BS EN 61251:2016

BSI Standards Publication

Electrical insulating materials and systems — A.C. voltage endurance evaluation

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National foreword

This British Standard is the UK implementation of EN 61251:2016. It is identical to IEC 61251:2015. It supersedes DD IEC/TS 61251:2008 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee GEL/112, Evaluation and qualification of electrical insulating materials and systems.

A list of organizations represented on this committee can be obtained on request to its secretary.

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EN 61251

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English Version

Electrical insulating materials and systems - A.C. voltage endurance evaluation (IEC 61251:2015)

Systèmes et matériaux isolants électriques - Évaluation de l'endurance a la tension alternative
(IEC 61251:2015)

Elektrische Isolierstoffe und -systeme - Ermittlung der Wechselspannungsbeständigkei
(IEC 61251:2015)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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European foreword

The text of document 112/338/FDIS, future edition 1 of IEC 61251, prepared by IEC/TC 112 "Evaluation and qualification of electrical insulating materials and systems" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 61251:2016.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2016-09-23
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2018-12-23

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Endorsement notice

The text of the International Standard IEC 61251:2015 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60243-1	NOTE	Harmonized as EN 60243-1.
IEC 60243-2	NOTE	Harmonized as EN 60243-2.
IEC 60243-3	NOTE	Harmonized as EN 60243-3.
IEC 60343	NOTE	Harmonized as EN 60343.
IEC 61649	NOTE	Harmonized as EN 61649.

Annex ZA
(normative)
Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 62539	-	Guide for the statistical analysis of electrical insulation breakdown data	-	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTRICAL INSULATING MATERIALS AND SYSTEMS – AC VOLTAGE ENDURANCE EVALUATION

FOREWORD

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International Standard IEC 61251 has been prepared by IEC technical committee 112: Evaluation and qualification of electrical insulating materials and systems.

This first edition of IEC 61251 cancels and replaces the second edition of IEC TS 61251, published in 2008. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the second edition of IEC TS 61251:

a) upgrade from Technical Specification to an International Standard;
b) clarification of issues raised since publication of IEC TS 61251.

The text of this standard is based on the following documents:

FDIS	Report on voting
112/338/FDIS	112/347/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

This International Standard covers insulating materials and systems. Voltage endurance tests are used to compare and evaluate insulating materials and systems. It is complex to determine the capability of electrical insulating materials and systems to endure a.c. voltage stress. The results of voltage endurance tests are influenced by many factors. Therefore this International Standard can be considered as an attempt to present a unified view of voltage endurance for simplified planning and analysis.

ELECTRICAL INSULATING MATERIALS AND SYSTEMS – AC VOLTAGE ENDURANCE EVALUATION

1 Scope

This International Standard describes many of the factors involved in voltage endurance tests on electrical insulating materials and systems. It describes the voltage endurance graph, lists test methods illustrating their limitations and gives guidance for evaluating the sinusoidal a.c. voltage endurance of insulating materials and systems from the results of the tests. This International Standard is applicable over the voltage frequency range 20 Hz to 1 000 Hz. The general principles can also be applicable to other voltage shapes, including impulse voltages. The terminology to be used in voltage endurance is defined and explained.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62539, *Guide for the statistical analysis of electrical insulation dielectric breakdown data*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1
voltage endurance
VE
measures of the capability of a solid insulating material to endure voltage

Note 1 to entry: In this International Standard, only a.c. voltage is considered.

Note 2 to entry: This note only applies to the French language.

3.1.2
life
time to dielectric breakdown

3.1.3
voltage endurance coefficient
VEC
numerical value of the reciprocal of the slope of a straight line log-log VE plot

Note 1 to entry: This note only applies to the French language.

3.1.4
specimen
representative test object for assessing the value of one or more physical properties

3.1.5
sample
group of nominally identical specimens extracted randomly from the same manufacturing batch

3.2 Symbols

c, c'	constants in the inverse-power model
E	electric stress
E_o	short-time electric strength
E_t	electric threshold stress
f	frequency
h, k	constants in the exponential model
L	life
m	scale parameter in the Weibull distribution (one variable)
M	scale parameter in the generalized Weibull distribution (two variables)
n	exponent of stress in the inverse-power model coinciding with the VEC
n_d	differential VEC
R	dimensional ratio
t	time
t_c	time to dielectric breakdown at constant stress
t_o	time to dielectric breakdown at constant stress E_o
t_p	time to dielectric breakdown with progressive stress
$\tan \delta$	dissipation factor
α	scale parameter (63,2 percentile) in the Weibull distribution of times to dielectric breakdown at constant stress
β	shape parameter in the Weibull distribution of times to dielectric breakdown at constant stress
γ	shape parameter of the Weibull distribution of the dielectric breakdown stresses from a progressive stress test

4 Voltage endurance

4.1 Voltage endurance testing

To evaluate the voltage endurance of insulating materials or systems, a number of specimens are subjected to a.c. voltage and their times to dielectric breakdown are measured. In practice, several samples of many specimens are tested at different voltages to reveal the effect of the applied voltage on the time to dielectric breakdown. The arithmetic mean time to dielectric breakdown of each sample is the average time to dielectric breakdown of all specimens tested at that voltage. The time at which a certain percentage of specimens break down is the estimated time to dielectric breakdown with a probability equal to this percentage.

The statistical treatment of the data (either by analytical or graphical methods) allows the extraction of additional data such as other failure percentiles or confidence bounds and, possibly, determination of the distribution (Gaussian, Weibull, lognormal, etc.).

4.2 Electrical stress

In general, reference to electrical stress (voltage per unit thickness) instead of voltage is required. For a uniform field, electrical stress is given by the voltage (effective value) divided by the thickness of specimens.

If the electric field is not uniform, the maximum value shall be considered by the relevant equipment committees.

4.3 Voltage endurance (VE) graph

The VE graph represents the time to dielectric breakdown (life) versus the corresponding value of electrical stress. In the VE graph, the electrical stress is plotted as the ordinate with either a linear or logarithmic scale. The times to dielectric breakdown are plotted on the abscissa with a logarithmic scale. The voltage endurance line on this graph gives the final result of the VE tests as it allows clear and complete evaluation of voltage endurance of the specimens under the specified test conditions. For maximum significance, materials or systems shall be compared at equal thickness and using the same type of electrodes, temperature, humidity and ambient gas, or as agreed by the relevant equipment committees.

An accurate plotting of the line requires more than three tests at different voltages and one or more tests are required at voltages which result in times to failure longer than 1 000 h. In any case, a minimum number of three tests is required to draw the VE graph.

The voltage endurance line is straight or curved. In the latter case, its trend can often be approximated by a few straight regions: sometimes a first part for short times with a low slope, a middle region (which can extend to long times) with a steeper slope and finally a further trend of the line showing a tendency to become horizontal (see Figure 1, where a general VE line is shown). It is likely that the shape of the VE graph changes significantly from one material or system to another. With a curve as shown in Figure 1, the VEC is not constant, and the VEC will be different at different times (see n_d in Figure 2).

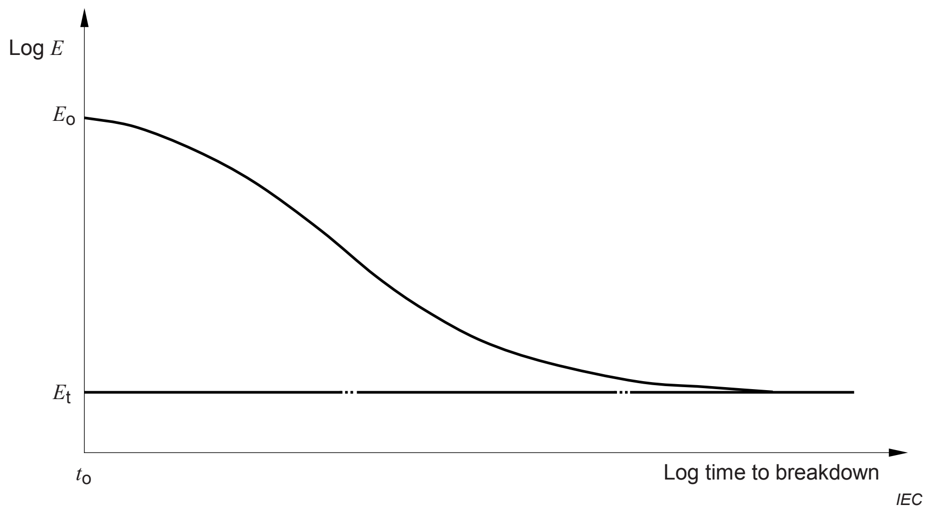

Figure 1 – General voltage endurance line

4.4 Short-time electric strength

The short-time electric strength is measured using a linearly increasing voltage. The duration of such a test, as used in this International Standard, is of the order of one minute up to some tens of minutes. The arithmetic mean value of the breakdown field for the tested sample is E_o.

The results of electric strength tests (or, in general, of tests with increasing voltage) are not represented directly in the VE graph. Instead, a constant voltage test at the same stress as the mean electric strength, E_o (or very close to it, $0{,}9E_o$ or as agreed), is made to determine the time to dielectric breakdown, t_o, with constant stress. The point (E_o, t_o) is the origin of the VE line. More details on this procedure are given in 5.5. However, when this procedure is used, the following precautions shall be taken.

a) The electric strength tests shall be carried out under the same conditions (humidity, temperature, etc.), in the same test cell and with the same procedures as for the voltage endurance tests.

b) The test specimens, the breakdown path and the conditions of the specimen after dielectric breakdown shall be examined and recorded for future use in the analysis of the results. The latter is to ensure that the mode of failure at high stress is the same as that of the other specimens tested later at lower stress.

4.5 Voltage endurance coefficient (VEC)

The slope of the VE line, n, is an indicator of the response of a material or system to electrical stress. The parameter n is dimensionless. With a small slope of the VE line (i.e. a large value of VEC), even a small reduction of stress produces a great increase in life. The reciprocal of the slope is taken to be consistent with the numerical value of the exponent n in Formula (1). A large value of the VEC does not correspond necessarily to high electric strength. It can happen that the material with lower VEC has a longer time to dielectric breakdown at a given stress if its short-time electric strength is so high that its poorer endurance is compensated for. The value of n shall be associated with a high mean electric strength before attributing a high endurance to the material. What is most significant is the retention of usable electric strength for long periods of time.

4.6 Differential VEC (n_d)

If the VE line is curved in log-log coordinates, its slope is measured by means of the tangent at any point. For any electrical stress, and thus for any point on the line, the differential voltage endurance coefficient, n_d, can be defined as the absolute value of the reciprocal of the slope of the curve at that point (Figure 2) according to the life model described in Clause 5.

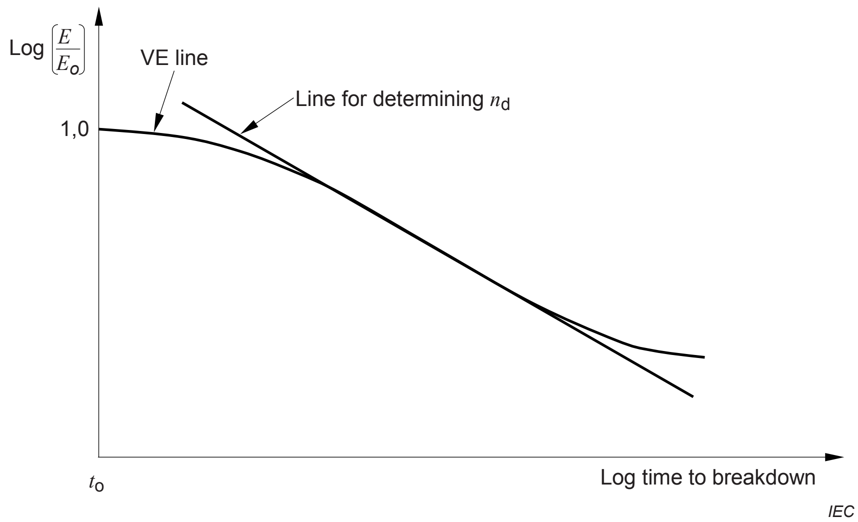

Figure 2 – Determination of the differential VEC n_d at a generic point P of the VE line

4.7 Electrical threshold stress (E_t)

If the VE line tends to become horizontal with decreasing stress within the test stress-times, this indicates the presence of a limiting stress, E_t, below which electrical ageing becomes negligible. This limit is called the electrical threshold stress. The tendency of the line to become horizontal is detected by means of tests of suitable duration. However, the tests do not always succeed in revealing such a trend in a reasonable time. Some insulating materials or systems do not show any electrical threshold stress even for very long test times.

4.8 Voltage endurance relationship

The VE relationship is the mathematical model of life under electrical stress or voltage, i.e. the formula relating electrical stress and time to dielectric breakdown, whose graphical representation is given by the VE line. If this line is straight on log-log graph paper, the formula is of the type:

$$L = c\,E^{-n} \tag{1}$$

where

L is the time to dielectric breakdown or time to failure or life;

E is the electrical stress;

c and n are constants dependent on temperature and other environmental parameters.

Formula (1) constitutes the so-called inverse-power model, which is the voltage-life model often encountered with voltage endurance data on solid electrical insulation. In this case the VEC is n, and it is constant. When data are available for time to dielectric breakdown at two constant-voltage stresses, this model shall be used to get a rough estimate of the value of n by using Formula (2):

$$\frac{L_1}{L_2} = \left(\frac{E_1}{E_2}\right)^{-n} \tag{2}$$

If the VE test data do not form a straight line on log-log paper, the use of the inverse-power model is incorrect. If the line approaches an electrical threshold stress, E_t, other models have been proposed, among them

$$L = c'\,(E - E_t)^{-n}\ , \tag{3}$$

which becomes the inverse-power model if E_t tends to 0 and is preferably used when the data for short and medium times fit a straight line on log-log coordinates. Alternatively, another model is

$$L = \frac{k \exp(-h\,E)}{E - E_t}\ , \tag{4}$$

which derives from the exponential model, corresponding to an approximately straight line in semilog coordinates for $E > E_t$ but gives infinite time to dielectric breakdown when E tends to E_t. In Formulas (3) and (4), constants c', n, k, h and E_t depend on temperature and other environmental conditions.

Formulas (3) and (4) generate two new formulas which define the trend of the VE line between any two points, (L_1, E_1) and (L_2, E_2). The following formulas are obtained:

$$\frac{L_1}{L_2} = \left(\frac{E_1 - E_t}{E_2 - E_t}\right)^{-n}\ , \tag{5}$$

$$\frac{L_1}{L_2} = \frac{\exp\{-h\,(E_1 - E_2)\}}{(E_1 - E_t)/(E_2 - E_t)}\ . \tag{6}$$

The formulas of the VE line for a straight line or a straight-line segment on log-log plot are Formulas (1) and (2). When there is a tendency toward a threshold after an approximately linear trend on log-log or semilog graph paper, Formulas (3), (4), (5) and (6) apply.

By taking the logarithms, the inverse-power model, Formula (1), becomes

$$\ln (L) = \ln (c) - n \ln (E) \ . \tag{7}$$

This is the formula of the straight VE line in log-log coordinates. Its slope is $-1/n$. As the numerical value of the reciprocal of the slope is equal to n, the VEC can also be defined as the exponent n in the inverse-power model.

5 Test methods

5.1 Introductory remarks

Different methods of carrying out the VE test can be used. The differences concern the way of applying voltage (constant or increasing with time), the frequency (service or higher) and the time at which the test is interrupted (the time to dielectric breakdown for all sample specimens (complete life tests) or a shorter time for some of the specimens of the sample (censored life tests).

In general to enable comparisons to be made, the type of ageing cell or test object shall be the same, whatever the choice of the parameters above. However, with respect to the choice of the frequency of the applied voltage, the amount of heating from either dielectric loss or from partial discharges shall be such that the temperature rise from these causes is less than 3 K.

When testing materials, the ageing cell or test object should result in a uniform electric field. This can be achieved by electrodes having a flat surface rounded at the edges. To avoid partial discharges and flashover along the specimen surface, the specimen shall extend a suitable distance beyond the edges of the electrodes. If preliminary tests indicate that this extension beyond the electrodes is not enough to avoid partial discharges and flashover, the electrodes shall be immersed or embedded in an appropriate dielectric having the same or higher permittivity than that of the material under test.

The form and processing of the specimen will depend on the purpose of the test. For research purposes, internal degradation studies as a function of cavity size and shape have been performed. However, this lies outside the scope of this International Standard. Evaluation and comparison of materials from the point of view of degradation by external discharge are dealt with in IEC 60343.

For insulation systems, the test objects shall represent adequately the form taken in service and be determined by the relevant IEC equipment committee.

5.2 Tests at constant stress

5.2.1 Conventional VE test

In the constant stress test, the magnitude of the voltage applied to each specimen is kept constant during the test. This magnitude is usually selected in such a way that the arithmetic mean time to dielectric breakdown of the sample is between a few tens and a few thousands of hours. The time to dielectric breakdown of some specimens, especially at the lower stresses, can be so long that it is impracticable to wait for dielectric breakdown of all specimens of the sample. In this case, the interruption of the test after dielectric breakdown of some of the specimens requires the use of statistical procedures for censored data (see IEC 62539).

Usually, three or four different levels of voltage or electric field are used, thereby providing three or four points for the VE line. Four points are often not enough to demonstrate curvature of the line. On the other hand, the amount of data required for tests at more than four voltages is expensive to obtain.

The fit of the data to a straight line shall be established through regression analysis as specified in IEC 62539. If the quality of fit is good, that is the correlation coefficient R^2 is 0,90 or higher, the VE line can be fitted to a straight line, with the negative reciprocal of the slope of the line being the VEC. If R^2 is below 0,90, the VE line is curved and a straight line model is not appropriate.

For any test voltage, the times to dielectric breakdown of the specimens of a sample can be tested for their fit to various breakdown time probability functions. If the data fit the Weibull distribution, the experimental data give rise to a straight line (on Weibull paper) whose slope is the shape parameter, β, of the distribution (see Annex A). Proceeding in the same way for every test at different voltages, the variance of β can be checked.

5.2.2 Diagnostic measurements

In some cases there is no need to measure diagnostics. In those cases where the measurement of diagnostics is necessary, diagnostic quantities such as tan δ or partial discharge shall be monitored during the test. Where tan δ or partial discharge versus time curves obtained at different voltages are compared, similar patterns can be observed. This provides a contribution to understanding ageing behavior and prediction of the behavior of the VE line for other samples.

Short-time electric strength measurements can also be carried out on specimens that have not failed after a fixed ageing time, in order to evaluate their state of ageing. Thus the short-time electric strength is a diagnostic quantity to determine the degree of ageing caused by electrical stress.

To investigate the ageing process thoroughly, it is useful to employ chemical and microscopic analyses. The results are often related to the variation of macroscopic properties: short-time electric strength, conductivity, tan δ, etc.

5.2.3 Detection of an electrical threshold

The experimental points sometimes show a tendency of the VE line to become horizontal after long voltage exposure times. Moreover, many reports of VE investigations include points indicating much longer times to failure at the lower levels of stress than expected from extrapolation of the trend at higher voltages. These results can indicate the existence of an electrical threshold. It is desirable to test the data for the presence of such a threshold (E_t).

A check for the threshold voltage can be made by a test at elevated frequency, as illustrated in 5.3. Another method which permits evaluation of the trend of the VE line at low stresses is given in 5.6. The threshold stress is influenced by temperature, usually decreasing as temperature rises. For temperatures higher than room temperature, the VE line is usually displaced towards the left of the graph and the times to dielectric breakdown are shorter for the same electric stress. The VE test is often carried out at room temperature but tests at higher temperatures provide information on the type of ageing processes, on the shape of the VE line and, in particular, on the existence of a threshold and its dependence on temperature.

5.3 Tests at higher frequency

In order to reduce the test times, the frequency of the applied voltage may be increased. The time to dielectric breakdown, L_f, at power frequency f is often derived from the time to dielectric breakdown, L_h, at the test frequency, f_h, by means of the following relationship:

$$L_f = L_h \frac{f_h}{f} \tag{8}$$

However, the validity of this relationship is not proved, especially for organic materials when the test frequency is more than 10 times f. Sometimes, acceleration is found to be proportional to the frequency ratio raised to a power different from unity. This exponent depends also on temperature, environmental conditions and type of prevailing ageing mechanism. Because permittivity and tan δ depend on frequency and temperature, dielectric heating, which is proportional to the product of the frequency, permittivity and tan δ, affects the time to dielectric breakdown. Also, partial discharges in micro-voids or defects inside the material and/or on the specimen surface have a different influence at a different frequency. Therefore, it is important that the interpretation of frequency-accelerated experiments is done with caution.

High-frequency tests at low stresses can be performed to infer the existence and, possibly, estimate the value of the electrical threshold. If the results of power-frequency tests seem to indicate the possible presence of a threshold, a high-frequency test shall be made at a voltage close to the voltage of the suspected threshold. If the time to dielectric breakdown at that voltage is considerably longer than would be expected according to the trend of the VE line at higher voltages combined with Formulas (3) to (6), the presence of the threshold is almost certainly confirmed and its estimation can be performed through fitting of the life curve to such formulas

5.4 Progressive stress tests

In the progressive stress test, the magnitude of the stress applied to each specimen in a sample increases with time until failure. The rate of the stress rise shall be the same for all specimens in a sample. However, to create a VE line, different rates of stress rise shall be used on each sample (i.e. collection of specimens). See Figure 3.

In this test, all specimens fail. Statistical treatment of the data is particularly useful due to the large quantity of information obtained. If the data relevant to each sample fit to the Weibull distribution, the corresponding points fit a straight line in Weibull paper. The slope of the line is the shape parameter γ of the distribution (see Clauses A.2 and A.3). Note that if γ is the same at different rates of voltage rise, the VEC can be derived from the ratio of γ to β (see Clause A.4). For this reason, in the VE test on materials and systems for which constancy of the VEC is expected in the test voltage range, a good practice is to carry out a progressive stress test in order to determine γ before starting with the constant stress tests. The VEC can then be derived theoretically. This permits a check of the value of the VEC to be made and thus the likely duration of the test program.

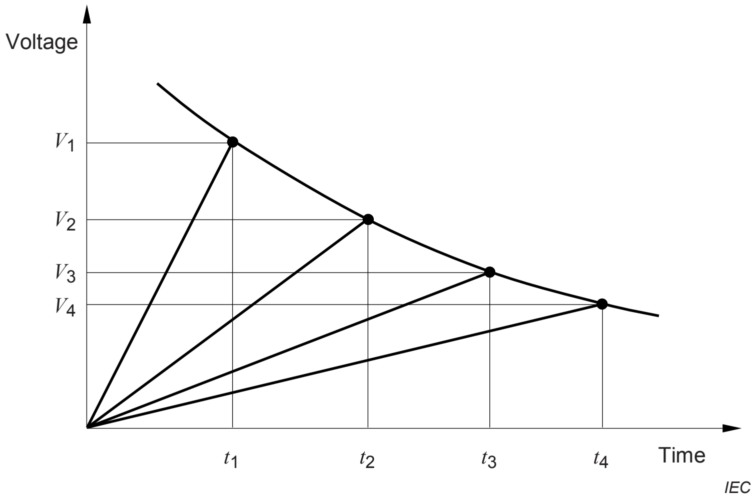

Figure 3 – Plotting the VE line in a progressive stress test using different rates of stress rise

Knowledge of the value of γ is of great importance when the results have to be reported for specimens of different size, i.e. area or volume. The dielectric breakdown probability at the same voltage stress is an increasing function of the dimensions of specimens. In order to transform the data – for instance the dielectric breakdown stress with a given probability – from the specimens for which these data have actually been obtained to specimens of different dimensions, it is necessary to know the relationship between probability, stress and dimensions. If the Weibull distribution is valid, the ratio between two stresses, E_1 and E_2, corresponding to the same dielectric breakdown probability for two elements, 1 and 2, of different area is given by

$$\frac{E_1}{E_2} = R^{1/\gamma} , \qquad (9)$$

where R is the dimensional ratio, i.e. the ratio of the dimensions (area) of element 2 to those of element 1. See Formula (A.2).

The progressive stress test data are usually less scattered than those from constant stress tests. If the VE line is straight on a log-log plot, its slope is also the same for progressive stress. The progressive stress data are related to those at constant stress by the following formula:

$$t_p = t_c (n + 1) , \qquad (10)$$

where t_p and t_c are the times to dielectric breakdown at progressive and constant stress, respectively, for the same value of stress and n is the VEC.

Since n is usually in the range 8 to 15, t_c is shorter than t_p. The times to dielectric breakdown with progressive stress are significantly shorter than the failure times from constant stress tests. Therefore, the progressive stress test is useful only for evaluation of the VEC in the short-times range. If the VEC is not constant, it is not possible to predict time to dielectric breakdown at constant stress starting from progressive stress data. In any case, no information on the long-time behavior of the test material, let alone on the threshold, is obtainable by progressive stress testing.

NOTE n is typically between 9 and 12 for mica-epoxy materials.

5.5 Preliminary tests to determine the initial part of the VE line

Preliminary tests are useful to determine the initial high-voltage part of the VE line, as well as an initial estimate for the value of n. These tests provide data for planning the future lower voltage tests. They include the following:

a) A progressive stress test or a step voltage test similar to a short-time electric strength test. The arithmetic mean dielectric breakdown voltage from this test is E_o. The aim is to puncture the specimen rather than cause flashover of the specimen. The failure shall not be a flashover and shall resemble the dielectric breakdowns obtained at lower voltages and longer times, thus involving the same ageing mechanism. The time to dielectric breakdown in this test is often longer than the value suggested in IEC 60243-1.

b) A constant stress test at or near E_o. The voltage shall be raised to the value of E_o without overshoots, and time t_o is calculated as the average of the breakdown times of the sample specimens. A zero crossing switch can be used to initiate the test to avoid overshoots and a counter to count the number of a.c. cycles to dielectric breakdown.

c) Constant stress tests at stresses slightly lower than E_o, for example 0,9 E_o, 0,8 E_o.

According to Formula (10), the theoretical ratio of the arithmetic mean time to dielectric breakdown with progressive stress, t_p, to the arithmetic mean time to dielectric breakdown with the constant stress, t_c, is $n + 1$. From this an estimate of the value of n at the initial part of the VE line can be calculated. Note that the point (E_o, t_o) is on the VE line.

5.6 Recommended test procedure

In order to characterize insulating materials or systems comprehensively from the point of view of electrical endurance, the following procedure is recommended.

a) Perform preliminary tests at high stress, as described in 5.4.

b) Perform constant stress tests at lower stresses. A sufficient number of tests at different stresses shall be performed to plot the VE graph and to obtain a reliable prediction of the long-time behaviour of the material under test. In any case, at least three test voltages are required. Other diagnostic measurements are also useful.

When the graph shows a tendency towards a threshold stress, the following procedure is often a useful check for the existence of a threshold. Perform a test at a stress about 5 % below the expected threshold stress with increased frequency. After a few thousand hours, remove some of the specimens and perform chemical-physical analysis and short-time electric strength measurements. No statistically significant variation of properties with respect to unaged specimens, e.g. decrease of electric strength, shall be found if the voltage applied is below the threshold.

6 Evaluation of voltage endurance

6.1 Significance of the VEC

Considering a VE line, the larger the value of the VEC, the longer the time to dielectric breakdown for the same value of the ordinate (E/E_o), all other parameters being equal. Hence, when a stress equal to the same percentage of E_o is applied to two materials having different VECs, the time to dielectric breakdown is longer for the one having the larger VEC. Therefore, the VEC is an important parameter for voltage endurance evaluation of insulating materials.

Since the VE line is sometimes nonlinear and thus the VEC is not constant, it is important to specify the stress range within which the VEC has been determined. If the constancy of the VEC has not been proved and an average of VEC values is considered, this shall be reported. In the case of a curved line, the differential coefficient, n_d, has been defined in 4.6. The range of stress at which n_d has been determined constitutes additional information which shall be provided.

It can be noted that n_d gives direct information on the actual slope of the line. Therefore, a specification such as "n_d decreasing from 15 to 8 for stresses decreasing from 100 % to 50 % of E_o" is a useful way to describe the VE line in that range of stresses.

6.2 Significance of the electrical threshold stress

If the material or system under consideration presents an electrical threshold stress of technical interest for insulation design (that is to say, not so low that its practical importance is negligible), this threshold stress becomes a useful factor to be determined in the VE test.

6.3 Dispersion of data and precision requirements

When the stress applied to an insulating material or system is higher than the threshold stress, the dielectric breakdown probability shall be calculated by statistical treatment of test data, as specified in IEC 62539. In order to obtain statistically valid results:

a) the test specimens of a sample shall be taken by a random procedure from a large batch (coming from the same manufacturing process);
b) specimens of uniform thickness and consistency shall be tested;
c) identical test cells or test objects shall be used for every specimen and the temperature and environmental conditions shall be the same during each test or from one test to another.

In many cases, the VE line for very low dielectric breakdown probabilities is more useful than the mean or the median VE line. Statistical treatment of the test data is then carried out to calculate times to dielectric breakdown at low probabilities, generally using the Weibull distribution, besides checking the linearity of the graph.

The difference between the arithmetic mean or median time to dielectric breakdown and the time to dielectric breakdown with a given low dielectric breakdown probability is a function of the dispersion of times to dielectric breakdown inherent in the material under test. By increasing the number of specimens, more precise estimates of this dispersion and thus low dielectric breakdown probability times can be obtained with reasonable confidence.

To have an immediate view of test accuracy, the confidence bounds for each experimentally determined point on the VE graph shall be reported.

An *F*-test is effective to check that the data satisfy tolerance regarding departure from linearity. The life data usually span several decades in time. The higher the value of the VEC, the larger the number of decades required to define it with precision.

6.4 Presentation of the results

In order to have a complete evaluation of voltage endurance of an insulating material or system, the VE line (preferably the lines corresponding to different percentiles) shall be shown, including the confidence intervals. The VE graph shall always accompany the test report, which shall include all the data necessary to understand the graph and its reliability. The following items shall be indicated in the report:

– unique identification of the material;
– thickness and shape of specimens;
– preparation technique;
– conditioning of specimens (if any);
– shape and dimensions of electrodes;
– test method and apparatus used;
– rate of voltage rise for any progressive stress test;
– frequency of the test voltage;

– test temperature;
– number of specimens tested at each test voltage;
– scatter or confidence bounds of each point plotted on the graph;
– any other information of interest.

If the results are given in terms of VEC, the requirement of linearity of the graph shall be satisfied. If the graph does not satisfy such requirements, values of n_{d} shall be supplied, together with the corresponding stress ranges.

The type of statistical analysis used shall also be specified and graphs of breakdown times on probability paper shall be provided. Special conditions to be satisfied for any particular kind of VE test will be indicated by special documents.

Annex A
(informative)

The Weibull distribution

A.1 Weibull distribution times to dielectric breakdown

The two-parameter Weibull distribution of the times to dielectric breakdown is usually written as

$$P(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] , \qquad \text{(A.1)}$$

where

$P(t)$ is the dielectric breakdown probability at time t;

β is the shape parameter;

α is the scale parameter, i.e. the time corresponding to $P = 1 - 1/e = 0{,}632$.

By taking logarithms twice one obtains:

$$\ln \ln (1/(1 - P)) = \beta \ln (t/\alpha) \qquad \text{(A.2)}$$

which, in coordinates ln ln (1/(1 − P)) versus ln (t), represents a straight line of slope β.

The Weibull paper is a special plotting paper which has scales according to such a coordinate system.

A.2 Weibull distribution dielectric breakdown stresses

The Weibull distribution of the dielectric breakdown stresses with linearly increasing voltage can be written as

$$P(E) = 1 - \exp (-mE^{\gamma}) , \qquad \text{(A.3)}$$

where

γ is the shape parameter;

m is proportional to the scale parameter and the dimensional ratio, R (see 5.4).

On Weibull paper, a straight line of slope γ is obtained.

If two elements of different dimensions are stressed by two stresses, E_1 and E_2, so that their dielectric breakdown probability is the same, P, then

$$1 - P = \exp (-m_1 E_1^{\gamma}) = \exp (-m_2 E_2^{\gamma}) = \exp (-Rm_1 E_2^{\gamma}) . \qquad \text{(A.4)}$$

From Formula (A.4), relationship (10) of 5.4 is easily derived.

A.3 Generalized Weibull distribution of the dielectric breakdown stresses

The generalized Weibull distribution for times and stresses can be written as

$$P\ (t,\ E) = 1 - \exp\ (-M\ t^{\beta}\ E^{\gamma})\ , \tag{A.5}$$

which becomes Formula (A.1) for E = constant and Formula (A.3) for t = constant. For progressive stress ($E = \rho t$) the result is

$$t^{\beta} E^{\gamma} = \rho^{\gamma} t^{(\beta+\gamma)} = \frac{E^{(\beta+\gamma)}}{\rho^{\beta}}\ . \tag{A.6}$$

Therefore, in the progressive stress test the slope of the line "probability as a function of stress" on Weibull paper is given by ($\beta + \gamma$) and not by γ.

However, γ is usually much greater than β; thus the difference can be so small that it can be neglected (γ is of the order of 10 or more, β around 0,5 to 2).

A.4 Inverse power model for the time to dielectric breakdown

If the data obtained at different stresses fit the same Weibull distribution (with constant values of the shape parameters β and γ), the equation of a line at constant dielectric breakdown probability, $\overline{P}$, is the following:

$$1 - \overline{P} = \exp\left(-Mt_f^{\beta}\ E^{\gamma}\right), \tag{A.7}$$

where t_f is the dielectric breakdown time with probability $\overline{P}$.

From Equation (A.7) the following relationship derives:

$$t_f^{\beta}\ E^{\gamma} = \text{constant}\ ,$$

and, since β and γ are constant,

$$t_f = C\ /\ E^{\gamma/\beta}\ , \tag{A.8}$$

which is an inverse power model for the time to dielectric breakdown, with $n = \gamma/\beta$.

Therefore, the validity of a Weibull distribution (see also IEC 61649) in a given range of stresses proves the validity of the inverse power model for time to dielectric breakdown in the same stress range, and vice versa.

The constancy of n in a given stress range indicates the same dielectric breakdown mechanism for any stress belonging to that range. In only that case can the progressive stress be applied and the transformation formula

$$t_p = t_c\ (n + 1) \tag{A.9}$$

be used.

Bibliography

IEC 60243-1, *Electric strength of insulating materials – Test methods – Part 1: Tests at power frequencies*

IEC 60243-2, *Electric strength of insulating materials – Test methods – Part 2: Additional requirements for tests using direct voltage*

IEC 60243-3, *Electric strength of insulating materials – Test methods – Part 3: Additional requirements for 1,2/50 μs impulse tests*

IEC 60343, *Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges*

IEC 61649, *Weibull analysis*

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