des liquides isolants*

3 Termes et définitions

Aucun terme n'est défini dans le présent document.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse https://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse https://www.iso.org/obp

4 Appareillage électrique

4.1 Généralités

L'appareillage électrique se compose des éléments suivants:

1) régulateur de tension,
2) transformateur élévateur,
3) système de commutation,
4) résistances de limitation de courant,
5) dispositif de mesure.

Deux de ces éléments ou plus peuvent être réunis dans un système de mesure intégré.

4.2 Régulateur de tension

La tension d'essai doit être augmentée à l'aide d'un réglage automatique pour une vitesse de montée en tension uniforme exigée. Il convient que le dispositif ne crée pas de perturbations harmoniques (< 3 %) et que la source de tension alternative soit exempte d'harmonique.

4.3 Transformateur élévateur

La tension d'essai est obtenue au moyen d'un transformateur élévateur ou à résonance alimenté à partir d'une source de tension alternative dans la plage de fréquences comprise entre 48 Hz et 62 Hz (forme d'onde sinusoïdale). La valeur de la source de tension est augmentée de façon continue. Les commandes de la source basse tension variable doivent permettre de faire varier la tension d'essai sans à-coups, d'une manière uniforme, et sans dépassements ni transitoires de tension. L'incrémentation (obtenue, par exemple, à l'aide d'un autotransformateur variable ou d'un amplificateur) ne doit pas dépasser 2 % de la tension de claquage attendue.

Il convient que le point milieu de l'enroulement secondaire du transformateur soit relié à la terre.

4.4 Système de commutation

Le circuit doit s'ouvrir automatiquement quand un arc maintenu se produit entre les électrodes et quand la tension entre les électrodes chute.

NOTE En règle générale, une chute de tension est détectée dans la plage de 500 V.

Le circuit primaire du transformateur élévateur doit être équipé d'un disjoncteur fonctionnant sous l'action du détecteur du courant qui résulte du claquage de l'échantillon et doit couper la tension en moins de 10 ms.

La sensibilité des dispositifs détecteurs de courant ou de tension dépend du dispositif de limitation d'énergie utilisé et seules des recommandations approximatives peuvent être fournies.

Un temps de coupure < 100 µs, tel qu'indiqué dans l'édition précédente du présent document, est nécessaire pour réaliser plusieurs claquages sur les liquides silicones.

4.5 Résistances de limitation de courant

Afin de protéger le matériel et pour éviter une décomposition excessive au moment du claquage des liquides (par exemple des liquides silicones ou esters), une résistance de limitation du courant de claquage doit être insérée en série avec la cellule d'essai.

Le courant de court-circuit du transformateur et de ses circuits associés doit être compris entre 10 mA et 25 mA pour toutes les tensions supérieures à 15 kV. Ce résultat peut être obtenu par une combinaison de résistances placées dans l'un ou l'autre des circuits primaire ou secondaire du transformateur haute tension ou dans les deux circuits.

4.6 Système de mesure

Dans le cadre du présent document, l'amplitude de la tension d'essai est définie par sa valeur de crête divisée par $\sqrt{2}$.

La tension de sortie du transformateur élévateur peut être mesurée au moyen d'un système de mesure comprenant un diviseur de tension ou un enroulement de mesure du transformateur élévateur relié à un voltmètre de crête. Le système de mesure doit être étalonné jusqu'à la tension maximale à mesurer. L'utilisation d'un étalon de transfert est une méthode d'étalonnage qui s'est révélée satisfaisante. Il s'agit d'un dispositif de mesure auxiliaire placé entre les bornes haute tension, à la place de la cellule d'essai, et présentant une impédance identique à celle des liquides en essai. Ce dispositif auxiliaire est étalonné séparément à partir d'un étalon primaire [2], [3].

5 Dispositif d'essai

5.1 Généralités

L'essai de tension de claquage est réalisé selon la méthode décrite ci-après comme essai individuel de série.

5.2 Cellule d'essai

Le volume de la cellule doit être compris entre 350 ml et 600 ml.

La cellule doit être constituée de matériaux isolants électriques qui ne sont pas hygroscopiques. La cellule doit être transparente, chimiquement inerte et résistante à l'isolant liquide ainsi qu'au produit de nettoyage qui doit être utilisé. Quoique le verre soit un matériau couramment utilisé, d'autres matériaux appropriés (comme les plastiques ou les polymères) conviennent à condition qu'ils présentent une résistance chimique élevée aux isolants liquides (notamment les huiles minérales, les esters liquides, etc.).

La cellule doit être équipée d'un couvercle et doit être conçue de manière à permettre le démontage facile des électrodes pour leur nettoyage et leur maintenance. Pour améliorer l'homogénéisation du liquide en essai, il est recommandé d'utiliser une cellule à fond arrondi. Les récipients et les couvercles doivent être nettoyés avec un solvant approprié ou un isolant liquide propre afin d'éliminer toute trace d'un échantillon antérieur. Après nettoyage, les récipients doivent être immédiatement couverts et rester fermés jusqu'à ce qu'ils soient utilisés à nouveau. Les électrodes doivent être stockées dans des isolants liquides propres.

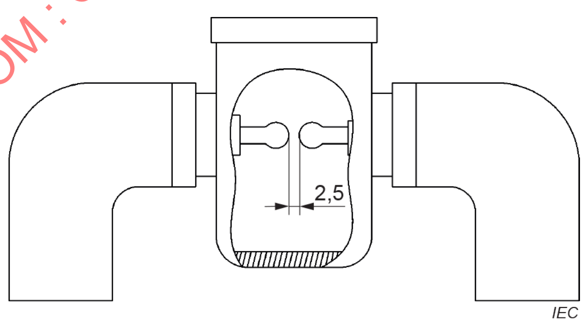
NOTE 1 Il est préférable, dans le cas des esters, d'utiliser un liquide similaire pour stocker les électrodes.

Des électrodes de différentes formes donnent des résultats différents. Sauf indication contraire, l'électrode partiellement hémisphérique doit être utilisée.

NOTE 2 Si la différence de forme des électrodes est minime, la différence dans les résultats l'est également.

La Figure 1 et la Figure 2 présentent des exemples de cellules appropriées.

Dimensions en millimètres



NOTE L'agitateur peut être monté sur le dessus ou dans le fond de la cellule.

Figure 1 – Exemple de cellule d'essai avec des électrodes sphériques de diamètre compris entre 12,5 mm et 13,0 mm