भारतीय मानक

Indian Standard

IS 15382 (Part 4) : 2024
IEC 60664-4 : 2005

निम्न-वोल्टता पद्धतियों के भीतर उपकरणों के लिए विद्युतरोधी समन्वय

भाग 4 उच्च-आवृति वोल्टेज दाब को ध्यान में रखते हुए

(दूसरा पुनरीक्षण)

Insulation Coordination for Equipment within Low-Voltage Systems

Part 4 Consideration of High-frequency Voltage Stress

(Second Revision)

ICS 29.080.30

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NATIONAL FOREWORD

This Standard (Part 4) (Second Revision) which is identical to IEC 60664-4 : 2005 ‘Insulation coordination for equipment within low-voltage systems — Part 4: Consideration of high-frequency voltage stress’ issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the High Voltage Engineering Sectional Committee and approval of the Electrotechnical Division Council.

This standard was first published in 2003 and subsequently revised in 2017. This revision has been undertaken to align it with the latest version of IEC 60664-4 : 2005.

This standard is published in several parts. The other parts in this series are:

Part 1	Principles requirements and tests
Part 2/Sec 1	Application guide, Section 1 Explanation of the application of the IEC 60664 series, dimensioning examples and dielectric testing
Part 2/Sec 2	Interface considerations, Section 2 Application guide
Part 3	Use of coating potting or moulding for protection against pollution
Part 2/Sec 1	Application guide, Section 1 Explanation of the application of the IEC 60664 series, dimensioning examples and dielectric testing

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

a) Wherever the words ‘International Standard’ appears referring to this standard, they should be read as ‘Indian Standard’; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

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

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60112 : 2003 Method for determining the comparative and the proof tracking indices of solid insulating materials under moist conditions	IS 2824: 2007/IEC 60112 : 2003 Method for the determination of the proof and the comparative tracking indices of solid insulating materials (*second revision*)	Identical
IEC 60664-1 : 1992 Insulation coordination for equipment within low-voltage systems — Part 1: Principles, requirements and tests	IS 15382 (Part 1) : 2022/ IEC 60664-1 : 2020 Insulation coordination for equipment within low — Voltage systems: Part 1 principles, requirements and tests (*second revision*)	Identical with IEC 60664-1 : 2020

(*Continued on third cover*)

INTRODUCTION

High electrical stress also occurs in low-voltage equipment. The frequency is usually 50/60 Hz, but in some applications a higher frequency (400 Hz) or a lower frequency (16 2/3 Hz) or d.c. can occur. A particular situation exists in high-power RF transmitters. The development of such equipment had motivated earlier research on the withstand capability of insulation at radio frequencies. Since that time, the aspect of high-frequency voltage stress had not been pursued with much effort.

At present, high-frequency working voltages exceeding 30 kHz are often used in low-voltage equipment, and the use of frequencies in the MHz range is likely in the future. Many of the voltage shapes are non sinusoidal. Small dimensions are necessary for miniaturization and for high efficiency, for instance in high-frequency transformers. Consequently, very high stresses are common in solid insulation.

By increasing the frequency the deteriorating effect of partial discharges is also increased roughly proportionally to the frequency, so that the impact of partial discharges on dimensioning is much higher compared to power frequency.

As dimensions are likely to decrease further and frequencies increase, this situation will be aggravated in the future. Therefore, with respect to safety of personnel and reliability of equipment, the stress due to high frequencies up to 100 MHz has to be considered for insulation coordination of low-voltage equipment, (see note 2 in the Scope of Part 1).

This standard summarizes the most important available data concerning high-frequency stress of insulation, and identifies how materials and their dimensioning are influenced. Data for dimensioning of clearances, creepage distances and solid insulation are specified. This standard also describes how tests can be performed with respect to this stress.

Indian Standard

INSULATION COORDINATION FOR EQUIPMENT WITHIN LOW-VOLTAGE SYSTEMS

PART 10 CONSIDERATION OF HIGH-FREQUENCY VOLTAGE STRESS

(Second Revision)

1 Scope and object

This part of IEC 60664 deals with basic, supplementary and reinforced insulation subjected to high-frequency voltage stress within low-voltage equipment. The dimensioning values directly apply for basic insulation; for reinforced insulation additional requirements apply according to Part 1. It is applicable for the dimensioning of clearances, creepage distances and solid insulation stressed by any type of periodic voltages with a fundamental frequency above 30 kHz and up to 10 MHz.

This part of IEC 60664 can only be used together with IEC 60664-1 or with IEC 60664-5 (in this standard called Part 1 or Part 5). By using Part 1 or Part 5 together with this part the frequency limit of Part 1 or Part 5 is extended to frequencies higher than 30 kHz.

This part also applies to Part 3 for frequencies greater than 30 kHz and protection of type 1. For type 2 protection this question is under consideration.

NOTE 1 Dimensioning values for frequencies above 10 MHz are under consideration.

NOTE 2 This standard does not consider the high-frequency emission to the mains. In normal use of equipment, it is assumed that the interference of high-frequency voltages emitted to the mains is negligible with respect to insulation stress. Therefore it is not necessary to take it into account.

It applies to equipment for use up to 2 000 m above sea level having a rated voltage up to a.c. 1 000 V.

It specifies the requirements for clearances, creepage distances and solid insulation for equipment based upon their performance criteria. It includes methods of electric testing with respect to insulation coordination.

The minimum clearances specified in this part do not apply where ionized gases occur. Special requirements for such situations may be specified at the discretion of the relevant technical committee.

This part does not deal with distances

- through liquid insulation,
- through gases other than air,
- through compressed air.

NOTE 3 Higher voltages may exist in internal circuits of the equipment.

NOTE 4 Requirements for altitudes exceeding 2 000 m can be derived from Table A.2 of Annex A of Part 1.

The object of this standard is to guide technical committees responsible for different equipment in order to rationalise their requirements so that insulation coordination is achieved when specifying clearances in air, creepage distances and solid insulation for equipment.

2 Normative references

The following referenced documents are indispensable for the application 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 60112:2003, *Method for determining the comparative and the proof tracking indices of solid insulating materials under moist conditions*

IEC 60664-1:1992, *Insulation coordination for equipment within low-voltage systems: Part 1: Principles, requirements and tests*

Amendment 1 (2000)

Amendment 2 (2002)

IEC 60664-5:2003, *Insulation coordination for equipment within low-voltage systems: A comprehensive method for determining clearances and creepage distances equal to or less than 2 mm*

IEC Guide 104:1997, *The preparation of safety publications and the use of basic safety publications and group safety publications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in Part 1, as well as the following terms and definitions, apply.

3.1
approximately homogeneous field
for frequencies exceeding 30 kHz, the field is considered to be approximately homogeneous when the radius of curvature of the conductive parts is equal or greater than 20 % of the clearance

3.2
inhomogeneous field
for frequencies exceeding 30 kHz the field is considered to be inhomogeneous when the radius of curvature of the conductive parts is less than 20 % of the clearance

3.3
$U_{\mathbf{peak}}$
peak value of any type of periodic peak voltage across the insulation

3.4
$f_{\mathbf{crit}}$
critical frequency at which the reduction of the breakdown voltage of a clearance occurs

3.5
$f_{\mathbf{min}}$
frequency at which the maximum reduction of the breakdown voltage of a clearance occurs

3.6
PD-voltage
generic term for both partial discharge inception voltage U_i and partial discharge extinction voltage U_e

3.7
electrical field strength E
voltage gradient per unit length usually expressed in kV/mm

4 Clearances

4.1 General conditions

This clause is applicable to clearances in air. The dimensioning data are valid for a maximum altitude of 2 000 m above sea level. For higher altitudes, the altitude correction factors of Table A.2 of Part 1 are applicable.

4.2 Basic information

According to the basic information given in Clause A.1 the withstand capability of clearances can only be influenced by the frequency of the voltage if periodic voltages are relevant (see 3.1.1.2 of Part 1 or Part 5). For transient overvoltages dimensioning according to 3.1.1.1 of Part 1 or Part 5 is sufficient.

4.3 Homogeneous and approximately homogeneous fields

4.3.1 Conditions for approximately homogeneous field

For frequencies exceeding 30 kHz, an approximately homogeneous field is considered to exist when the radius of curvature of the conductive parts is equal or greater than 20 % of the clearance.

4.3.2 Experimental data of breakdown characteristics

As a conclusion from A.2.1, the critical frequency f_{crit}, at which the reduction of the breakdown voltage occurs, depends upon the value of the clearance as follows:

$$f_{\text{crit}} \approx \frac{0{,}2}{d\,/\,\text{mm}} \quad \text{MHz} \tag{1}$$

where
d is the clearance.

The experimental data, presented in A.2.1 for homogeneous field conditions, shows a maximum reduction of the breakdown voltage with frequency of 20 % compared to the 50/60 Hz-values. The frequency, at which the maximum reduction occurs, is called f_{min}.

NOTE For the purposes of this standard, f_{min} as illustrated in Figure A.1 is accepted as 3 MHz.

4.3.3 Dimensioning of clearances for homogeneous and approximately homogeneous field conditions

The insulating characteristics of homogeneous field clearances in air at atmospheric pressure with respect to frequency can be summarized by the following statements.

- Above f_{crit} the breakdown voltage is reduced with increasing frequency. The maximum reduction of the breakdown voltage is about 20 %.
- The breakdown voltage reaches a minimum at a frequency f_{min}. For higher frequencies, the breakdown voltage is increased and can exceed the value at power frequency.

It is assumed that these characteristics are also applicable for approximately homogeneous field conditions.

Dimensioning for homogeneous fields is based upon Case B values of Table 7 of Part 1 or Table 3 of Part 5. The use of these values requires a withstand test according to 4.1.1 of Part 1 or Part 5.

Dimensioning for approximately homogeneous fields is based on Case A values of Table 7 of Part 1 or Table 3 of Part 5. No withstand test is required. However the radius of curvature of the conductive parts shall be equal or greater than 20 % of the clearance.

There are two methods for dimensioning:

1. If no detailed evaluation is intended, the clearance shall be designed within the frequency-scope of this standard for 125 % of the required withstand voltage according to Table 7 of Part 1 or Table 3 of Part 5.
2. If a detailed evaluation is intended, the following applies:
   a) For frequencies below f_{crit} (see Equation (1)) the clearance shall be designed for 100 % of the required withstand voltage according to Table 7 of Part 1 or Table 3 of Part 5.
   b) For frequencies above f_{min} the clearance shall be designed for 125 % of the required withstand voltage according to Table 7 of Part 1 or Table 3 of Part 5.
   c) For frequencies between f_{crit} and f_{min} the clearance shall be designed for

$$100\ \% + \frac{f - f_{\mathrm{crit}}}{f_{\mathrm{min}} - f_{\mathrm{crit}}} \times 25\ \% \qquad (2)$$

   of the required withstand voltage according to Table 7 of Part 1 or Table 3 of Part 5.

In order to obtain the critical frequency, in a first step the clearance is assumed for 100 % of the required withstand voltage according to Table 7 of Part 1 or Table 3 of Part 5. Then it has to be decided, if condition 2a, 2b or 2c is applicable. As this evaluation can be influenced by the result obtained (clearance), a second iteration can be required.

NOTE Further information about dimensioning is given in Annex F.

4.4 Inhomogeneous fields

4.4.1 Conditions for inhomogeneous field

For frequencies exceeding 30 kHz, an inhomogeneous field is considered to exist when the radius of curvature of the conductive parts is less than 20 % of the clearance.

4.4.2 Experimental data of partial discharge and breakdown characteristics

For inhomogeneous field conditions, f_{crit} can still be approximated from Equation (1). Above f_{crit}, the influence of frequency on the breakdown voltage is much more significant compared to homogeneous field conditions. The reduction of the breakdown voltage with respect to that at power frequency can be more than 50 %.

For inhomogeneous field conditions partial discharges (corona) must be expected at voltages below the breakdown voltage. Due to the high risk of deterioration caused by these discharges with high repetition frequency dimensioning shall be sufficient to avoid the occurrence of partial discharges (PD).

The experimental data are presented in A.2.2.

4.4.3 Dimensioning of clearances for inhomogeneous field conditions

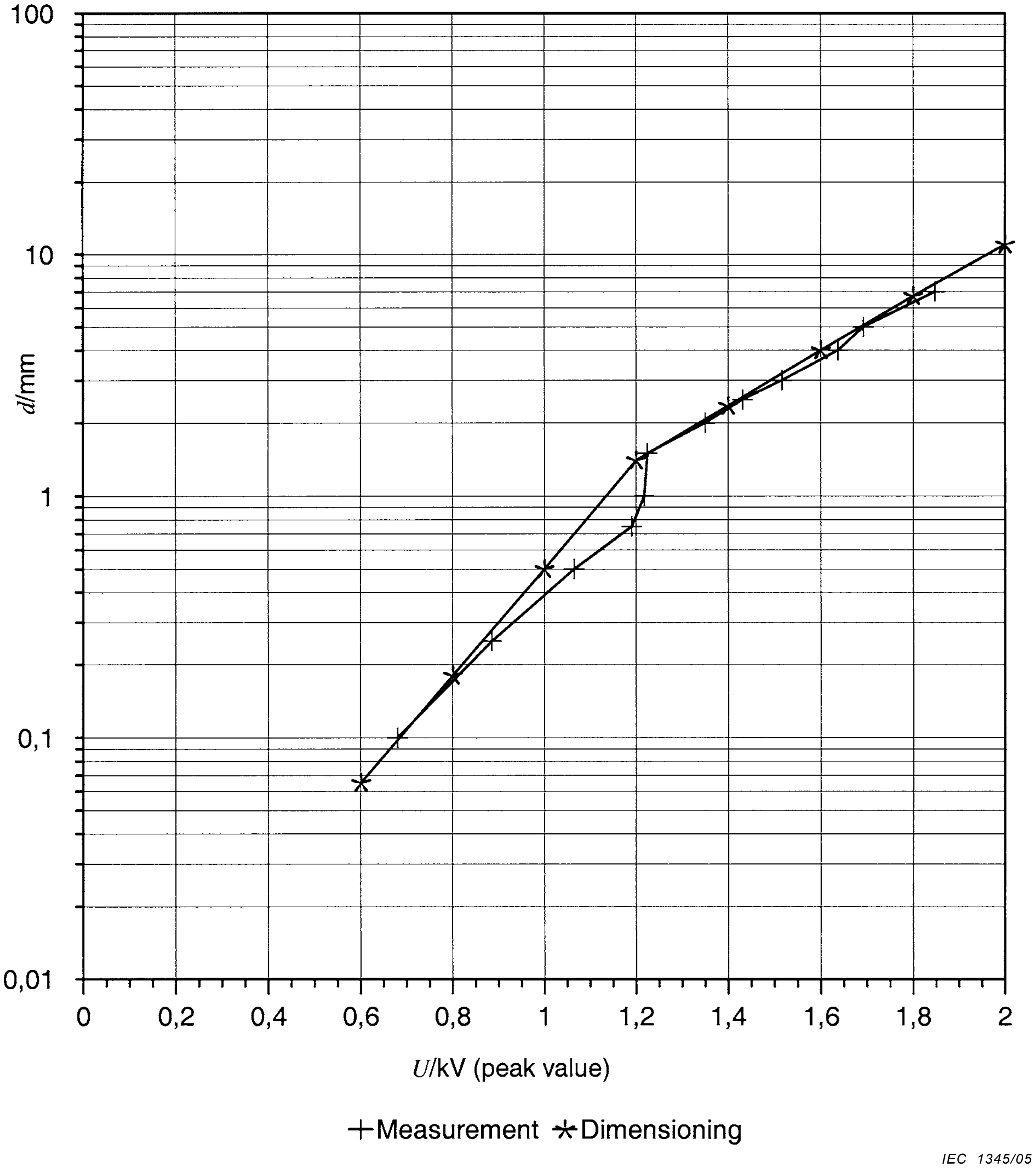
For frequencies below f_{crit} (see Equation (1)) the clearance shall be designed for 100 % of the required withstand voltage according to Table 7 of Part 1 or Table 3 of Part 5.

The frequency of the voltage shall be taken into account for dimensioning for frequencies equal to or greater than f_{crit}. As PD can be started by transient overvoltages and shall not be maintained by any steady state voltage (see 4.1.2.4 of Part 1), the PD-extinction voltage shall be used for dimensioning. The relevant data (see the note) is shown in Figure 1 (measurement) together with a limiting curve (dimensioning).

NOTE 1 For dimensioning, data from A.2.2 are applicable, obtained for clearances up to 0,75 mm from the breakdown voltages and above from the PD-extinction voltages at 1 MHz.

The dimensioning data for inhomogeneous fields are summarized in Table 1. These values are applicable if a small radius of curvature of the conductive parts occurs. In practice this condition is fulfilled if the radius of curvature of the conductive parts is smaller than 20 % of the clearance.

NOTE 2 Further information about dimensioning is given in Annex F.



Key

d clearance

Figure 1 – Dimensioning of inhomogeneous clearances in air at atmospheric pressure (point-plane-electrodes, 5 µm radius) to avoid PD (clearance ≥ 1 mm) or breakdown (clearance < 1 mm)

Table 1 – Minimum values of clearances in air at atmospheric pressure for inhomogeneous field conditions

Voltage U_{peak} kV	Clearance mm
Up to 0,6 [a)] [b)]	0,065
0,8 [a)]	0,18
1,0 [a)]	0,5
1,2 [a)]	1,4
1,4 [a)]	2,35
1,6 [a)]	4,0
1,8 [a)]	6,7
2,0 [a)]	11,0

[a)] For voltages between the values stated in this table, interpolation is permitted.

[b)] No data is available for voltages U_{peak} of less than 0,6 kV.

5 Creepage distances

5.1 Experimental data

The influence of frequency on the breakdown voltages of creepage distances is taken into account according to the data given in Annex B.

The experimental conditions for the investigations being performed and the materials being included in the experiments are described in Clause B.2.

The experimental data are shown in Clause B.3. Both the PD-voltages and the breakdown voltages are significantly influenced by the frequency of the voltage.

5.2 Dimensioning of creepage distances

Measuring data for three different frequency ranges up to 100 kHz, up to 1 MHz and up to 3 MHz are shown in Figure 2 (measurement) together with limiting curves (dimensioning). The dimensioning data for creepage distances are summarized in Table 2. The data for the additional frequency ranges have been obtained by linear interpolation. These data are valid for pollution degree 1.

NOTE 1 For dimensioning of creepage distances the data from Clause B.3 for the PD-extinction voltage are applicable as PD at high-frequency voltage will have a destructive effect on the base material, if it occurs during a longer period of time.

Experiments [5][1] have shown that creepage distances for pollution degree 2 and 3 can be derived from the distances determined for pollution degree 1 by application of a multiplication factor. For pollution degree 2, the multiplication factor 1,2 and for pollution degree 3 the multiplication factor 1,4 are applicable.

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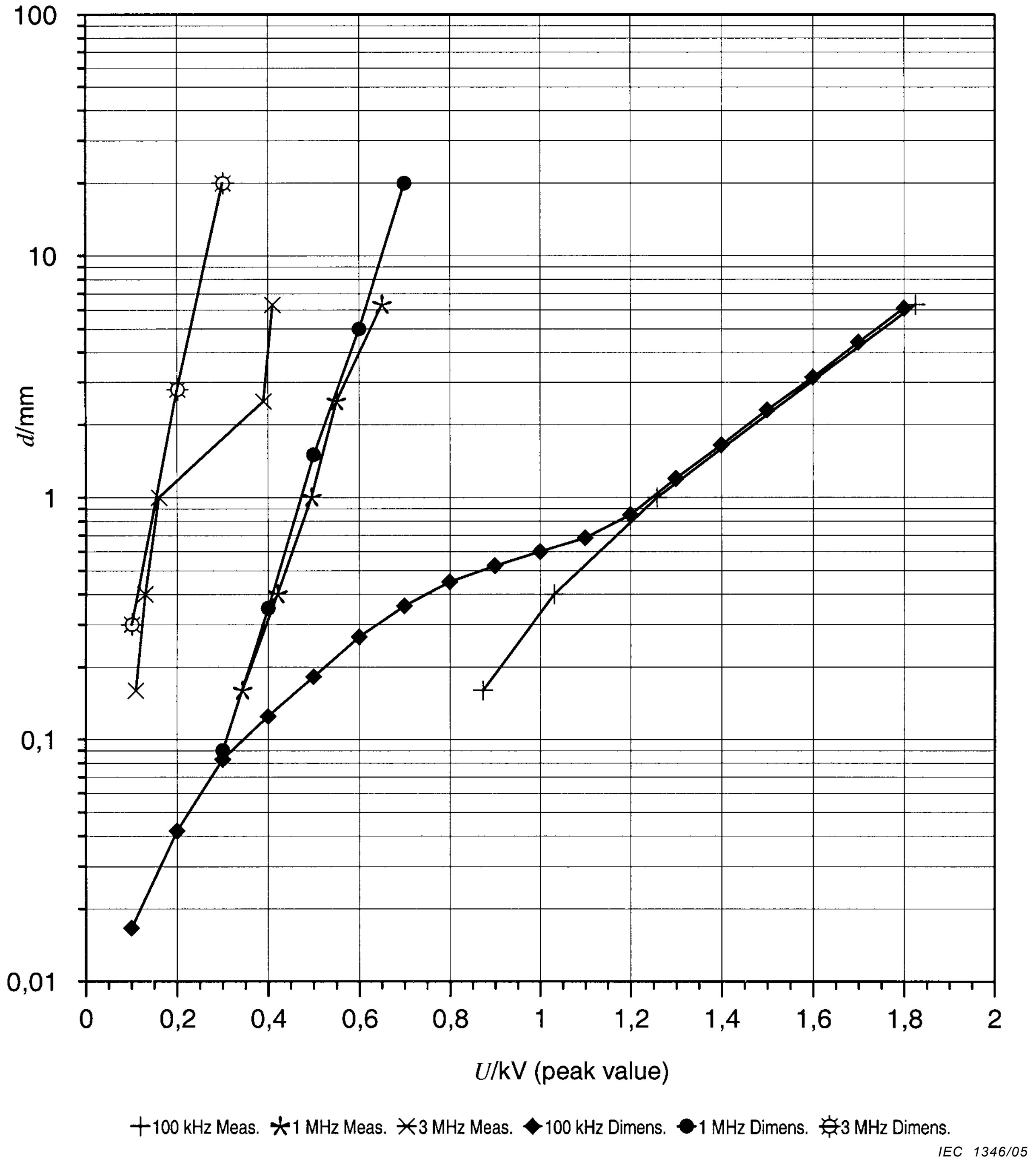
[1] Figures in square brackets refer to the bibliography.

The data given in Table 2 do not take into account the influence of tracking phenomena. For that purpose Part 1 or Part 5 of IEC 60664 have to be taken into account. Therefore if the values from Table 2 of this standard are smaller than the relevant values from Table 4 of Part 1 or Part 5, the latter are applicable.

These dimensioning data are applicable for all materials that can be deteriorated by thermal effects. For materials where such deterioration is not likely to occur (for example ceramics) dimensioning for clearances according to Clause 4 of this standard is sufficient.

NOTE 2 Further information about dimensioning is given in Annex F.



Key

d creepage distance

Figure 2 – Dimensioning of creepage distances to avoid partial discharge (creepage distance ≥ 1 mm) or breakdown (creepage distance < 1 mm)

Table 2 – Minimum values of creepage distances for different frequency ranges

Voltage	Creepage distance a) mm						
U_{peak} kV	for 30 kHz < $f \leq$ 100 kHz	for $f \leq$ 0,2 MHzb)	for $f \leq$ 0,4 MHzb)	for $f \leq$ 0,7 MHzb)	for $f \leq$ 1 MHzb)	for $f \leq$ 2 MHzb)	for $f \leq$ 3 MHzb)
0,1	0,0167						0,3
0,2	0,042					0,15	2,8
0,3	0,083	0,09	0,09	0,09	0,09	0,8	20
0,4	0,125	0,13	0,15	0,19	0,35	4,5	
0,5	0,183	0,19	0,25	0,4	1,5	20	
0,6	0,267	0,27	0,4	0,85	5		
0,7	0,358	0,38	0,68	1,9	20		
0,8	0,45	0,55	1,1	3,8			
0,9	0,525	0,82	1,9	8,7			
1	0,6	1,15	3	18			
1,1	0,683	1,7	5				
1,2	0,85	2,4	8,2				
1,3	1,2	3,5					
1,4	1,65	5					
1,5	2,3	7,3					
1,6	3,15						
1,7	4,4						
1,8	6,1						

a) The values for the creepage distances in the table apply for pollution degree 1. For pollution degree 2 a multiplication factor of 1,2 and for pollution degree 3 a multiplication factor 1,4 shall be used.

b) Interpolation between columns is allowed.

6 Solid insulation

6.1 General consideration

Compared to clearances in air, solid insulation can provide a breakdown field strength that is at least one order of magnitude higher. However in practical use the high breakdown field strength of solid insulation is of little use.

NOTE The mechanisms that are responsible for degradation and finally breakdown at much lower field strengths than expected are described in detail in Clause C.1.

6.2 Influencing factors

For a frequency of 1 MHz, the short-time breakdown field strength can be as low as 10 % of the power-frequency value. The breakdown field strength does not seem to reach a lower limit even at frequencies as high as 100 MHz.

NOTE High-frequency breakdown characteristics are shown in Clause C.2.

The dielectric strength of solid insulation in general, and especially at high-frequency voltage, can be further reduced by the influence of humidity and temperature. This influence is taken into account by conditioning before testing according to 7.3.

According to these characteristics solid insulation, which is intended for use in high-frequency applications, shall not be exposed for long period of time to humidity conditions higher than 92 % of relative humidity. Some materials e. g. glass and some ceramics are not influenced by humidity and therefore are not restricted by this limit of 92 %.

The breakdown field strength of solid insulation is a function of the thickness of the material. Very thin films can have a breakdown field strength that can be up to one order of magnitude higher than that of the test specimen with 0,75 mm thickness. So any dimensioning according to thickness of solid insulation shall take into account this dependency of the breakdown field strength upon the thickness of the insulation.

The influence of the temperature on the breakdown voltage can be seen in Clause C.2. Therefore the temperature is an important influencing factor, which shall be taken into account for dimensioning and testing.

Partial discharges at high-frequency voltages will have a high PD-impulse repetition frequency corresponding to the frequency of the voltage. Therefore no reasonable lifetime of solid insulation can be expected when partial discharges occur.

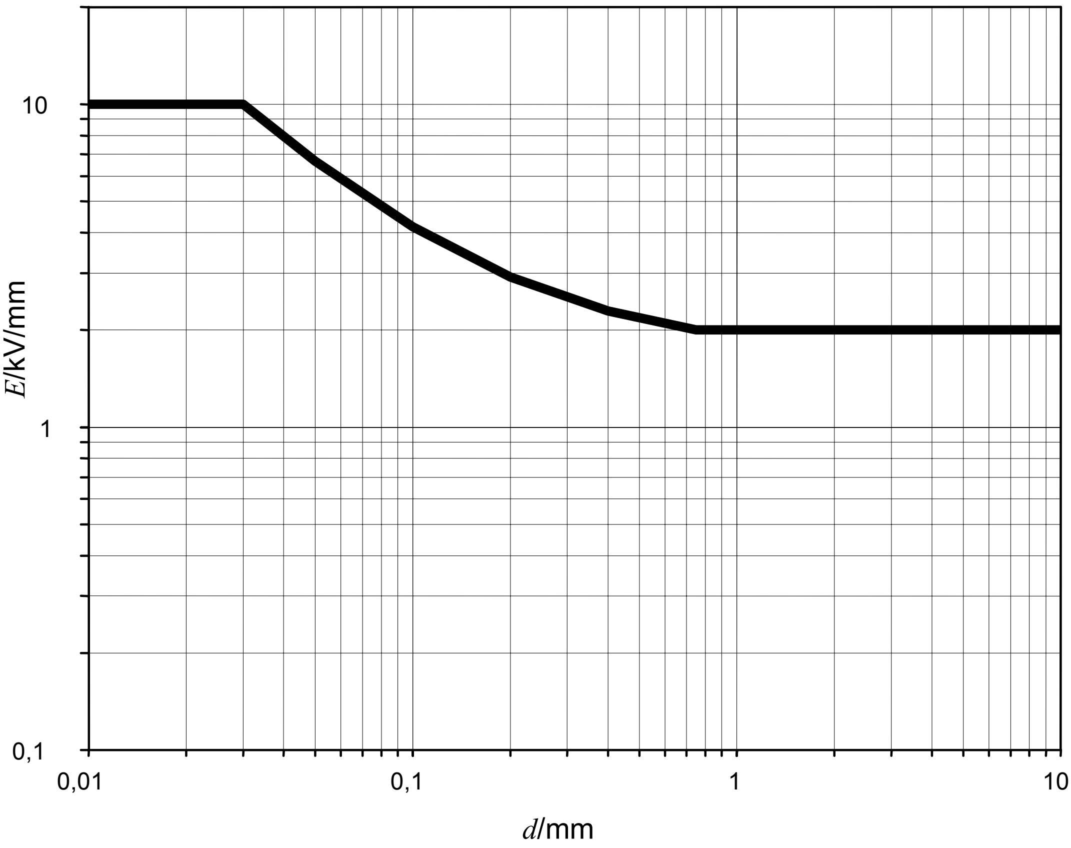
6.3 Dimensioning of solid insulation

The following method of dimensioning can be used instead of high-frequency testing according to Clause 7. It applies for a maximum frequency of the voltage 10 MHz, if the field strength is approximately uniform, not exceeding the specified values according to Equation (3) or Figure 3 respectively and no voids or air gaps are present in between the solid insulation. If these conditions cannot be fulfilled, high-frequency testing according to Clause 7 is required.

Dimensioning can be used if the electric field is approximately uniform (see the note). For thick layers of solid insulation of $d_1 \geq 0{,}75$ mm the peak value of the field strength E shall be equal or less than 2 kV/mm. For thin layers of solid insulation of $d_2 \leq 30$ µm the peak value of the field strength shall be equal or less than 10 kV/mm. For $d_1 > d > d_2$ Equation (3) shall be used for interpolation for a certain thickness d (see also Figure 3):

$$E = \left(\frac{0{,}25}{d} + 1{,}667 \right) \frac{\mathrm{kV}}{\mathrm{mm}} \qquad (3)$$

NOTE In this context, the electric field is considered to be approximately uniform if the deviations are less than ±20 % from the average value of the field strength.



Key

E field strength

Figure 3 – Permissible field strength for dimensioning of solid insulation according to Equation (3)

The use of the field strength for dimensioning of solid insulation requires an approximately uniform field distribution with no voids or air gaps in between. If the field strength cannot be calculated (because the field is not uniform) or if the peak value is higher than given from Equation (3) or Figure 3 respectively or if the presence of voids or air gaps cannot be excluded or for higher frequencies than 10 MHz, a withstand test or a PD-test with high-frequency voltage is required. The first applies to short time stresses the second applies to long time stresses according to 3.3.3.2.2 of Part 1.

7 High-frequency testing

7.1 Basic requirements

The following tests are conducted at the frequency of the applied voltage:

- verification of the short-time dielectric strength for clearances and for solid insulation through use of a high-frequency a.c. voltage test;
- verification that no partial discharges occur under steady-state conditions of high-frequency voltage application.

Due to the large capacitive load at high-frequency, high-frequency testing is primarily applicable to components and subassemblies. If an additional high-voltage test on complete equipment is required, this test can be performed according to 4.1.2 of Part 1 with power-frequency voltage.

7.2 Test voltage source

Test voltage sources are given in Clause D.1.

7.3 Conditioning

If not otherwise specified by technical committees, the test shall be performed with a new test specimen. Conditioning of the specimen by temperature and humidity treatment is intended to

- represent the most severe normal service conditions,
- expose possible weaknesses that are not present in the new condition.

The conditioning methods described in 4.1.2.1 of Part 1 also apply for high-frequency testing.

7.4 High-frequency breakdown test

This test is similar to the high-voltage test at power-frequency (see 4.1.2.3 of Part 1).

7.4.1 Test method

High-frequency withstand capability is influenced by equipment temperature and environmental conditions. Therefore the test shall be performed under the most severe conditions that can be encountered in service, including the temperature rise caused by normal operation of the equipment. The test duration is 1 min.

7.4.2 Test result

No breakdown shall occur during the test duration. After the test, no visible damage (burning, melting etc.) shall occur.

7.5 High-frequency partial discharge test

7.5.1 General considerations

The general methods for partial discharge testing are described in IEC 60270. For PD-testing of low-voltage equipment 4.1.2.4 of Part 1 and Annex C of Part 1 are applicable, but for a test with high-frequency voltage changes are required in the test equipment and methods that are specified in this standard.

In order to minimize the risk of test sample degradation, a PD-testing should be performed with precise procedures and measurements and with test voltages in the range of the PD-inception voltage. For the failure criterion, low PD-levels have to be specified, normally below 10 pC. As the specified PD-extinction voltage can be determined with limited accuracy and is influenced by additional parameters such as temperature and humidity which are not usually taken into account during testing, the PD-extinction voltage must include a safety factor of F_1 = 1,2 times the highest periodic peak voltages (see 4.1.2.4 of Part 1). For reinforced insulation a more stringent risk assessment is necessary and an additional safety factor of F_3 = 1,25 is required for the PD-extinction voltage (see 4.1.2.4 of Part 1).

The PD-test is primarily a component test, but testing of equipment is also possible. In that case localizing the PD-source can be difficult and the measured PD-magnitude will be a function of position within the apparatus. During type testing, the PD-test will verify the proper design of the insulation system, the appropriate selection of the insulation materials, and proper manufacturing processes. Such tests are also very useful during equipment design. By performing sampling and routine testing, the entire manufacturing process can be verified, which is of fundamental importance for quality insurance.

Due to the high-frequency test voltage, careful screening of the test system by conductive enclosures is required to avoid interfering with other electronics in the vicinity. Such screening measures are generally sufficient to meet the required interference level during PD-measurements.

7.5.2 Test method

Due to the high risk of deterioration of the test specimen at high-frequency voltage, the rate of voltage rise should be as high as possible without causing overshoot of the test voltage. In general, the noise level during high-frequency partial discharge testing will be significantly higher than during power frequency testing.

7.5.3 Test equipment

The measurement of partial discharges at high-frequency voltage is more difficult because the test voltage and the partial discharge signal can have overlapping frequency spectra which require appropriate methods of separation (filtering). As the frequency of the test voltage can vary over a wide range, tuned notch filters will be necessary. The centre frequency of these filters shall be tuned to the frequency of the test voltage. It is much more difficult to separate the signal of non-sinusoidal test voltage sources from the PD-signal; therefore such tests are not recommended within the scope of this standard. For measuring the PD-intensity, a digital storage oscilloscope is used in combination with a band-stop filter in order to suppress the high-frequency test voltage.

Examples of partial discharge test circuits with high-frequency voltage are shown in Clause D.2. The partial discharge detection is performed by digital integration with a digital storage oscilloscope of high sampling rate.

7.5.4 Test circuit

The PD-measurement is performed through detection of the PD-current. For this purpose, a measuring impedance R_m is connected in series with the test specimen. The voltage drop across this impedance is applied across a band-stop filter to one channel of a digital storage oscilloscope with high bandwidth (at least 100 MHz) so that together with the test circuit consisting of lumped elements, a total bandwidth of 60 MHz can be obtained. The band-stop filter removes the voltage drop caused by the capacitive current feeding the test specimen. By this technique a PD-sensitivity of 5 pC can be obtained.

The high-frequency test voltage is measured with a high-frequency voltmeter and the waveshape is monitored on the second channel of the digital storage oscilloscope. For further details of the test circuit see D.2.2.

7.5.5 Required bandwidth of the test circuit

In the following evaluation, the test circuit has a 1st order low-pass transfer characteristic (PT_1-characteristic) resulting in a lower cut-off frequency of zero and an upper cut-off frequency (3 dB) f_c that is equal to the bandwidth.

Considerations with respect to the effect of possible resonance points or the lower cut-off frequency of the test circuit are described in D.2.2.

7.5.5.1 Minimum bandwidth for PD-impulse resolution

For high-frequency test voltages, a high pulse repetition frequency of PD-impulses must be expected. Therefore the PD-impulse resolution must be sufficient to avoid overlapping pulses. For that reason, only so called „wide-band“ measuring equipment can be used. This is in contrast to the recommendations given in Part 1 for tests at power-frequency voltage.

The minimum bandwidth of the PD measuring circuit shall be equal to or greater than the PD-impulse frequency in order to avoid overlapping pulses. This is an absolute minimum requirement that does not provide a reproduction of the PD-pulse waveshape.

An upper test circuit cut-off frequency f_c of five times the PD-impulse frequency is usually sufficient, for details see D.2.2.2.1.

7.5.5.2 Minimum bandwidth for PD-impulse analysis

In order to analyse the source of the PD-signal and to make some analysis of the shape and size of the voids that are the origin of PD, much greater bandwidths are required. For further details see D.2.2.2.2.

7.5.6 Dimensioning of the test circuit

Proper dimensioning shall avoid overlap of PD-impulses and should allow some analysis of the PD-impulse waveshape. This dimensioning requires some analysis of the test circuit, which is performed in D.2.2.

7.5.6.1 Influence of the test circuit on the transfer characteristics

For adequate reproduction of the PD-impulses approximately aperiodic response of the test-circuit is required, and the upper cut-off frequency f_c should be as high as possible. Details are described in D.2.2.3.3.1.

To obtain aperiodic response of the test-circuit, the inductance L, which is the sum of that of the wiring L_W and the coupling capacitor L_{Ck}:

$$L = L_W + L_{Ck} \tag{4}$$

shall be limited to:

$$L \leq \frac{R_m^2 C}{4} \tag{5}$$

with R_m the measuring impedance for the PD-current. The effective capacitance C is

$$C = \frac{C_3\, C_k}{C_3 + C_k} \tag{6}$$

with the capacitance of the test specimen C_3.

In that case the upper cut-off frequency f_c can be approximated by assuming a simple RC-circuit:

$$f_c = \frac{1}{2\pi\, R_m\, C} \tag{7}$$

The lower cut-off frequency is zero.

7.5.6.2 Influence of the coupling capacitor on the transfer characteristics

The influence of the size of the coupling capacitor C_k on the transfer characteristics of the test circuit is evaluated in D.2.2.3.4 [5], which shows clearly that this influence is very strong and that small coupling capacitors compared to the capacitance of the test specimen C_3 are not appropriate.

Small coupling capacitors will reduce the measuring signal, which is taken into account by calibration. However the sensitivity of the PD-test circuit will also be reduced. The other problem is the differentiation of the measuring signal when using small coupling capacitors. From D.2.2.3.4, it can be seen that the minimum capacitance is $C_k = C_3$. If possible the capacitance should be $C_k \geq 10 \times C_3$.

The necessary value for the coupling capacitance is the greater of this value and the capacitance that is required for aperiodic response of the test circuit (see 7.5.6.1, Equation (5)).

7.6 Examples of test results

Many components for low-voltage equipment have been tested using high-frequency test voltage. Most of the data are proprietary. Some general results are shown in Clause D.3.

8 Non sinusoidal voltages

8.1 General considerations

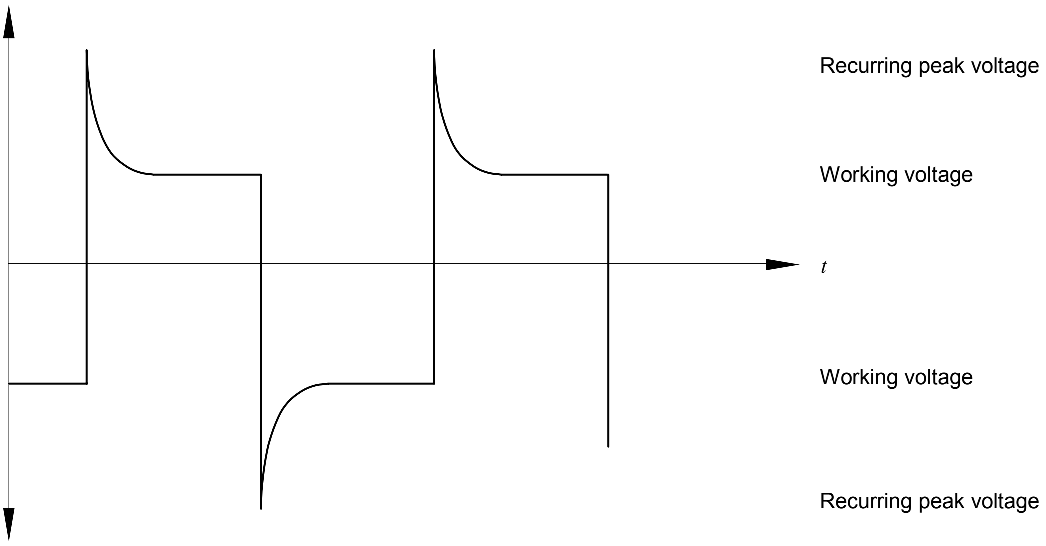
This standard addresses the influence of sinusoidal high-frequency voltages on the dimensioning and testing of insulation. In many practical cases, the actual voltage stress is far from being sinusoidal. Periodic pulses with greatly varying waveshapes can be found in many applications.

In this case, a harmonic analysis of the impulse shape is required, and the relevant sinusoidal frequencies have to be identified.

The following consideration does not take into account the effect of the voltage waveshape on the voltage distribution across the insulation of windings.

8.2 Periodic impulse voltage

An example of such a voltage waveshape is given in Figure 4.



IEC 1348/05

Figure 4 – Periodic impulse voltage (see Part 1)

8.3 Harmonic analysis

In Clause E.2 the harmonic analysis of periodic impulse voltages with different waveshapes is performed. In all cases the spectrum is dominated by the fundamental wave. The relation between the fundamental and the most important 3rd harmonic is not much changed by the overshoot considered. This is also true if a strong oscillation is superimposed.

Therefore it seems to be possible to design and test clearances, creepage distances and solid insulation for the fundamental frequency of the impulse voltage. Thereby the peak value of the non-sinusoidal voltage is taken into account by adjusting the amplitude of the fundamental wave to this peak value.

8.4 Dimensioning procedure and testing

For dimensioning of the clearances, the peak value of the non-sinusoidal voltage and the repetition frequency of the voltage peaks are relevant. The clearance shall be designed for a sinusoidal voltage for the same peak value and frequency. If the positive and the negative peaks are different, the higher value of both is applicable.

For dimensioning of creepage distances the same applies, as partial discharges and breakdown are considered to be the relevant factors for dimensioning.

For dimensioning of solid insulation, as stated already in 6.3, in general a high-voltage test with high-frequency voltage is required. From the harmonic analysis in 8.3, the amplitude of the fundamental is far greater than that of the 3rd harmonic even for waveforms with large periodic peaks. Thus the frequency of the sinusoidal test voltage shall be the component with the highest amplitude, which will usually be the fundamental frequency. However the amplitude of the sinusoidal test voltage shall correspond with the peak value of the original waveshape or with the amplitude of the 1st harmonic, whichever is greater.

This increase of the test voltage, as compared to the amplitude of the fundamental wave, addresses the influence of the higher harmonics, which are not taken into account during the test.

In the case of a maximum voltage frequency of 10 MHz, if the field strength is approximately uniform and no voids or air gaps are present in between the solid insulation, the dimensioning procedure described in 6.3 may be applied instead of testing.

Annex A
(informative)

Insulation characteristics of clearances at high-frequency voltages

A.1 Basic information about the breakdown of clearances

Breakdown of clearances usually occur in less than one microsecond. With respect to that time scale, an a.c. voltage of power frequency has an essentially constant amplitude. For instance at 50 Hz, the amplitude remains within 99 % of its peak value for 1 ms. Therefore, during the development leading to breakdown, the peak value of the voltage initiates the breakdown. For clearances within the scope of this standard this results in identical a.c. (peak) and d.c. breakdown voltages.

At much higher frequencies, a reduction of the voltage from its peak value and even polarity reversal have to be taken into account during the development of breakdown. This effect will result in an increase of the breakdown voltage.

Up to now, the effect of the ions (which are usually positive) that are generated during inception of breakdown has not been considered. These ions are generated at the crest of the sine-wave and there is usually enough time for them to travel to the electrodes during the remaining part of that half-wave. However, in large clearances or at high frequency, the polarity may be reversed before the ions have been extracted from the clearance. This will result in a distortion of the electrostatic field and will reduce the breakdown voltage. The average velocity v of the ions is approximately [1]

$$v = 6 \times 10^2 \ \frac{\mathrm{m}}{\mathrm{s}} \qquad \text{(A.1)}$$

for air at 1 bar. During the time interval between the crest and the zero crossing of the sine-wave the ions will move by the following distance s [2]:

$$s = \frac{v}{2\pi f} \qquad \text{(A.2)}$$

which is 1,91 m for f = 50 Hz. Therefore, at power frequency, this aspect will only be relevant for very large clearances. However, if frequency is increased to the kHz-range, this phenomenon will also be relevant for small clearances.

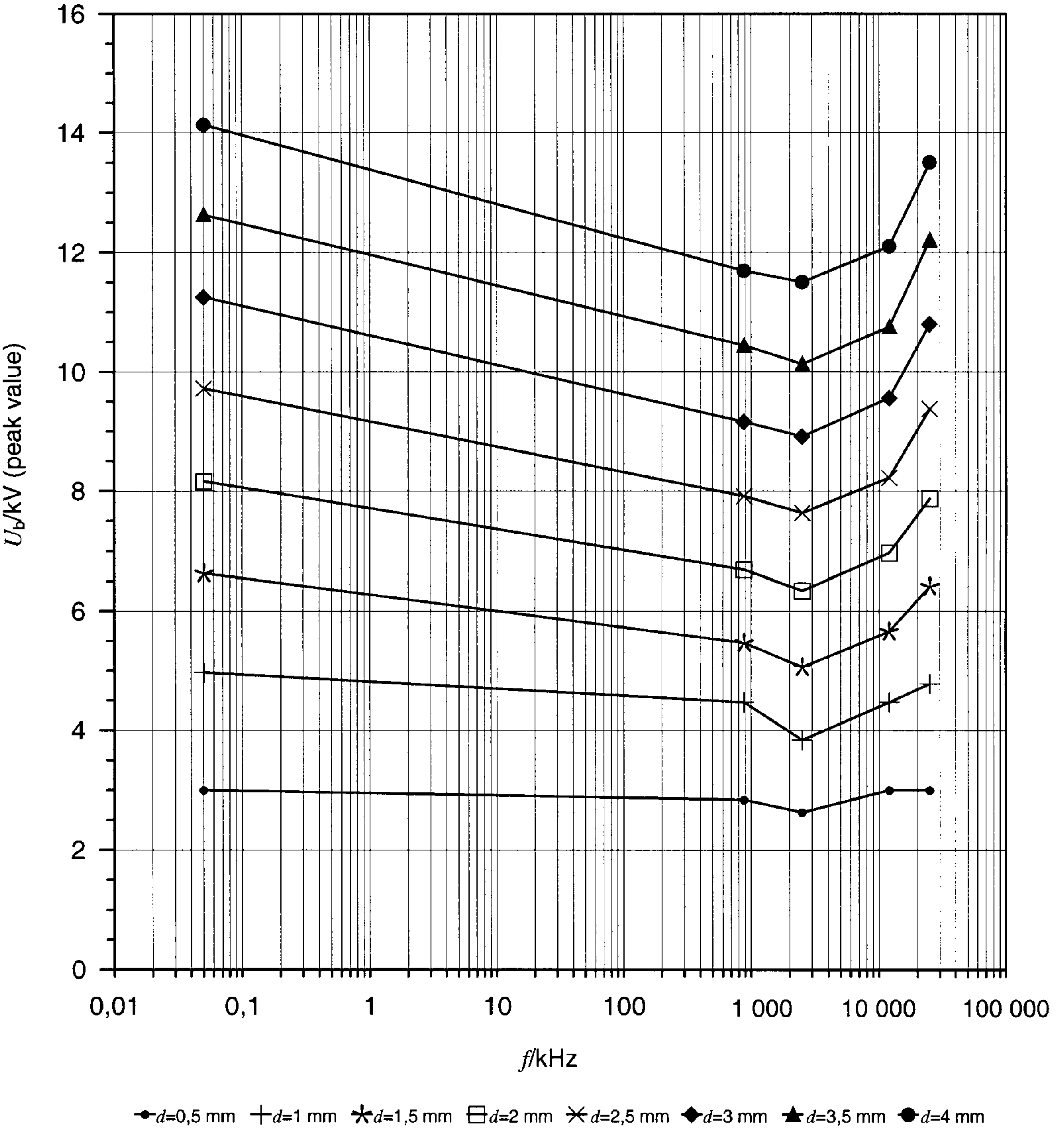
The superposition of both effects results in typical curves that exhibit a minimum breakdown voltage for a certain frequency f_{min}, which is in the order of 3 MHz.

A.2 Experimental data

A.2.1 Homogeneous and approximately homogeneous field distribution

For clearances with homogeneous field distribution, data of the breakdown voltage U_{b} is shown in Figure A.1 [3]. For frequencies in the order of 25 MHz, the breakdown voltage is nearly the same as at 50 Hz. The figure also shows that the value of the clearance is an important parameter with respect to this behaviour.

With respect to the frequencies presently used, the range with the initial decrease of breakdown voltage with increasing frequency is of greater interest. This frequency range, which is in the order of 3 MHz, is described in more detail in Figure A.2 [4]. This data is considered to be relevant within the scope of this standard.



Key

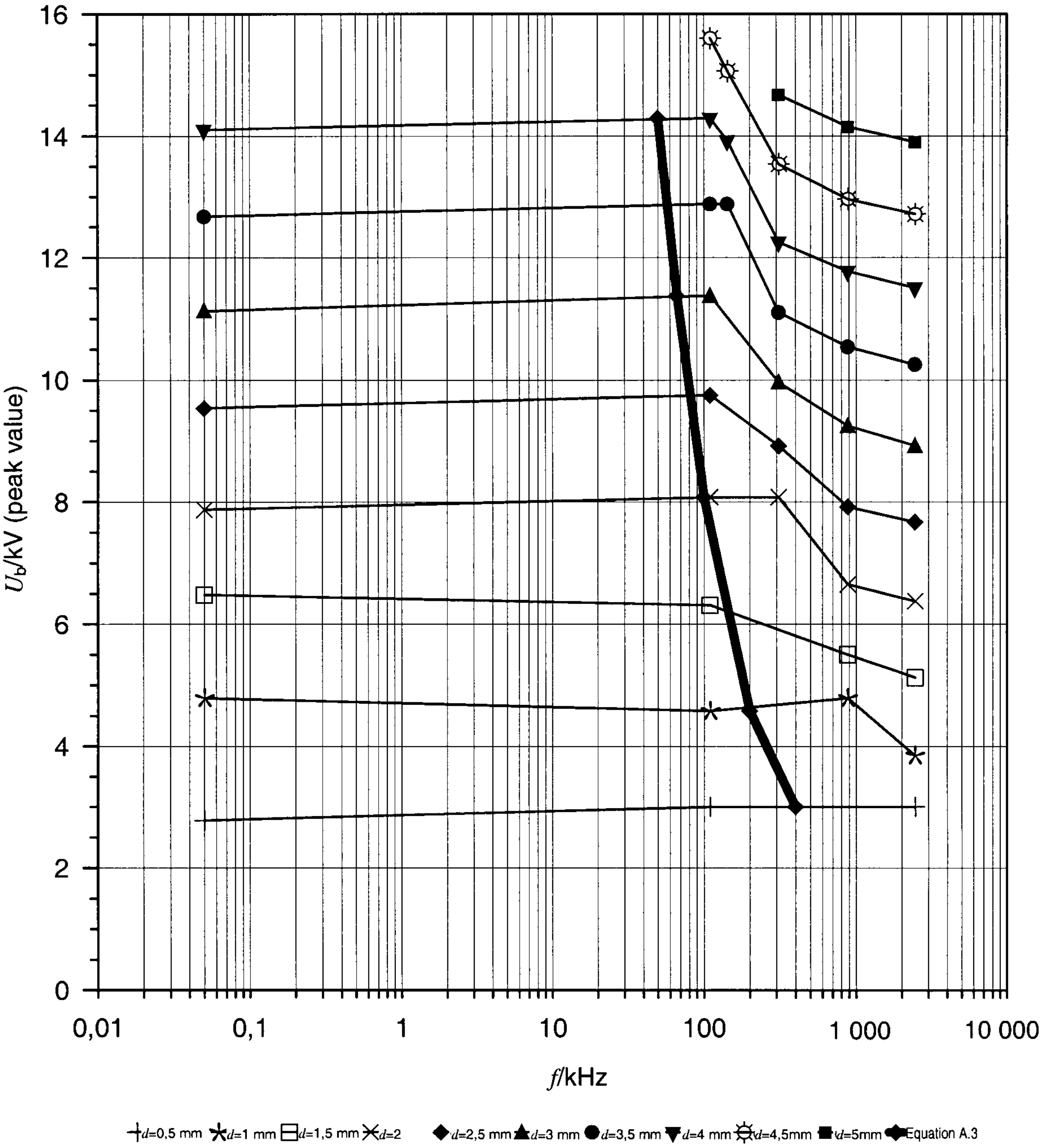
U_b breakdown voltage

d clearance

Figure A.1 – Breakdown at high frequency in air at atmospheric pressure, homogeneous field, frequency range 50 Hz – 25 MHz [3]

As a conclusion, for homogeneous field conditions, the maximum reduction of the breakdown voltage U_b with frequency is 20 % compared to the 50/60 Hz-values. The critical frequency f_{crit} at which the reduction of the breakdown voltage occurs [2] is for air at 1 bar depending from the value of the clearance:

$$f_{crit} = \frac{v}{\pi d} \quad \Rightarrow \quad f_{crit} \approx \frac{0{,}2}{d\,/\,\mathrm{mm}}\ \mathrm{MHz} \qquad \text{(A.3)}$$



IEC 1350/05

Key

U_b breakdown voltage

d clearance

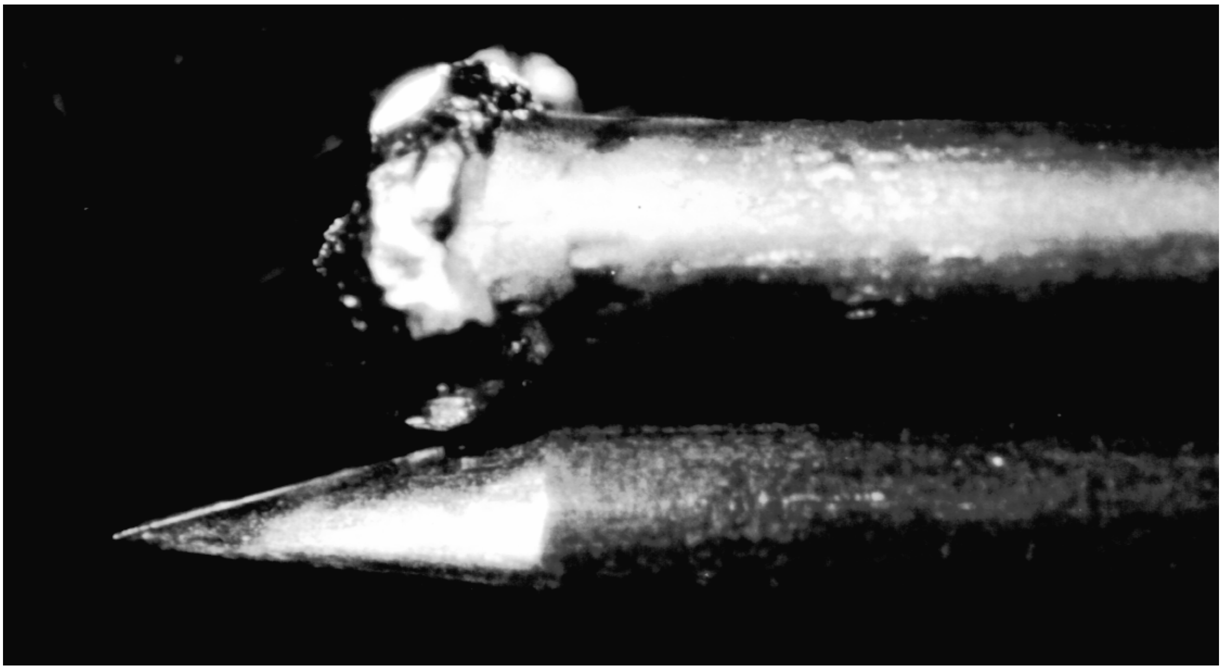
Figure A.2 – Breakdown at high frequency in air at atmospheric pressure, homogeneous field, frequency range 50 Hz – 2,5 MHz [4]

As can be seen from the additional curve according to Equation (A.3) in Figure A.2, there is some deviation between the available experimental data and the critical frequency given by Equation (A.3). As the experimental data is not complete and its precision is not known, Equation (A.3) will be used for the purpose of dimensioning.

A.2.2 Inhomogeneous field distribution

For inhomogeneous field conditions at high-frequency voltage stress intense luminous phenomena can be observed with the naked eye in the vicinity of the needle tip, if the partial discharge (corona) inception voltage is exceeded. After further increase of the voltage from this area a thin channel begins to develop towards the opposite electrode (plane) causing breakdown. Thereby deterioration of the needle tip is very likely. This is shown in Figure A.3.

For inhomogeneous field conditions, f_{crit} can still be approximated from Equation (A.3). Above f_{crit}, the influence of frequency on the breakdown voltage is much more significant compared to homogeneous field conditions. The reduction of the breakdown voltage with respect to that at 50 Hz can be more than 50 % [1].



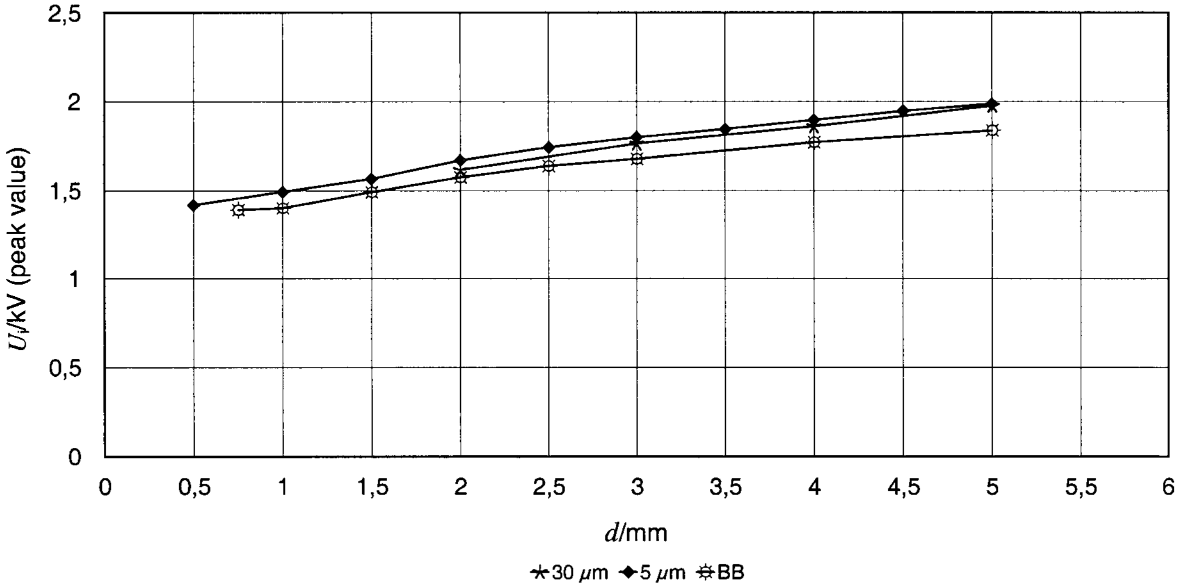
IEC 1351/05

Figure A.3 – Needle tip after (upper) and before (lower) breakdown

Recently very detailed measurements of the partial discharge (PD) inception voltage and the breakdown voltage of inhomogeneous gaps (point-plane) in air at atmospheric pressure have been performed [5] and [6]. As point electrodes treeing-needles (Ogura) with a radius of 5, 30 and 100 µm and one-way drain tubes according to ISO 7864 [7] (B. Braun) with an effective radius of approximately 5 µm have been used. The latter were mainly used and are called BB-needles.

In general needle electrodes can be used for simulation of inhomogeneous fields if the effective needle length is approximately 3 times the clearance [8]. Therefore the BB-needles with an effective needle length of approximately 20 mm can be used for a maximum clearance of 7 mm.

The comparative measurements in Figure A.4 [6], which were performed at a frequency of 100 kHz, show that there is no significant difference in the behaviour of treeing needles (Ogura; 30 µm and 5 µm) and BB-needles (approximately 5 µm). According to Figure A.4 the lowest data are obtained for the BB-needles. Therefore the dimensioning data were derived from measurements with BB-needles.



IEC 1352/05

Key

U_i PD inception voltage

d clearance

Figure A.4 – PD inception voltages in air at atmospheric pressure for f = 100 kHz, point-plane electrodes with different point radius [6]

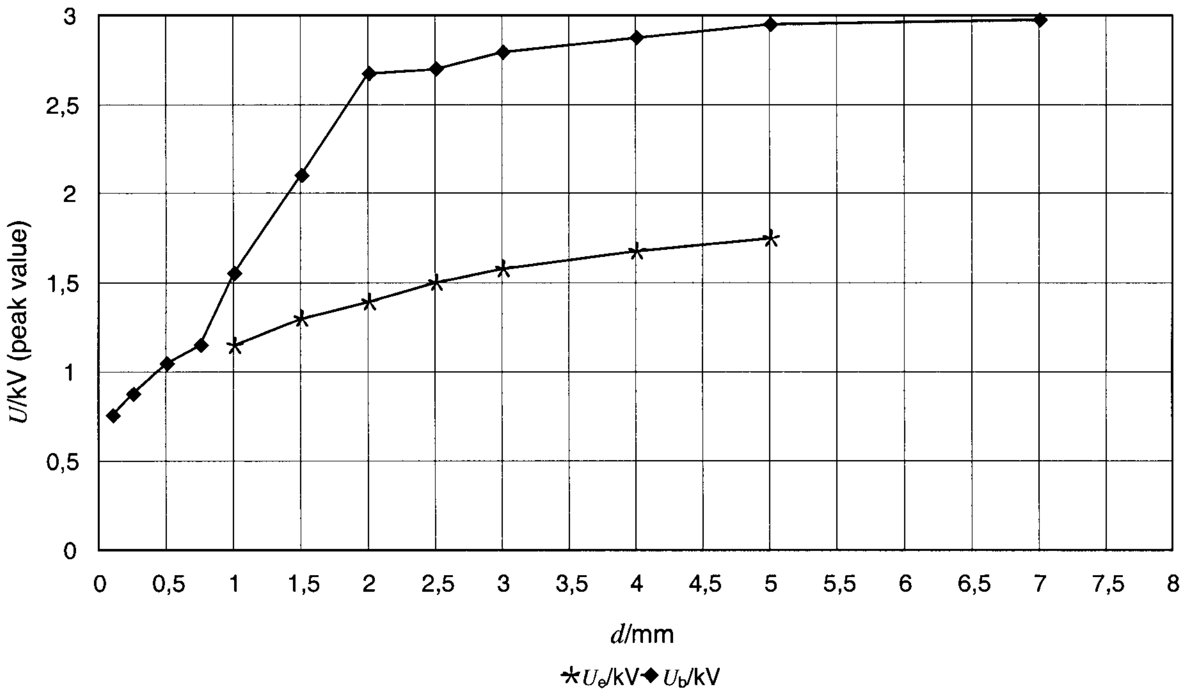
As the PD-extinction voltage is much more reproducible it should be specified. This is also the relevant value for dimensioning, as PD can be started by transient overvoltages and shall not be maintained by any steady state voltage (see 4.1.2.4 of Part 1).

From these measurements the PD-extinction voltages have been evaluated and are shown in Figure A.5 [6] for a frequency of 460 kHz together with the breakdown voltage. The latter tests were limited by the maximum test voltage of the source being used.

Further tests have been performed for a frequency of 1 MHz. As a result in Figure A.6 the PD-extinction voltages and the breakdown voltages are shown [6]. For clearances of less than 1 mm PD-inception nearly coincides with breakdown so that no distinction between breakdowns is possible.

For a frequency of 3 MHz only limited experiments could be performed, which provided some tentative data. This was nearly identical with the data obtained at 1 MHz. Therefore the data shown in Figure A.6 was considered to be relevant for dimensioning within the scope of this standard.

It should be noted that the measurement results of the PD-inception voltage are to some extent influenced by the rate of rise of the test voltage.

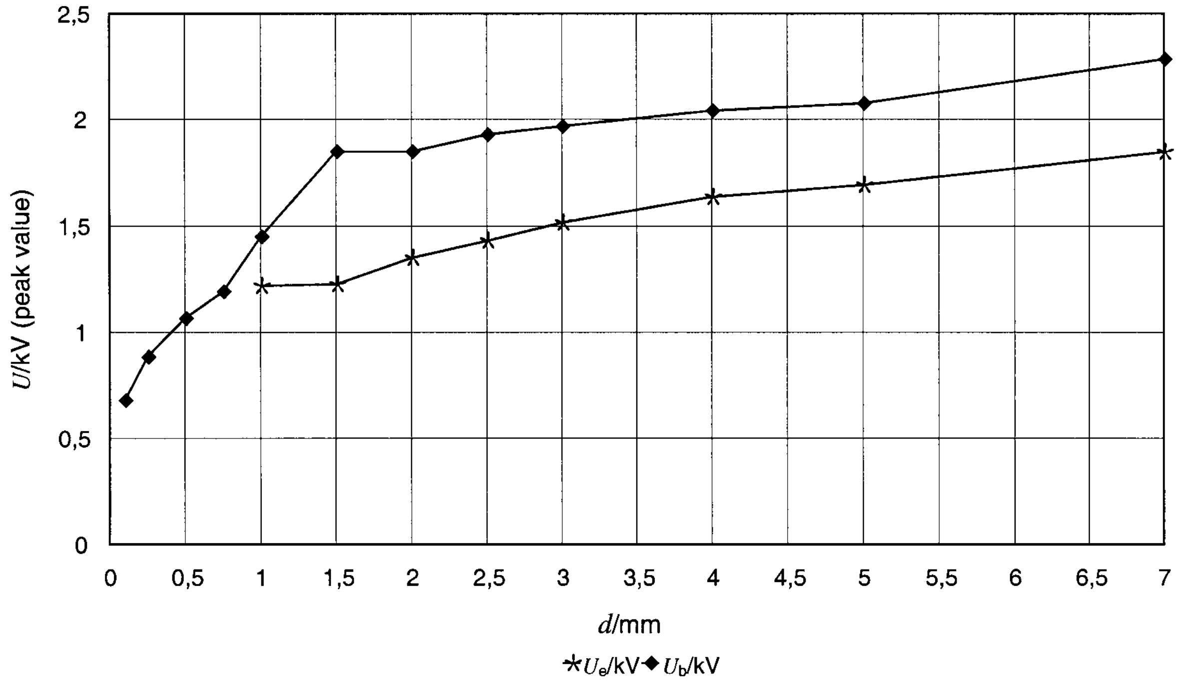


IEC 1353/05

Key

d	clearance
U_e	PD extinction voltage
U_b	breakdown voltage

Figure A.5 – PD extinction voltages and breakdown voltages in air at atmospheric pressure for f = 460 kHz, point-plane electrodes with BB-needles [6]



IEC 1354/05

Key

d clearance

U_e PD extinction voltage

U_b breakdown voltage

Figure A.6 – PD extinction voltages and breakdown voltages in air at atmospheric pressure for f = 1 MHz, point-plane electrodes with BB-needles [6]

Annex B
(informative)

Insulation characteristics of creepage distances at high-frequency voltages

B.1 Withstand characteristics of creepage distances

In Part 1, tracking is the only phenomenon, which is taken into account for dimensioning of creepage distances. However, more recent data [9] provides evidence that this only applies for severe environmental conditions, and if the materials used are not resistant to tracking (see IEC 60112). Under more favourable environmental conditions, tracking does not seem to be very relevant for dimensioning. In this case particularly for small distances below 2 mm, the breakdown voltage across the surface of the insulating material is reduced by pollution and has to be taken into account for dimensioning (see Part 5).

For less pollution and in particular for small distances, breakdown across the surface of the insulation seems to be relevant for dimensioning and the influence of the frequency on the breakdown voltages has to be considered.

B.2 Experimental conditions

The test specimen for measuring the withstand characteristics of small creepage distances is shown in Figure B.1. The materials, which were included in the investigations, are described in Table B.1. The printed conductors were applied according to standard manufacturing techniques. The specimens were clean and not coated. Each board has 15 measuring points between parallel conductors. The nominal electrode distances are also shown in Figure B.1. Both the PD-voltages and the breakdown voltages were measured.

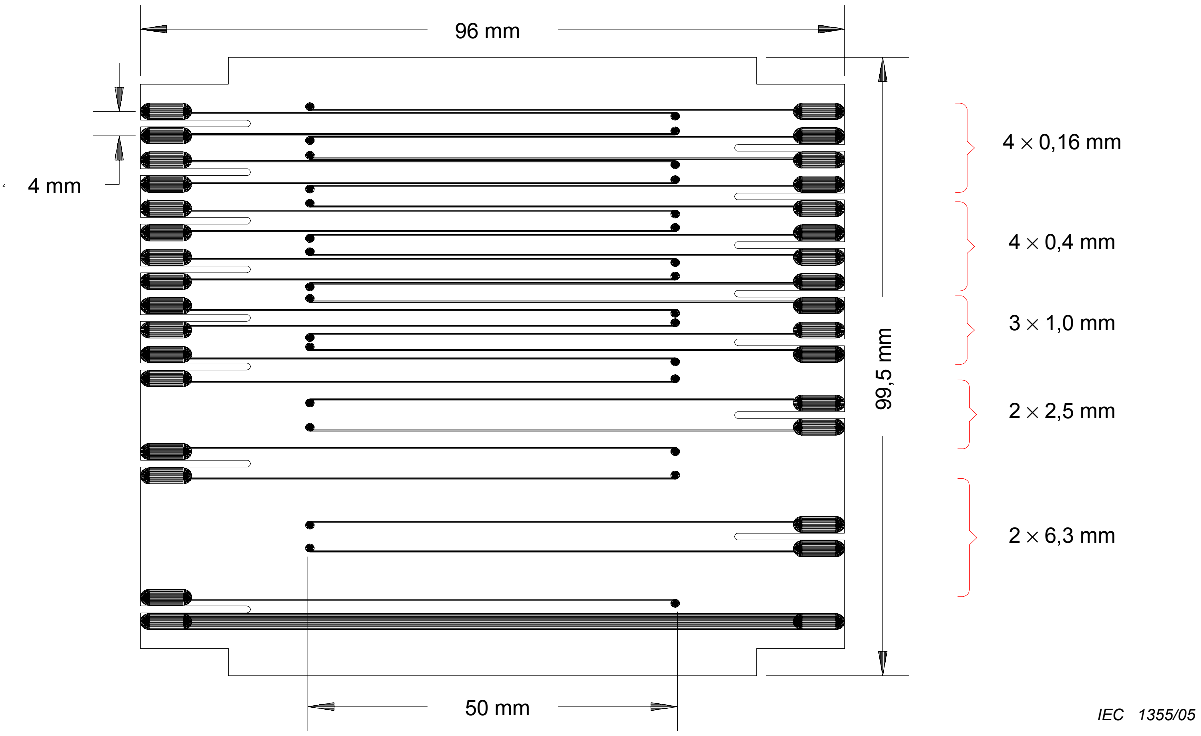


Figure B.1 – Test specimen for measuring the PD-voltages and the withstand voltages of creepage distances up to 6,3 mm

Table B.1 – Materials included in the investigations

Material classification	Material description
B	Glass-epoxy laminate FR4
C	Polyester resin (thermoset), type 802
D	Phenolic resin, type 31.5
E	Polyimide film laminated to glass-epoxy laminate FR4
G	Polyester laminate GPO III
H	Melamine resin, type 150

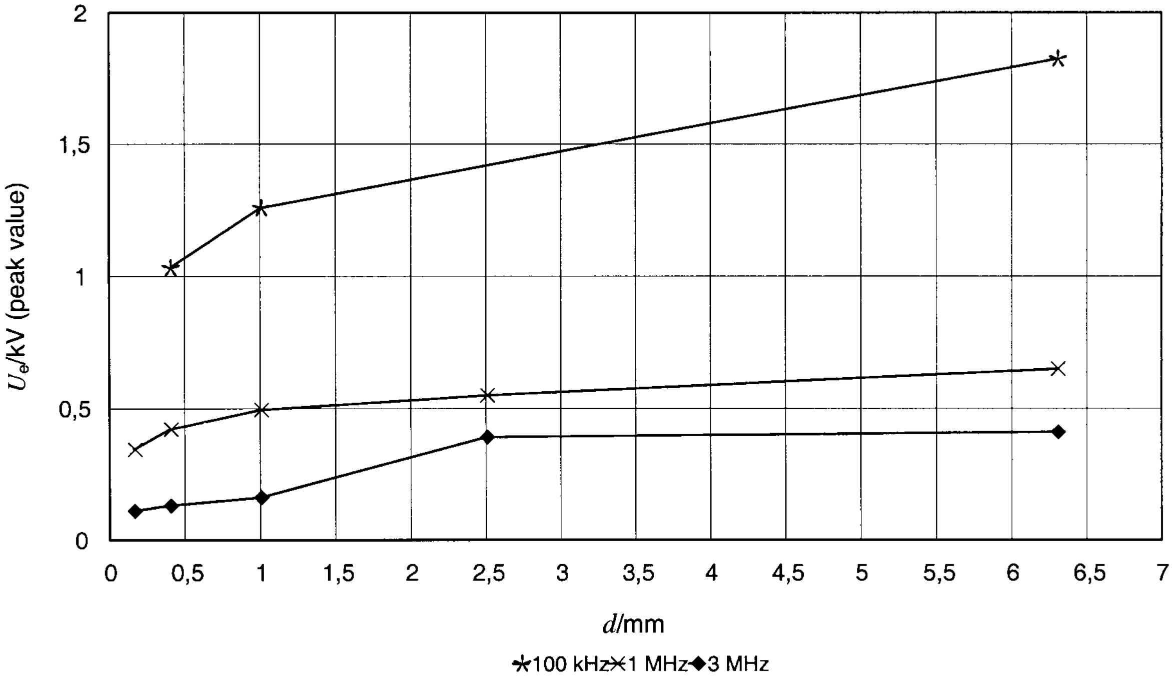
For measuring the PD-voltages and the breakdown voltages a rate of rise of the test voltage of approximately 300 V/s was selected. Thereby it is assured that no significant deterioration of the test specimen will occur during test. If the rate of rise is much lower (some 10 V/s) for high frequency of the test voltage, deterioration of the base material can occur during the test. This would result in the measured breakdown voltages being reduced in the order of 10 %.

B.3 Experimental data

The test results are shown in Figures B.2 and B.3 [6]; more details are described in [5]. Compared to a frequency of 100 kHz at 1 MHz the PD-inception voltage is only about 66 %. At a frequency of 3 MHz, these values are further decreased by about 30 %. So it is necessary to provide specific dimensioning criteria depending upon the frequency of the voltage.

The breakdown voltage is less dependent on the frequency of the voltage. However the saturation effect, which could already be seen for clearances, is so strong, that nearly no increase of the breakdown voltage could be obtained by varying the distances in the range of some millimetres.

During the measurements of the breakdown voltage on most of the test specimens the electrodes and/or the base material have deteriorated. The source of this damage, which can cause conductivity of the insulation material, seems to be related to two deterioration mechanisms. One of them is melting of the electrode material due to the high discharge energy during breakdown. The other phenomenon is caused by PD before breakdown occurs and results in a degradation of the base material.

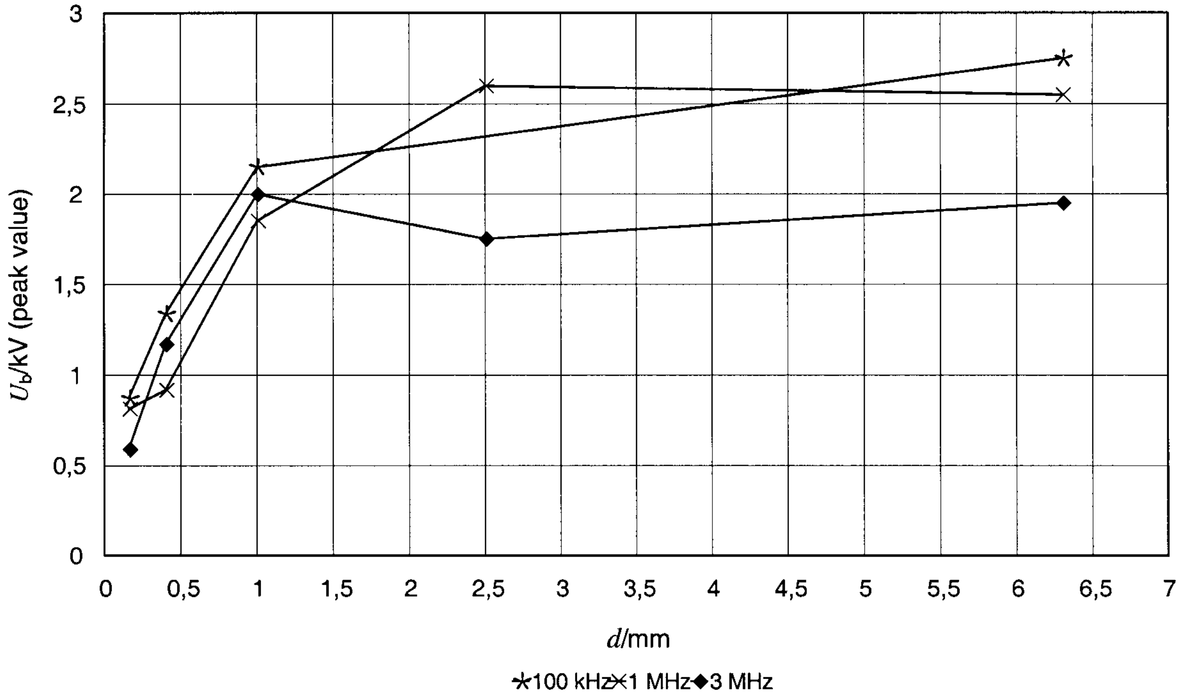


IEC 1356/05

Key

d creepage distance

Figure B.2 – Test results of the PD extinction voltage U_e of creepage distances up to 6,3 mm [6]



IEC 1357/05

Key

d creepage distance

Figure B.3 – Test results of the breakdown voltage U_b of creepage distances up to 6,3 mm [6]

Annex C
(informative)

Insulation characteristics of solid insulation at high-frequency voltages

C.1 Degradation mechanism of solid insulation

Compared to clearances in air, solid insulation can provide a breakdown field strength that is at least one order of magnitude higher. However there is a large dependency of the breakdown field strength on parameters such as thickness of insulation, temperature of the insulating material and duration of electrical stress [10]. Material specific influences related to composition and processing must also be considered. In general one can say, that for relatively small insulation thickness (<0,1 mm) and for short-time stress very high breakdown field strengths in the order of 100 kV/mm can be obtained at power frequency.

However, in practical use, the high breakdown field strength of solid insulation cannot by far be utilized. Caused by cavities in the material itself or by gas gaps within layered insulation systems partial discharges (PD) will occur far below the breakdown voltage. Thus, the gas within the cavity becomes conductive for a short period of time; the insulation however is maintained by the remaining part of the solid insulation. Since during the partial discharge within the cavity a breakdown of air (or similar gases) occurs, relatively low breakdown field strengths apply. A further aggravation results from the fact that for a.c. voltage stress due to capacitive voltage distribution and, according to the relatively high dielectric constant of solid insulation, the larger fraction of the voltage is applied across the gas filled cavity. Thereby the insulating gas with its lower breakdown field strength is even more stressed.

Therefore in real insulation systems partial discharges can occur far below the breakdown voltage. In the long run these lead to destruction of nearly all solid insulating materials [11]. As shown in the following example, the time duration until insulation failure under unfavourable conditions is so short, that even during power-frequency high-voltage tests deterioration of solid insulation is possible.

As an example a printed circuit board covered by an insulating film [12] is considered, where the stress is applied between a conductor and a neighbouring soldering pad at a nominal distance of 0,4 mm. When applying a high voltage, strong partial discharge exists underneath the insulating film (coating) which finally results in the destruction of the test sample. This is shown in Figure C.1 for a constant power-frequency test voltage U_t of 3,15 kV (r.m.s.). This test voltage is already 45 % above the PD-inception voltage of 2,2 kV (r.m.s.). Due to the high quality insulating material the test sample could withstand this stress for approximately 37 min in spite of PD-strengths q in the range of nanocoulombs.

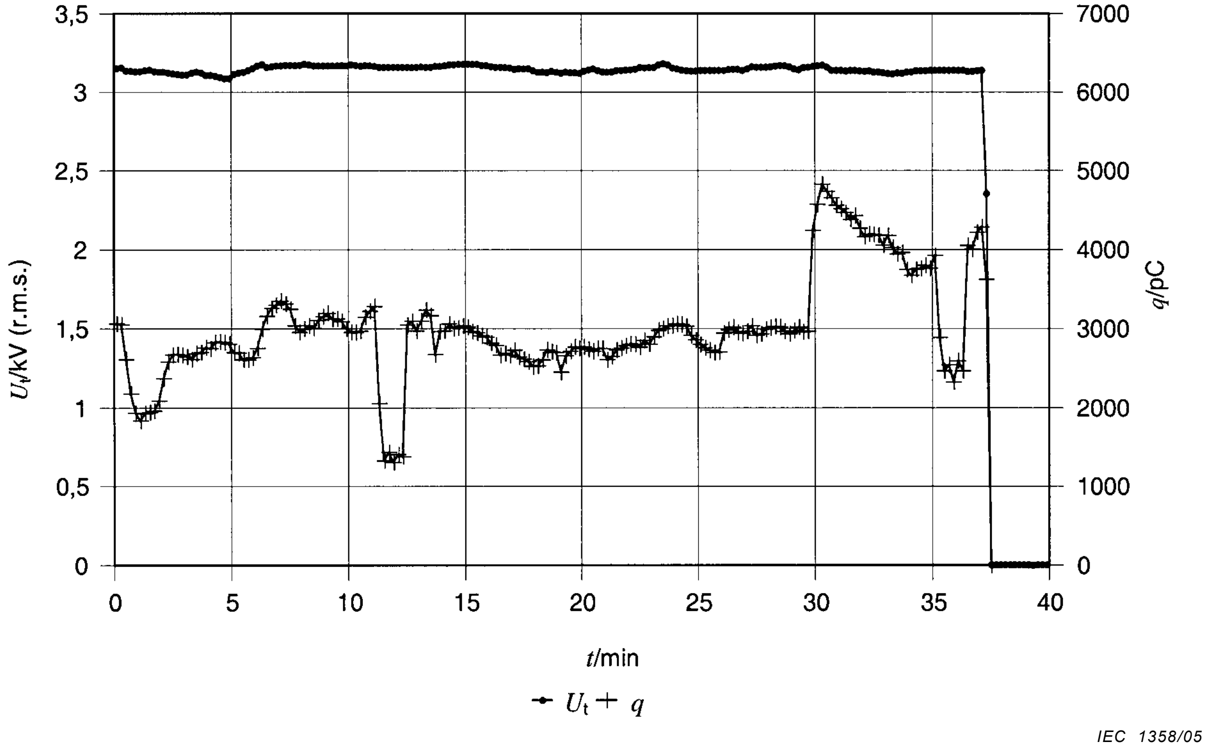


Figure C.1 – PD withstand capability of coatings; constant test voltage U_t (f = 50 Hz) [12]

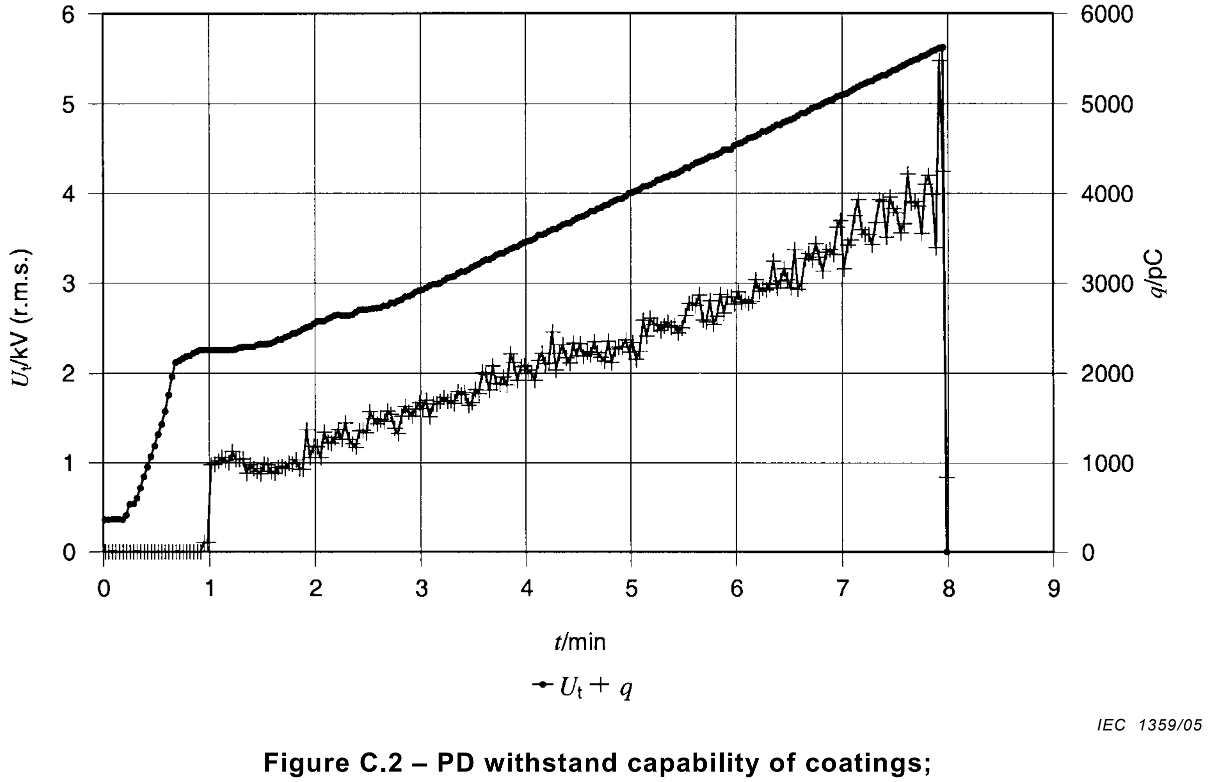


Figure C.2 – PD withstand capability of coatings; linearly increasing test voltage U_t (f = 50 Hz) [12]

In Figure C.2, the test sample is stressed by an approximately linearly increasing power-frequency test voltage U_t, with an initial rate of rise of approximately 4 kV per minute. The PD-inception at 2,2 kV (r.m.s.) is clearly visible. Typical for these test samples is the immediate occurrence of very high PD-intensity. PD-intensity and PD-impulse rate are approximately proportional to the value the test voltage. The sample can withstand this apparently much higher stress only for about 7 min. This example shows very clearly, that even for power-frequency voltages partial discharges can have a highly destructive potential during a relatively short period of time.

In addition during real life applications it has to be considered, that all stresses and their damaging effects that occur during the lifetime of the equipment are cumulative. Electrical, thermal [13] and also mechanical stresses are superimposed according to previously little known rules. Simulation of these long term effects through appropriate short time tests is a very difficult task. This can only be achieved through a combination of electrical tests and appropriate conditioning of the test specimen. For suitable conditioning methods, see 4.1.2.1 of Part 1.

These stresses influence the occurrence of partial discharges [14] and their damaging effect combined with dielectric heating cause a drastic reduction of the breakdown strength [15]. It is assured, that, as already demonstrated by time accelerated testing [16], the damaging effect due to partial discharges increases with the frequency of the voltage.

The most accurate time-acceleration can be made for pure thermal stress (Arrhenius law [17]). However even this can only be simulated, if it causes chemical ageing (oxidation). If however the deterioration mechanism changes (for example softening/flowing during drastically increased temperatures) during the accelerated stress, the time acceleration method is no longer permitted. In case of thermal stress this can easily foreseen and avoided. However, when applying increased electrical stress to achieve time-acceleration, a change of the deterioration mechanism is likely to occur [18].

Two failure mechanisms of solid insulation are normally relevant. One failure mechanism results from dielectric loss at high electric stress. Increased heating will occur, which can lead to thermal instability and thermal breakdown. This usually takes place within a few minutes and can be easily verified. Additionally, solid insulation can include gas gaps or voids, either caused by different layers of insulation, interfaces between insulating parts and conductive parts, or by imperfect manufacturing of the insulation material. In such small gaps, partial discharges are likely to cause eventual failure of solid insulation even if the dielectric stress is sufficiently low so as not to cause thermal breakdown.

For solid insulation, the frequency of the voltage is a very important influencing factor. The dielectric loss for a given frequency is obtained from the following Equation:

$$P_{\mathrm{v}} = 2\pi f U^2 C \tan\delta \tag{C.1}$$

where

P_{v} is the power dissipation;

f is the frequency of the voltage;

U is the r.m.s. value of the voltage across the solid insulation;

C is the capacitance of the insulation arrangement;

$\tan\delta$ is the dielectric loss factor of the insulation material.

Due to the dependency of the loss factor tanδ on frequency, the influence of frequency on the dielectric loss can be lower or higher than can be expected from the apparent linear dependency. This can result in a higher probability of thermal breakdown and a reduction of the short-time dielectric withstand capability.

It does not seem to be possible to simulate the effects of high-frequency stress on solid insulation. So the presence of high levels of such kind of stress in general will require testing of solid insulation with high-frequency voltage. The following experimental results shall give some information about those values of the electrical field strength that represent a high stress at a peculiar frequency so that a test with high-frequency voltage will be required.

C.2 Experimental results

High-frequency breakdown characteristics have been investigated on different insulating materials [15]. The most important results are shown in Figure C.3. For a frequency of 1 MHz, the short-time breakdown field strength E_b is only 10 % of the power-frequency value. The breakdown field strength does not seem to reach a lower limit even at frequencies as high as 100 MHz.

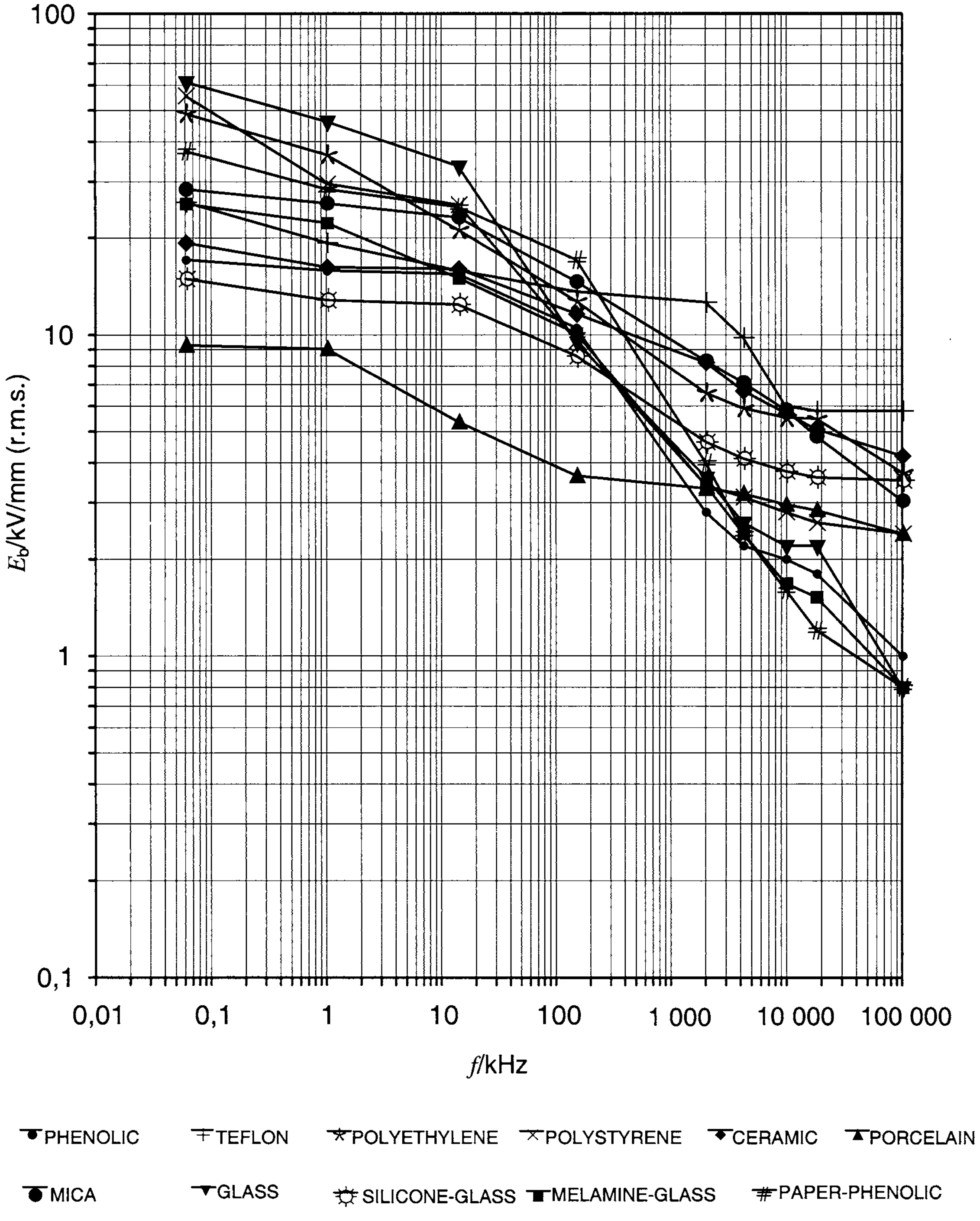
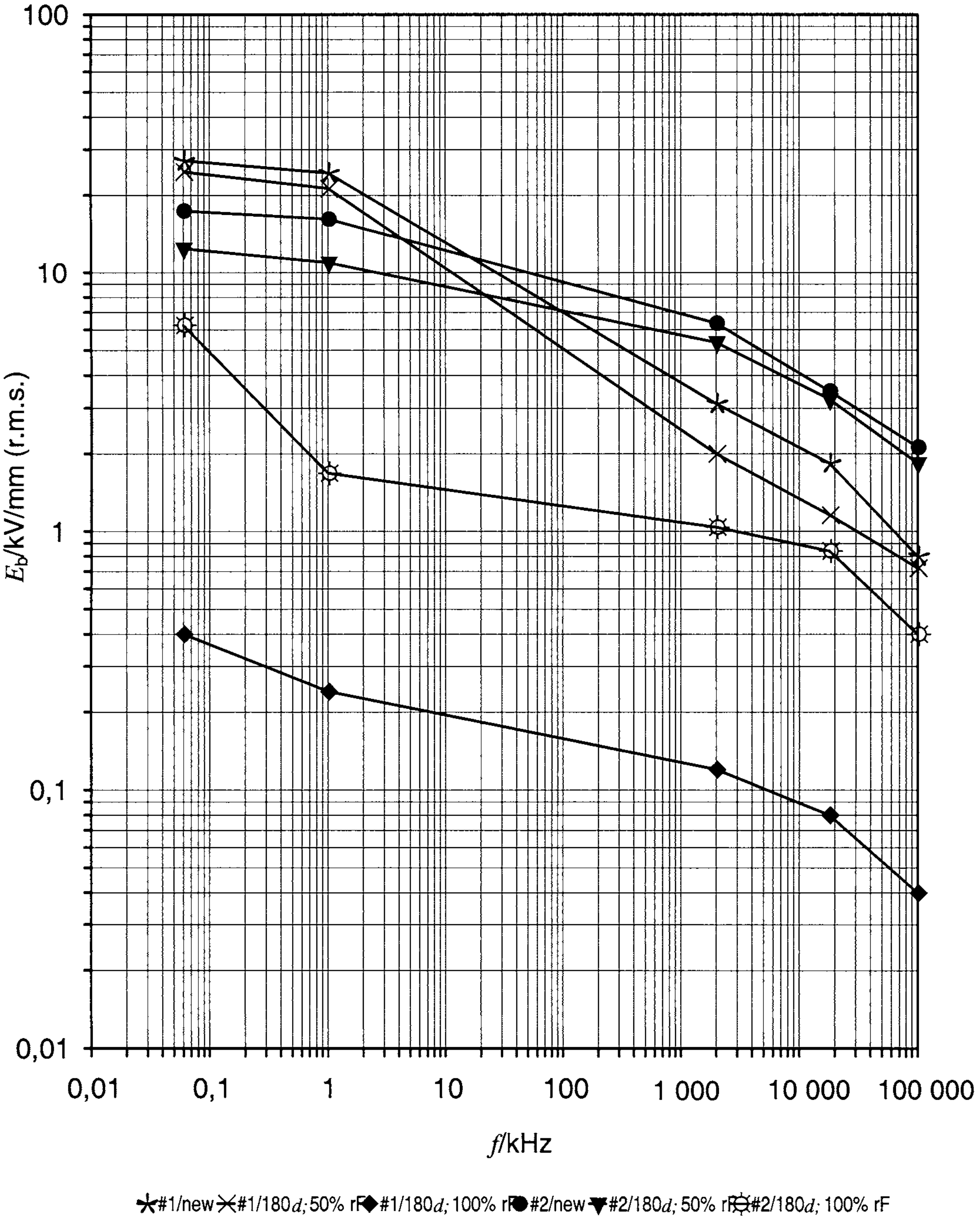


Figure C.3 – Breakdown at high frequency, solid insulation; d = 0,75 mm [15]

The dielectric strength of solid insulation in general, and especially at high-frequency voltage, is further reduced by the influence of humidity and temperature.

The influence of long-time storage under high humidity conditions on the breakdown field strength of solid insulation at high-frequency voltage is shown in Figure C.4 [19]. The reduction of the breakdown field strength of mica-filled phenolic is extraordinarily high. This is already a significant problem at power-frequency, but is further aggravated with increasing frequency. The poor performance of mica-filled phenolic is caused by its comparatively high water absorption, which was found to be in the order of 1 % by weight under such conditions.

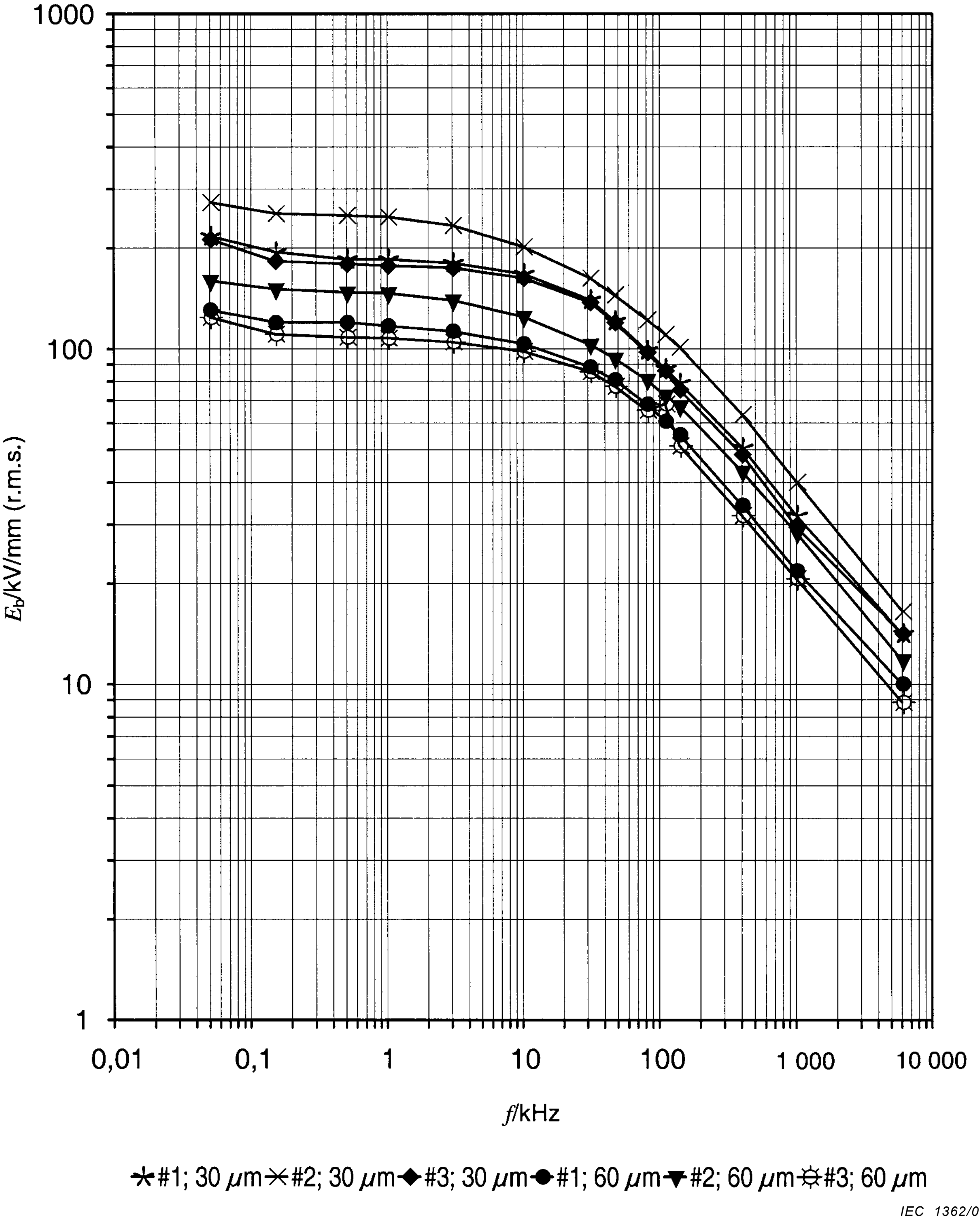
Under the same conditions, the water absorption of glass-silicone laminate was only 0,3 % by weight.



IEC 1361/05

Figure C.4 – Breakdown at high frequency, solid insulation, influence of humidity; conditioning at 50 °C; #1: mica-filled phenolic, d = 0,75 mm; #2: glass-silicone laminate, d = 1,5 mm [19]

The breakdown field strength of solid insulation is a function of the thickness of the material, and very thin films can have a breakdown field strength that can be up to one order of magnitude higher than that of the test specimen with 0,75 mm thickness. This is demonstrated in Figure C.5 [20]. With increasing frequency however, there is also a strong reduction of the values. At 1 MHz the breakdown values were only approximately 10 % of the 50 Hz values. This reduction is comparable to that of specimens having approximately 1 mm thickness. So any dimensioning according to thickness of solid insulation shall take into account this dependency of the breakdown field strength upon the thickness of the insulation.



IEC 1362/05

Figure C.5 – Breakdown at high frequency, insulating films; #1: cellulose-acetobutyrate, #2: polycarbonate; #3: cellulose-triacetate [20]

The influence of the temperature on the breakdown voltage can be seen in Figure C.6 [20]. Therefore the temperature is an important influencing factor, which shall be taken into account for dimensioning and testing.

Detailed results concerning the partial discharge characteristics at high-frequency voltage are available for frequencies up to a few kHz [16] and [21]. In that range, it has been established that the time to failure caused by partial discharges is inversely proportional to frequency. This relationship has already been used for accelerated testing. Therefore, especially at higher frequencies of the voltage, a reasonable lifetime of solid insulation cannot be expected when partial discharges occur.

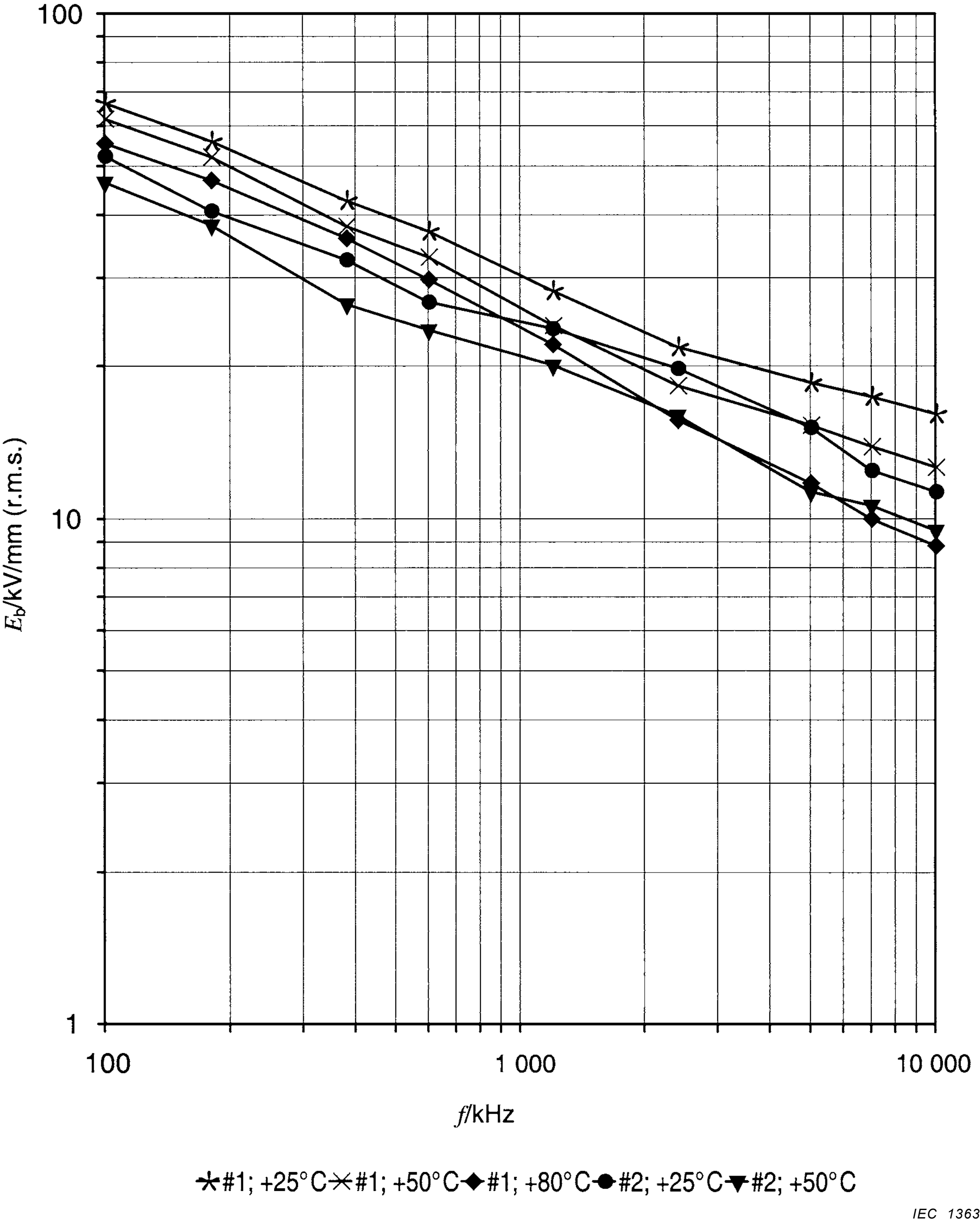


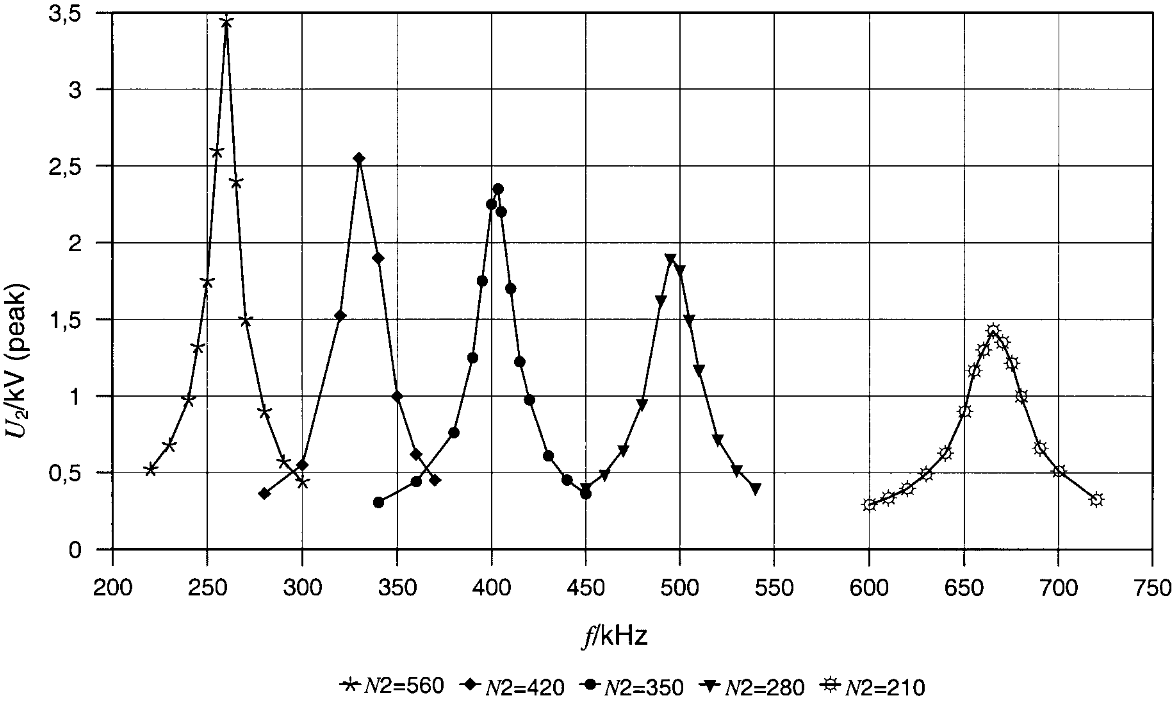
Figure C.6 – Breakdown at high frequency, insulating films; #1: Polystyrene, d = 80 µm, #2: Polyethylene, d = 50 µm [20]

Annex D
(normative)

Testing of insulation at high-frequency voltages

D.1 Test voltage source

With respect to any kind of high-voltage testing at frequencies that are much higher than the power frequency the suitability of appropriate test voltage sources with adjustable frequency is a fundamental question.



IEC 1364/05

Figure D.1 – High-frequency resonance transformer; influence of the number of turns of the secondary coil N_2 on the output voltage U_2; N_1 = 20; N_2 = 210/280/350/420/560 [22]

High-frequency resonance transformers can be used in combination with low-voltage high-frequency power generators [22]. The problems with this technique are demonstrated by the examples shown in Figure D.1. In order to obtain a high resonant frequency, the number of turns in the secondary winding of the transformer shall be reduced as shown in Figure D.1. Thereby the available output voltage will also be reduced.

In order to cover the entire frequency range, several resonant transformers are required. An additional problem of such test voltage sources is the strong reaction between the impedance of the test specimen and the frequency and the amplitude of the test voltage.

As an alternative, a high-frequency high power oscillator (transmitter) can be used as test voltage source. This provides higher frequencies combined with more power output [5], [6] and [20]. An example is shown in Figure D.2. The output voltage of this source is approximately 4 kV peak with a maximum frequency of 5 MHz (see Table 5).

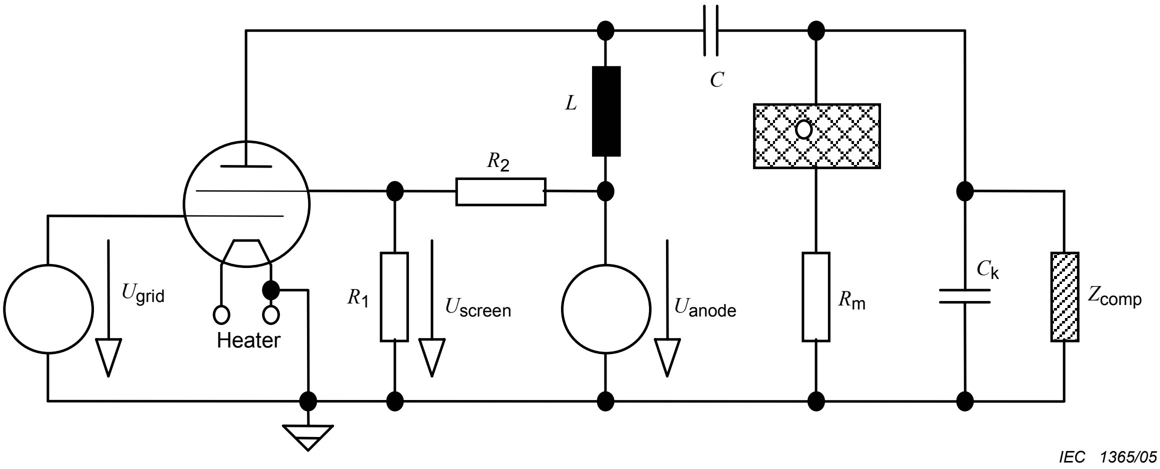


Figure D.2 – High-frequency high power oscillator [5] and [6]

The capability of the test voltage source to feed large capacitive loads is one of the most important issues in selecting a test voltage source. As a PD coupling capacitance should be larger than the capacitance of the test specimen, the coupling capacitor usually determines the capacitive load.

Table 5 presents some typical data for a powerful test voltage source that was used in [5] and [6]. The output voltage is generated by a vacuum tetrode that is fed by a powerful high-voltage supply (4 kV, 400 mA). The series resonant circuit, which is formed by the variable anode inductance and the total load capacitance, is tuned to the frequency being used. Both maximum test voltage and maximum load capacitance (which is mainly the PD coupling capacitance) are given in Table D.1. The total harmonic distortion of this test voltage source is less than 2 % as a result of the resonant operation.

Table D.1 – Data of the test voltage source [5] and [6]

Frequency	Coupling capacitance	Maximum test voltage	Required test current
100 kHz	1100 pF	2,7 kV	1,9 A
200 kHz	1100 pF	4,0 kV	5,5 A
500 kHz	450 pF	3,4 kV	4,8 A
1 MHz	520 pF	2,7 kV	8,8 A
3 MHz	320 pF	1,0 kV	6,0 A

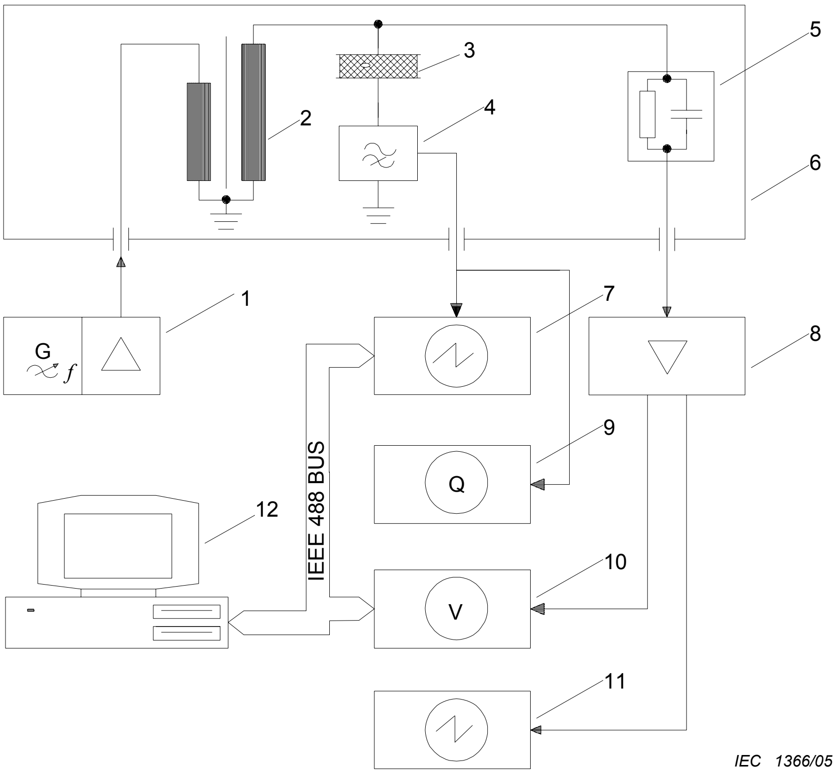
D.2 High-frequency partial discharge test

D.2.1 Test equipment

Some additional problems are encountered, if PD-tests at high-frequency voltage are required [5] and [6], as no standard PD-measuring equipment can be used. However in general a digital storage oscilloscope in combination with means for suppression of the high-frequency test voltage will be appropriate.

Many of the reported PD-measurements with high-frequency test voltage were performed with the test circuit shown in Figure D.3 [24]. The partial discharge detection is performed by digital integration with a digital storage oscilloscope of high sampling rate.

This circuit in Figure D.3 is based on a high-frequency resonant transformer (2) that is fed by a high-frequency amplifier (1) [22]. A possible alternative is the use of a high-frequency power oscillator operated in resonance, as shown in Figure D.2. This allows the generation of significantly higher frequencies [5] and [6] while maintaining low harmonic distortion that is desirable in order to ease rejection of the test voltage during PD-measurements.



Key

1 high-frequency generator and amplifier
2 high-frequency resonance transformer
3 test specimen
4 band-stop filter
5 high-voltage probe
6 screened cabinet
7 high-speed digital storage oscilloscope
8 decoupling amplifier
9 PD measuring instrument (narrow band, only for monitoring purposes)
10 digital voltmeter
11 analog oscilloscope
12 control computer

Figure D.3 – PD test circuit for high-frequency voltage tests [22]

D.2.2 Test circuit

D.2.2.1 General considerations

The PD-measurement is performed through detection of the PD-current. For this purpose, a measuring impedance R_m is connected in series with the test specimen. The voltage drop across this impedance is applied across a 3rd order band-stop filter to one channel of a digital storage oscilloscope with high bandwidth (at least 100 MHz) so that together with the test circuit consisting of lumped elements, a total bandwidth of 60 MHz can be obtained. A band-stop filter removes the voltage drop caused by the capacitive current feeding the test specimen. By this technique a PD-sensitivity of 5 pC can be obtained.

The high-frequency test voltage is measured with a high-frequency voltmeter and monitored on the second channel of the digital storage oscilloscope. As the test specimen is not visible in many cases (climatic cabinet), a video camera should be used in order to detect any external discharge activity or flashover. The test circuit is controlled by a PC via the IEEE 488-Bus. The schematic arrangement of the test circuit is shown in Figure D.4 [5] and [6].

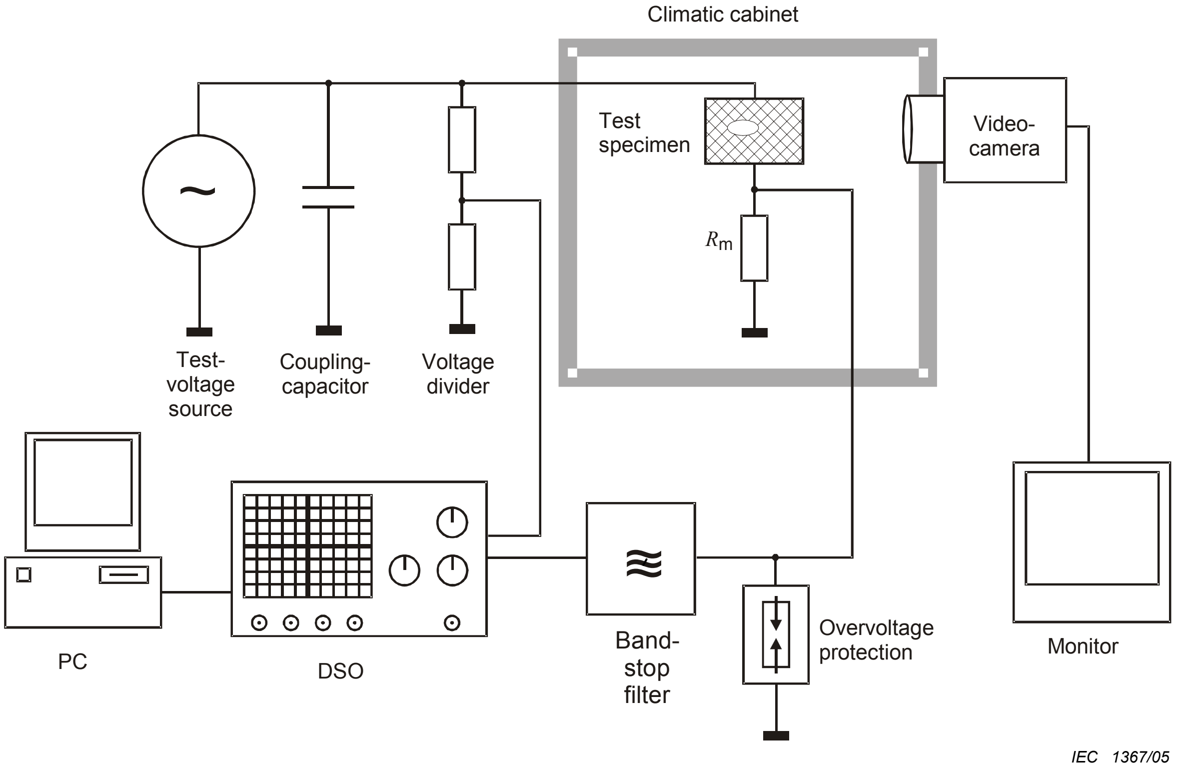


Figure D.4 – Diagram of the test circuit [5] and [6]

For test specimens that are transparent, the video-camera would also allow visual detection of PD. However in general this cannot replace the electrical measurements, as the sensitivity of this technique even at high-frequency voltage is much lower. The use of a photomultiplier tube (PMT) to detect light emission from a transparent test specimen can result in excellent PD-detection sensitivity, but the PD-magnitude cannot be calibrated. However the use of a PMT to trigger an oscilloscope can result in greatly improved PD-detection as the scope can often be triggered in this way below the electrical noise.

D.2.2.2 Required bandwidth of the test circuit

In the following evaluation, the test circuit has a 1st order low-pass transfer characteristic (PT_1-characteristic) resulting in a lower cut-off frequency of zero and an upper cut-off frequency (3 dB) f_c that is equal to the bandwidth.

Considerations with respect to the effect of possible resonance points or the lower cut-off frequency of the test circuit are described in D.2.2.3.

D.2.2.2.1 Minimum bandwidth for PD impulse resolution

For high-frequency test voltages, a high pulse repetition frequency of PD-impulses must be expected. Therefore the PD-impulse resolution must be sufficient to avoid overlapping pulses. For that reason, only so called „wide-band“ measuring equipment [23] can be used. Thus PD-detection is usually performed using a wide-band oscilloscope.

It is difficult to specify a certain value for the required bandwidth of the test circuit. For instance with a test voltage frequency of 100 kHz, PD-impulse frequencies of up to 1 MHz have been observed in point-plane gaps. For twisted-pair wires [25], where PD can occur simultaneously at many locations, PD-impulse frequencies exceeding 10 MHz have been observed.

The minimum bandwidth of the PD-measuring circuit shall be equal or greater than the PD-impulse frequency in order to avoid overlapping pulses. This is an absolute minimum requirement that does not provide a reproduction of the PD-pulse waveshape.

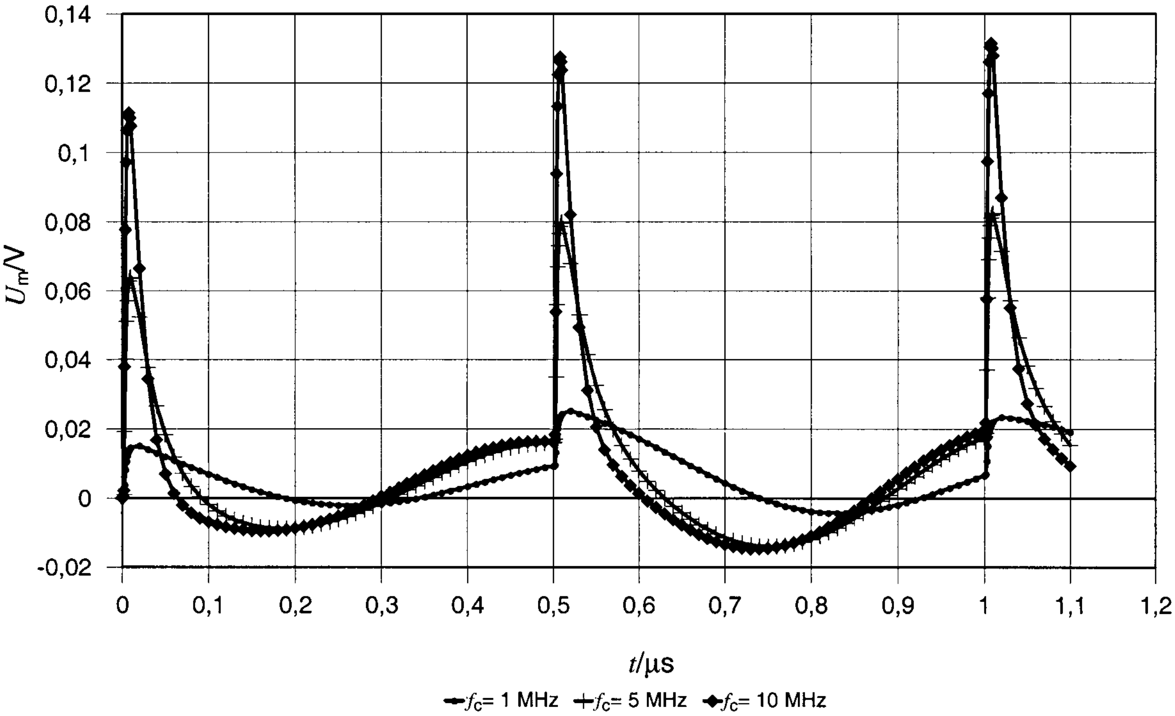


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Figure D.5 – PD impulse response for an assumed PD impulse frequency of 2 MHz for different upper cut-off frequencies f_c of the test circuit; this includes a 3rd order band-stop filter with f_{centre} = 1 MHz [5] and [6]

An upper test circuit cut-off frequency f_c of five times the PD impulse frequency is usually sufficient. This condition together with other examples of insufficient upper cut-off frequencies is shown in Figure D.5 for an assumed PD-impulse frequency of 2 MHz. For simplification it was assumed that only positive PD-impulses occur.

This ratio also provides sufficient bandwidth around the excitation frequency of the band-stop filter for good PD-detection sensitivity. The example shown in Figure D.5 is based upon the use of a 3rd order band-stop filter with f_{centre} = 1 MHz.

D.2.2.2.2 Minimum bandwidth for PD-impulse analysis

In order to analyse the source of the PD-signal and to make some analysis of the shape and size of the voids that are the origin of PD, much greater bandwidths are required. In case of Streamer-like PD with a risetime on the order of ≤1 ns [26], a bandwidth in the order of 1 GHz would be required for true impulse response.

Such wide bandwidths usually can only be provided by means of coaxial test circuits, i.e., in the laboratory [26] and [27]. With lumped elements, a bandwidth in the order of 50 MHz can be obtained rather easily. Thereby a PD impulse of very short risetime would be reproduced with approximately 7 ns risetime. This would still be sufficient for the discrimination between Streamer-like PD-impulses (typical risetime 1 ns) and Townsend-like PD-impulses (typical risetime 20 ns) [26].

D.2.2.3 Dimensioning of the test circuit

Proper dimensioning shall avoid overlap of PD-impulses and should allow some analysis of the PD-impulse waveshape.

D.2.2.3.1 Analysis of the PD test circuit

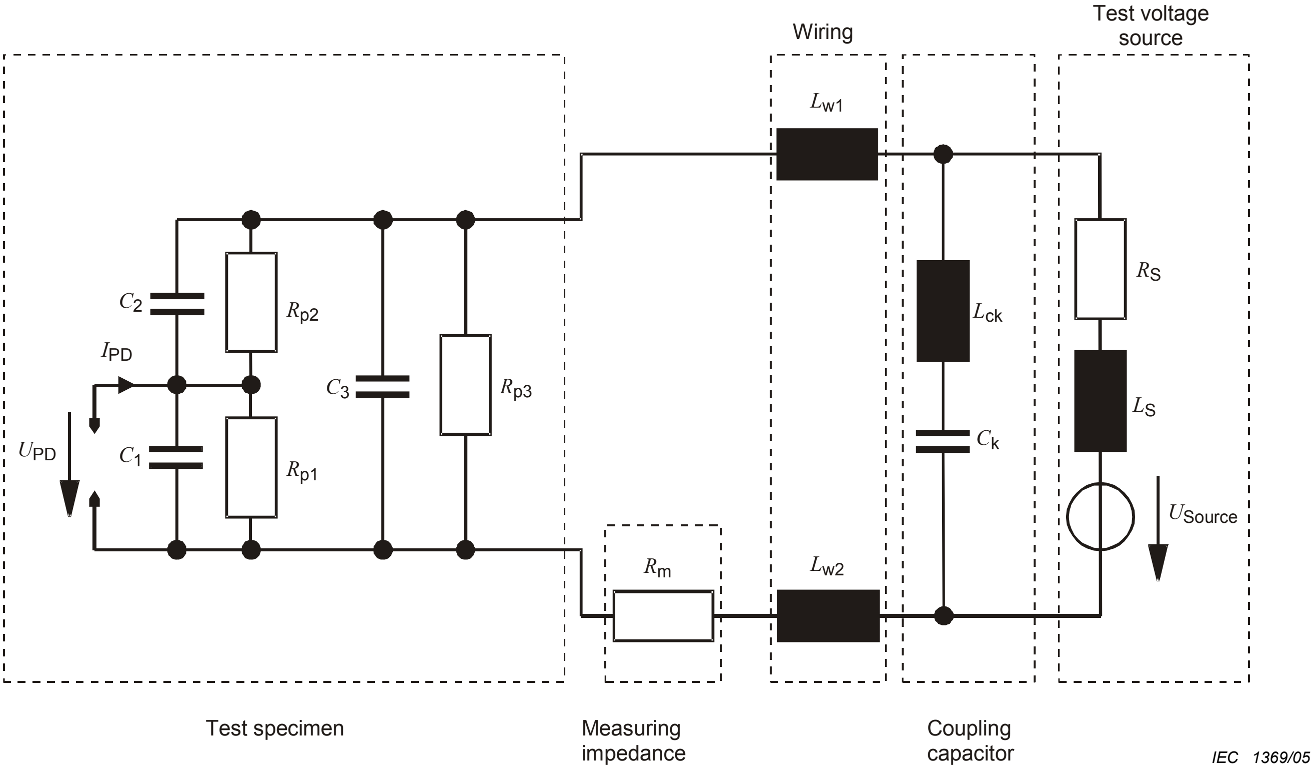

Figure D.6 – Equivalent circuit of a PD test circuit with lumped elements [5]

Coaxial circuits are only of interest for laboratory experiments and shall not be considered in this context. Test circuits consisting of lumped elements (*RLC*-circuits) can be described by the equivalent circuit shown in Figure D.6 [5].

In general, inductive components (wiring inductance L_W, inductance of source L_S and coupling capacitor L_{Ck}) of the PD-test circuit cannot be ignored. Together with the capacitive components (coupling capacitor C_k, capacitance of the test specimen C_3) resonance points in the transfer characteristics of the PD-test circuit can occur which will greatly influence the reproduction of the PD-impulses. Therefore an approximately aperiodic response of the test-circuit is required, and the upper cut-off frequency f_c should be as high as possible.

D.2.2.3.2 PD voltage source versus PD current source

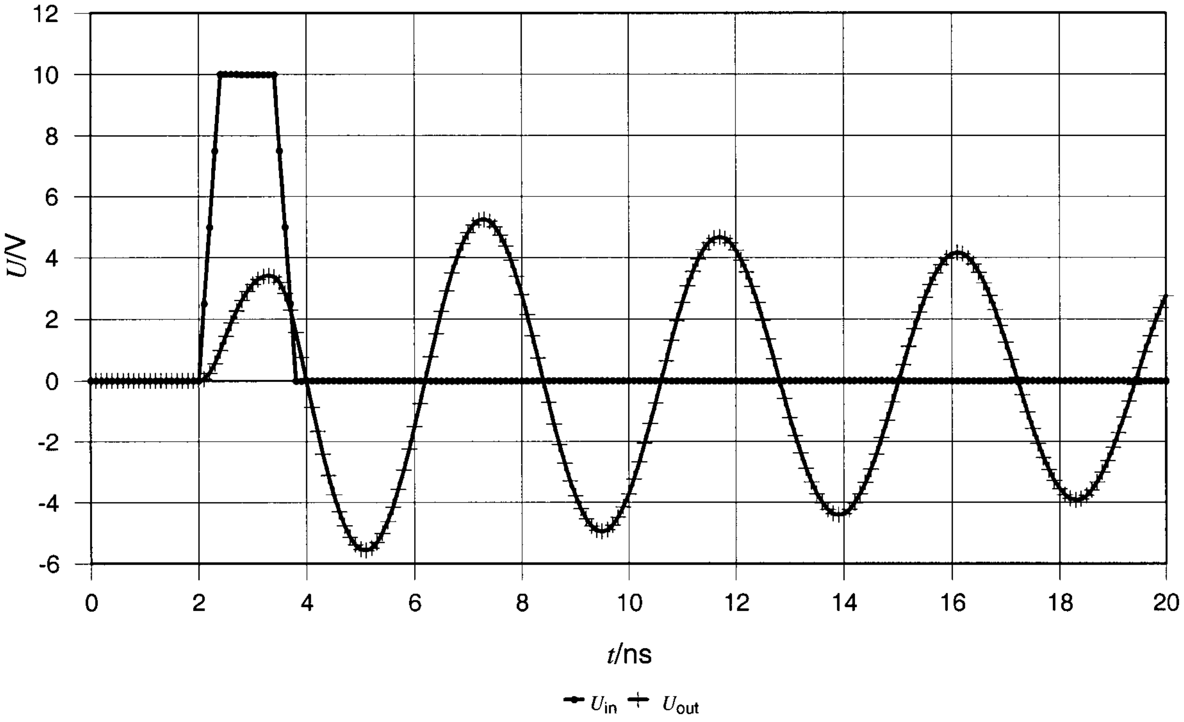

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Figure D.7a – PD impulse voltage source

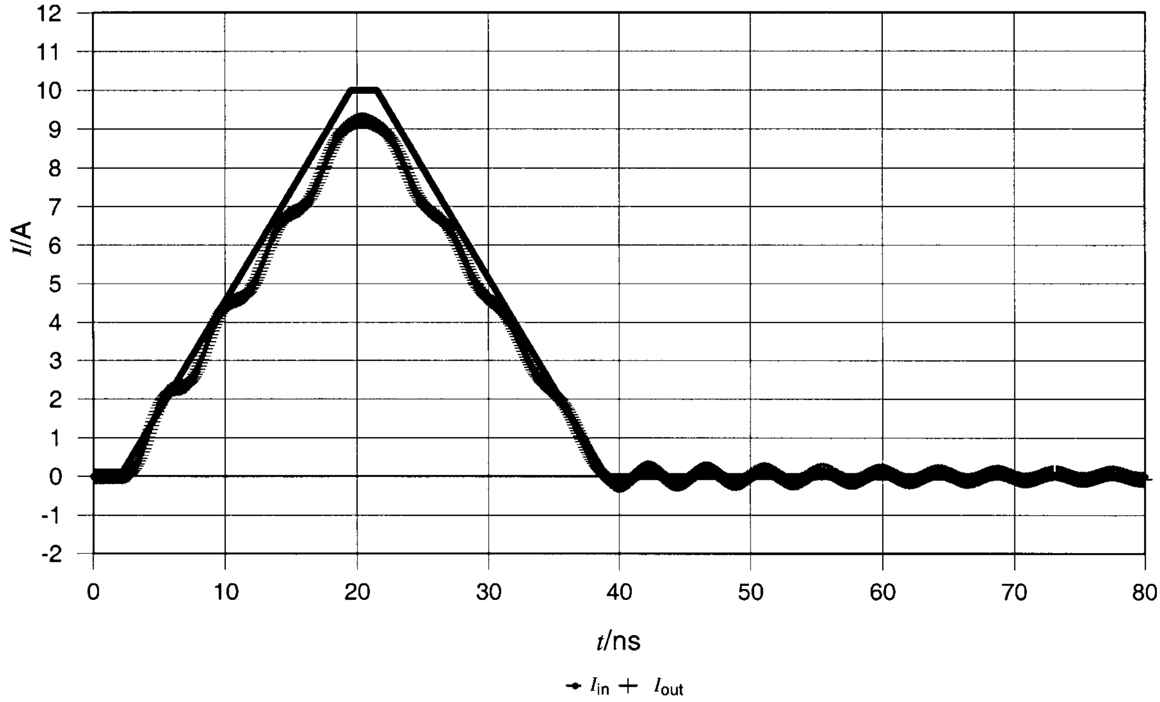

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Figure D.7b – PD impulse current source

Figure D.7 – Transfer characteristics of PD test circuits when using a PD-impulse voltage source versus a PD impulse current source [5]

The most appropriate model for the PD-impulse source seems to be a current source. On the other hand in the standard for PD-testing [23], a voltage source is used for calibration of the test circuit. It can be shown, that the transfer characteristics of the PD-test circuit are dependent on the kind of PD-impulse source being used for calibration.

In Figure D.7a a PD-impulse voltage source has been used, which does not allow proper reproduction of the PD-signal. If in the same test circuit a PD-impulse current source is used (Figure D.7b), the transfer characteristics are appropriate. More details about the transfer characteristics of test circuits can be found in [5].

In the following, only PD-impulse current sources will be considered in order to provide appropriate transfer characteristics. Of course this does not solve the conflict when calibrating PD-test circuits by using the standard impulse voltage source [23].

D.2.2.3.3 Analysis of the PD-test circuit

The transfer characteristics of the test circuit can be analysed by using the equivalent circuit shown in Figure D.6. This can be done by network analysis or by circuit simulation using appropriate software [28].

D.2.2.3.3.1 Network analysis

The analysis is performed for a PD-impulse current source using a capacitive equivalent circuit of the test specimen (Figure D.6). Compared to the other inductances L_S can be neglected for the calculation of the series resonance frequency. L_W1 and L_W2 are added to L_W. Together with L_Ck, where the coupling capacitor C_k is not low inductive or has significant wiring, the total inductance L is obtained.

$$L = L_\mathrm{W} + L_\mathrm{Ck} \tag{D.1}$$

Due to the relation

$$C_3 >> C_1 >> C_2 \tag{D.2}$$

the capacitance of the test specimen can be approximated with C_3. Therefore the effective capacitance for a PD-impulse current source is

$$C = \frac{C_3\, C_\mathrm{k}}{C_3 + C_\mathrm{k}} \tag{D.3}$$

and the resonance frequency:

$$f_\mathrm{r} = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{D.4}$$

In practice, the damping of this series resonant circuit is caused by R_m alone. The loss factor d is obtained from

$$d = \frac{R_\mathrm{m}}{\sqrt{L/C}} \tag{D.5}$$

For aperiodic response, the loss factor shall be:

$$d \geq 2 \tag{D.6}$$

Therefore, the inductance shall be limited to:

$$L \leq \frac{R_m^{\,2}\,C}{4} \tag{D.7}$$

In this case the upper cut-off frequency f_c can be approximated by assuming a simple RC-circuit:

$$f_c = \frac{1}{2\pi\,R_m\,C} \tag{D.8}$$

The lower cut-off frequency is zero.

D.2.2.3.3.2 Circuit simulation

More detailed analysis of the test circuit is possible by means of circuit simulation using an appropriate code (PSPICE) [28]. This technique had already been used in order to obtain the results described in D.2.2.2.1. Now it is applied in order to evaluate the influence of the size of the coupling capacitor on the transfer characteristics of the test circuit.

D.2.2.3.4 Influence of the coupling capacitor on the transfer characteristics

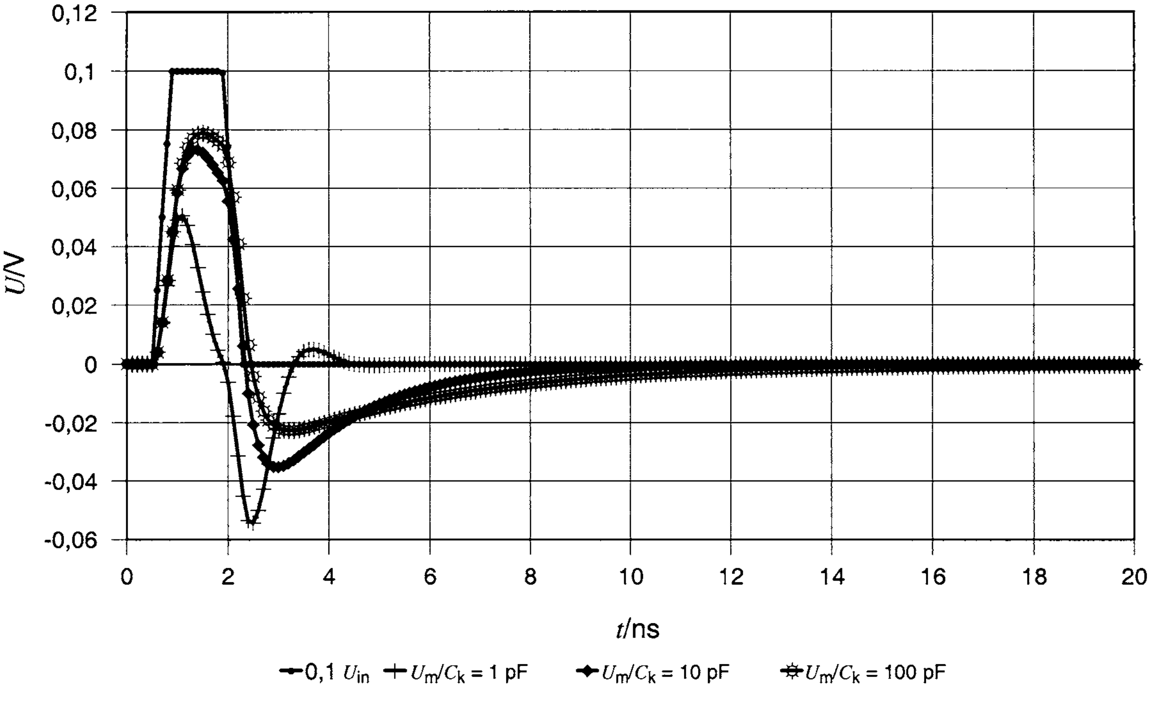

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Figure D.8 – Input signal U_{in} and measuring signal U_m depending upon the capacitance of the coupling capacitor C_k (capacitance of the test specimen C_3 = 10 pF) [5]

The influence of the size of the coupling capacitor C_k on the transfer characteristics of the test circuit is demonstrated in Figure D.8 [5] which shows clearly that this influence is very strong and that small coupling capacitors compared to the capacitance of the test specimen C_3 are not appropriate [29].

Small coupling capacitors will reduce the measuring signal, which is taken into account by calibration. However, the sensitivity of the PD-test circuit will also be reduced. The other problem is the differentiation of the measuring signal when using small coupling capacitors. From Figure D.8, it can be seen that the minimum capacitance is in the order of $C_k = C_3$. Preferably, $C_k \geq 10 \times C_3$.

The necessary value for the coupling capacitance is the greater of this value and the capacitance that is required for aperiodic response of the test circuit (see D.2.2.3.3.1, Equation (D.7)).

There is no theoretical upper limit for the size of the coupling capacitance. In practice it will be limited by the strong reaction on the test voltage source especially at high frequencies of the test voltage. This special problem is described in [29]. Some practical data are given in Table D.1.

D.3 Examples of test results

Many components for low-voltage equipment have been tested using a high-frequency test voltage. Most of the data are proprietary. Some general results have been published recently [30] and are shown here in part.

For optocouplers, there can be a significant decrease of the PD-voltages, as shown in Figure D.9 [30]. Even more onerous is the strong increase of the PD-intensity with increasing frequency of the voltage. As the repetition frequency of the PD-impulses will increase almost inproportion to the frequency of the voltage, this will cause an extremely high stress on the insulation.

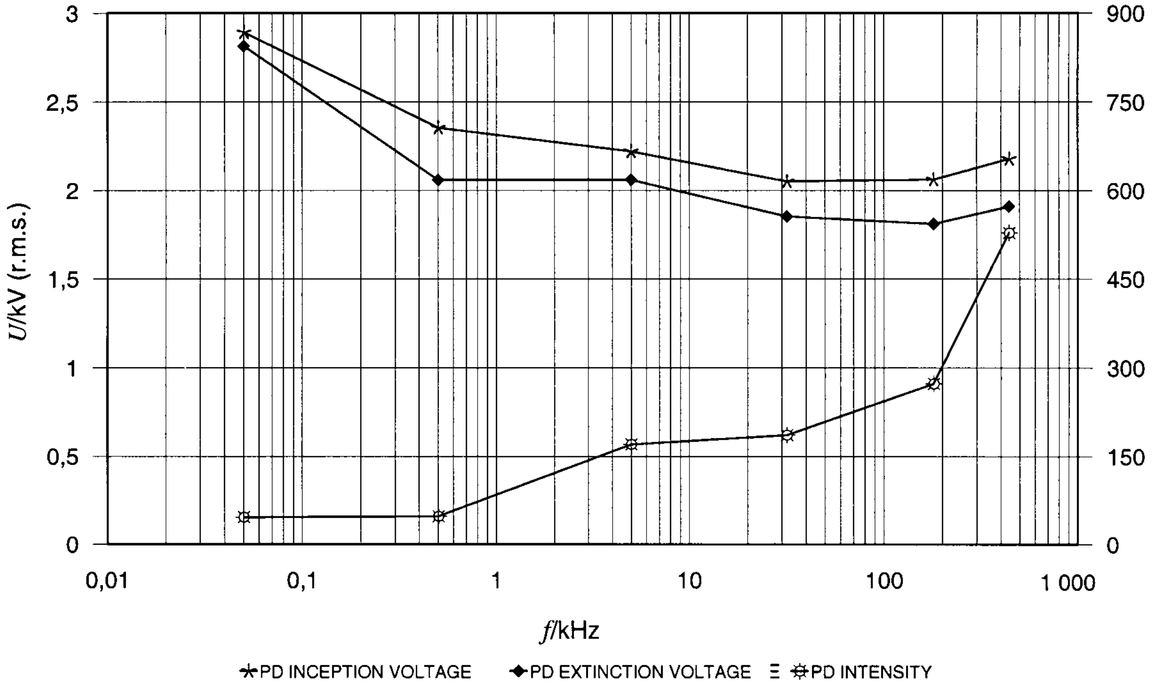

Figure D.9 – PD testing of optocouplers at high-frequency voltage [30]

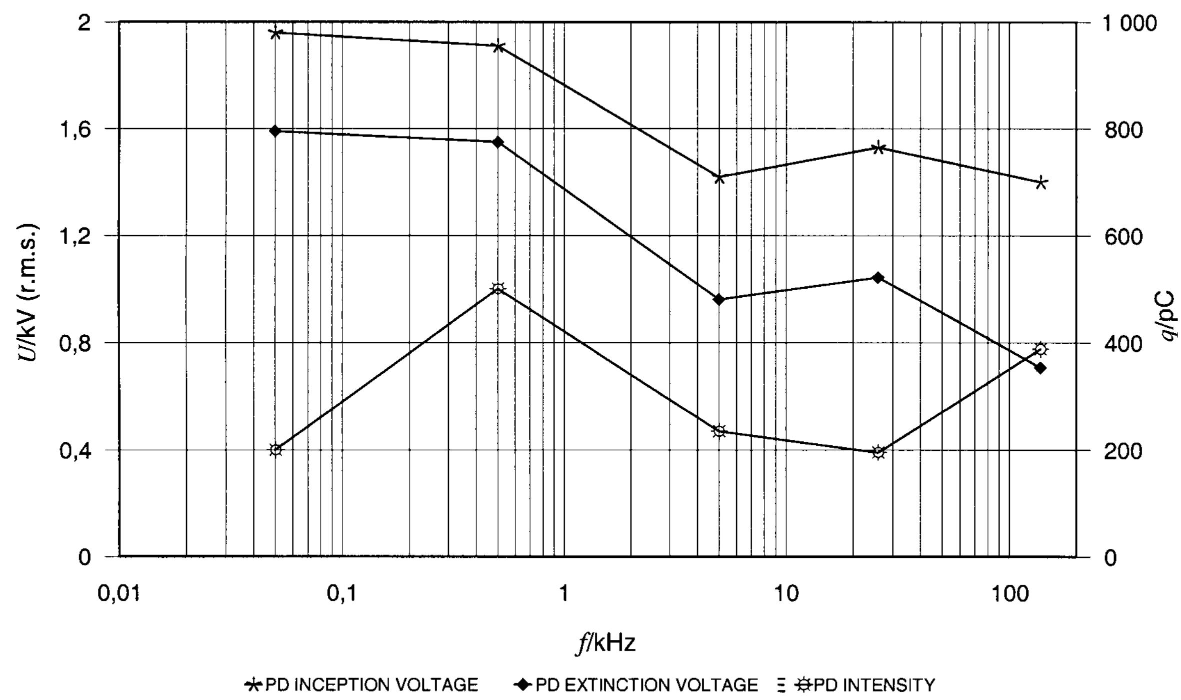

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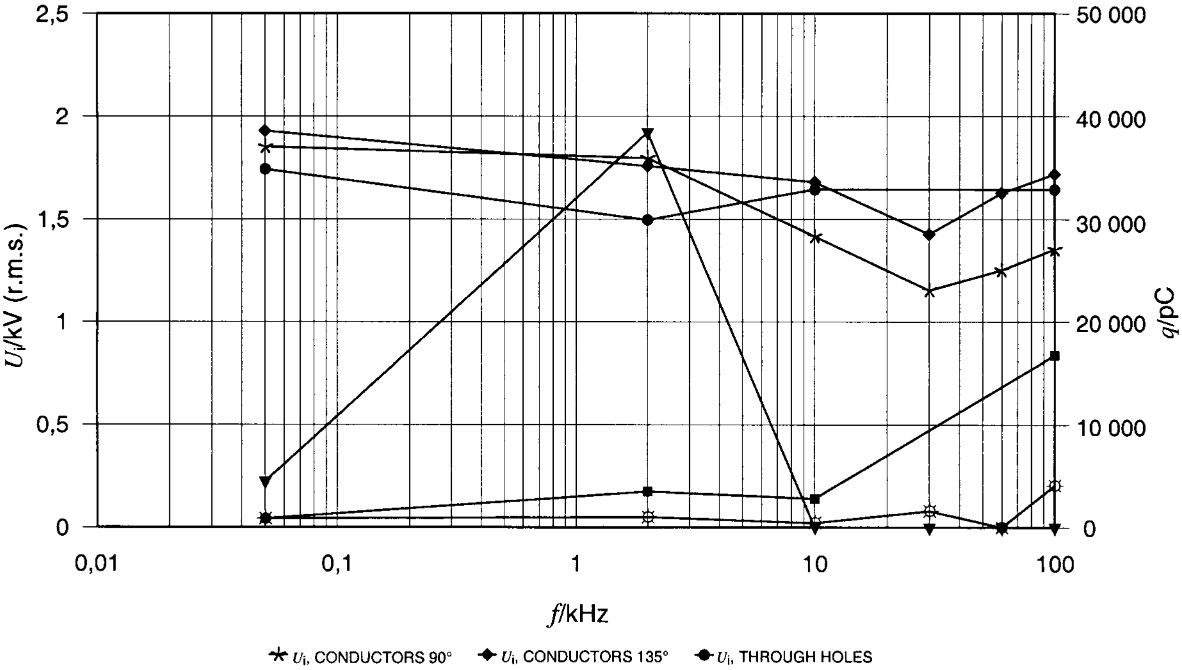
Figure D.10 – PD testing of impulse transformers; influence of the frequency of the voltage [30]



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d clearance

U_i PD inception voltage

Figure D.11 – PD testing of coated printed circuit boards; U_i, d = 0,2 mm [30]

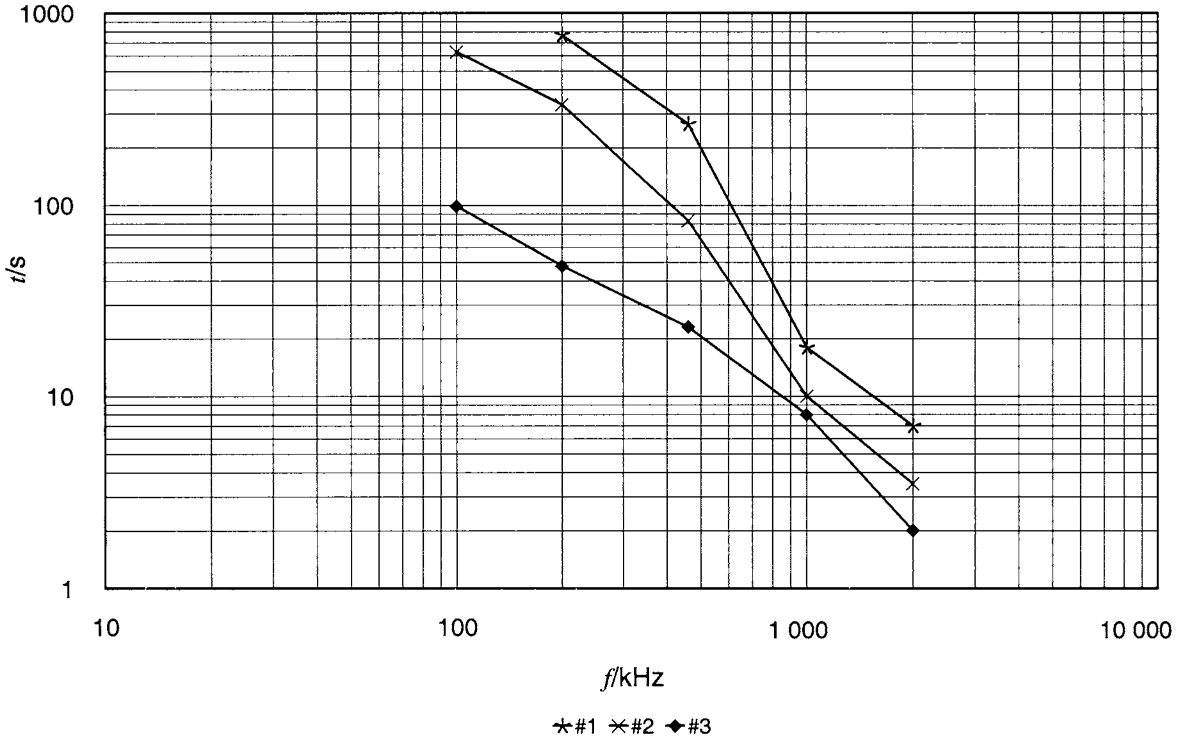

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Figure D.12 – Lifetime *t* of enamelled wires (twisted pair) at high-frequency voltage; stress is 10 % above the PD inception voltage [31]

For impulse transformers, the frequency of the voltage is an important influencing factor. By increasing the frequency above power frequency, the PD-characteristics are degraded significantly. As shown in Figure D.10 [30], the PD-extinction voltages are reduced. The PD-intensity is not particularly high, but the repetition frequency of the PD-impulses increases in proportion to the test frequency, which results in an increasing potential of degradation.

For coated printed circuit boards the insulation characteristics are not so much affected by the frequency of the voltage. As shown in Figure D.11 [30] for different conductor patterns the PD-inception voltage is only slightly reduced with the frequency of the voltage. However due to the high PD-intensity and the high frequency only a very short life time can be expected if PD occurs. Therefore even the PD-test, which is usually regarded as non destructive, can degrade the test specimen severely.

Some idea of the lifetime *t* of thin insulating films in case of PD under high-frequency voltage stress can be obtained from Figure D.12 [31]. Although the voltage is only 10 % above the PD-inception voltage, the lifetime can be in the order of minutes or less so that this specimen even cannot pass a 1 min high-voltage test with high-frequency voltage.

Annex E
(informative)

Insulation stressed with non-sinusoidal high-frequency voltages

E.1 Objective

This standard addresses the influence of sinusoidal high-frequency voltages on the dimensioning and testing of insulation. In many practical cases, the actual voltage stress is far from sinusoidal. Periodic pulses with greatly varying waveshape can be found in many applications.

In this case, a harmonic analysis of the impulse shape is required, and the relevant sinusoidal frequencies have to be identified.

The following consideration does not take into account the effect of the voltage waveshape on the voltage distribution across the insulation of windings.

E.2 Harmonic analysis

In Figures E.1 to E.8, the harmonic analysis of periodic impulse voltages is performed. In Figures E.1 and E.2 a symmetrical rectangular waveshape is analysed only for comparison purposes. In Figures E.3 and E.4 a more practical case is analysed, which was taken from Amendment 2 to Part 1. This waveshape was already shown in Figure 4.

In both cases, according to Figures E.2 and E.4, the spectrum is dominated by the fundamental wave. The relation between the fundamental and the most important 3rd harmonic is not much changed by the overshoot.

This is also true, if according to Figures E.5 and E.6, a ringing waveshape with similar overshoot as in Figure E.3 is assumed. In that case the 3rd harmonic is even reduced, but due to the 1 MHz oscillation the 9th and the 11th harmonic are significantly enhanced.

Even if the overshoot is greatly increased, as shown in Figures E.7 and E.8, the result in principle is the same. It should be noted that this example is rarely encountered in practical cases.

The spectrum is dominated by the fundamental. The relation between the fundamental and the 3rd harmonic is not much changed by the overshoot. Therefore it seems to be possible to design and test solid insulation for the fundamental frequency of the impulse voltage. In addition, the peak value of the non-sinusoidal voltage is taken into account by adjusting the amplitude of the fundamental wave to this peak value.

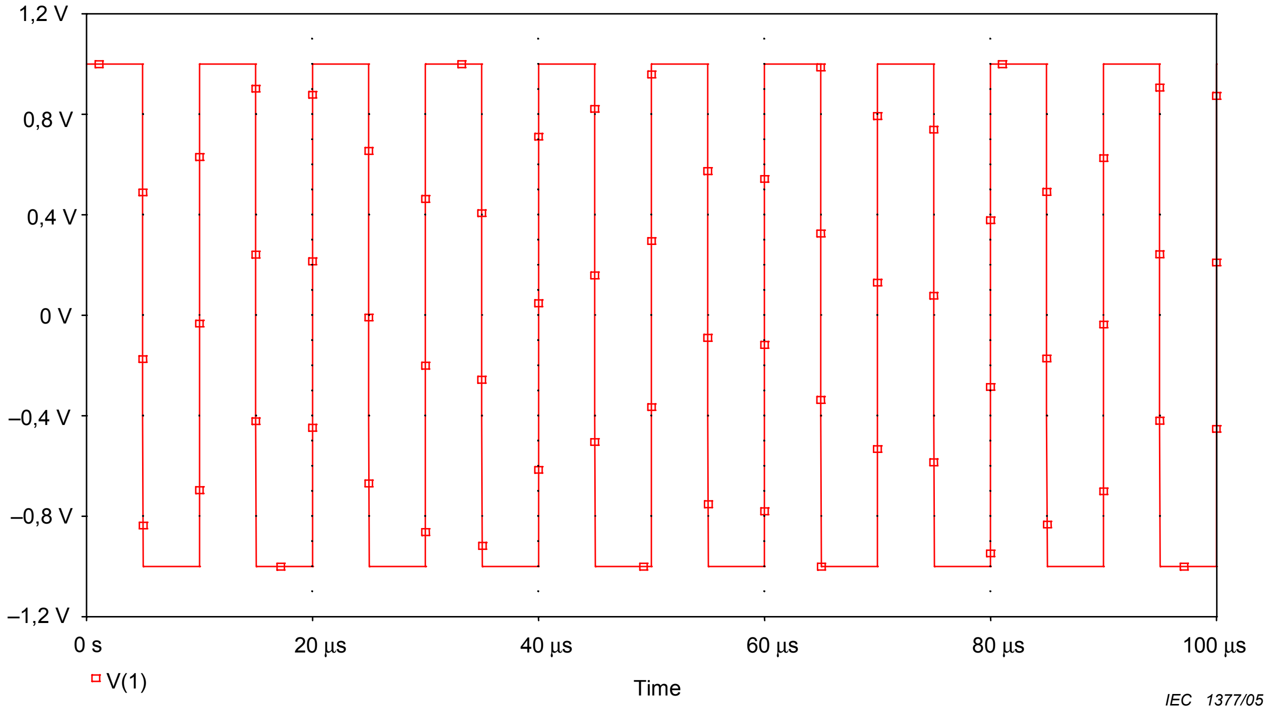


Figure E.1 – Periodic impulse voltage, rectangular waveshape

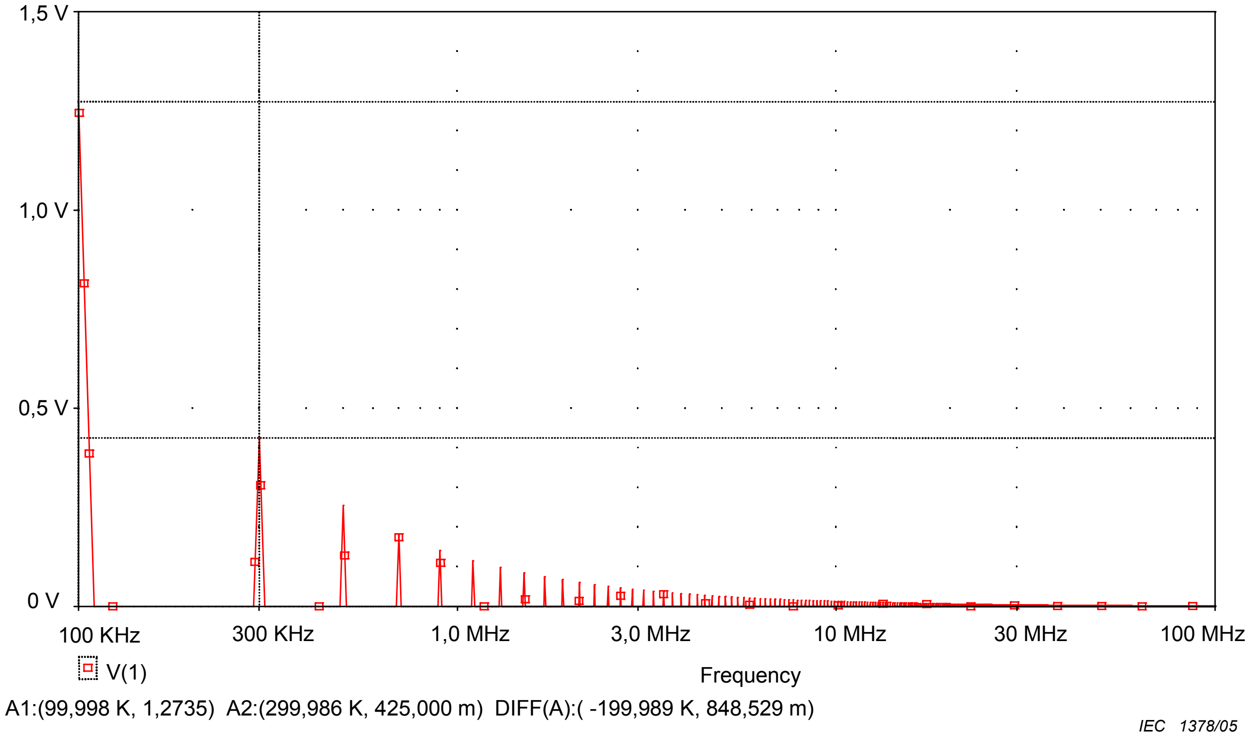


Figure E.2 – Periodic impulse voltage, rectangular waveshape, spectrum

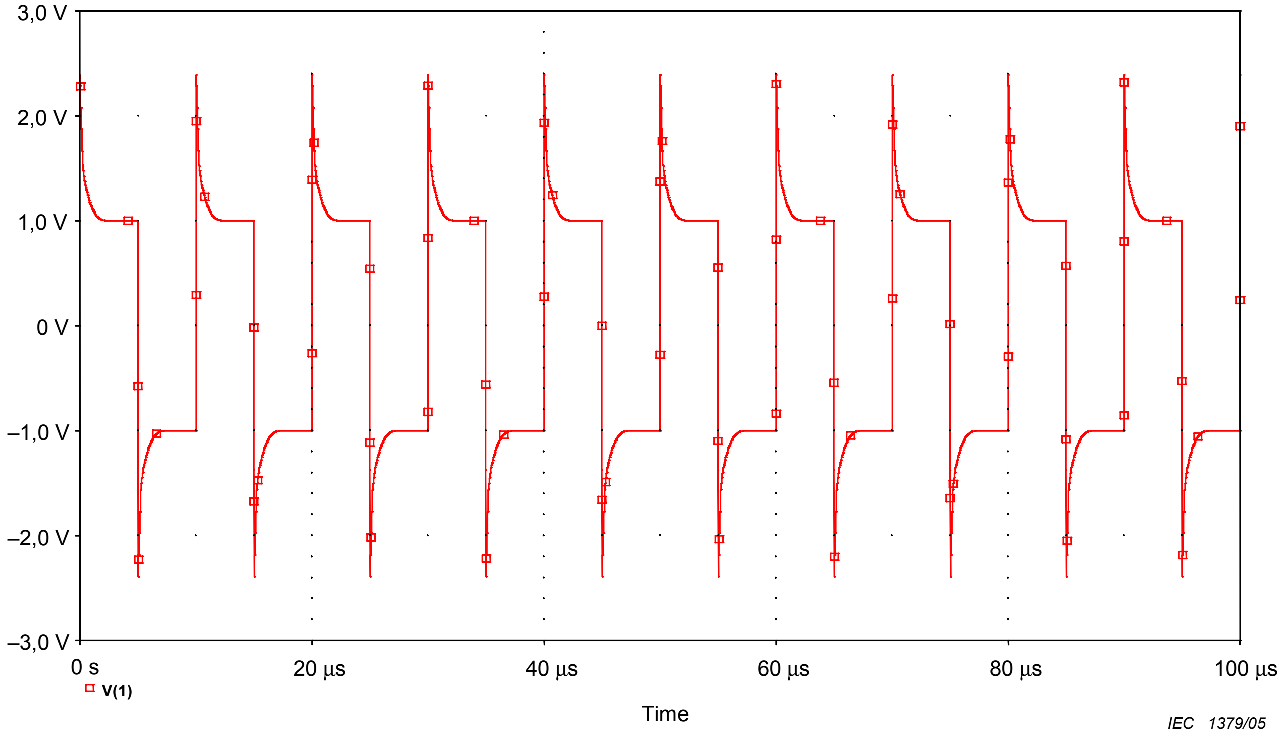
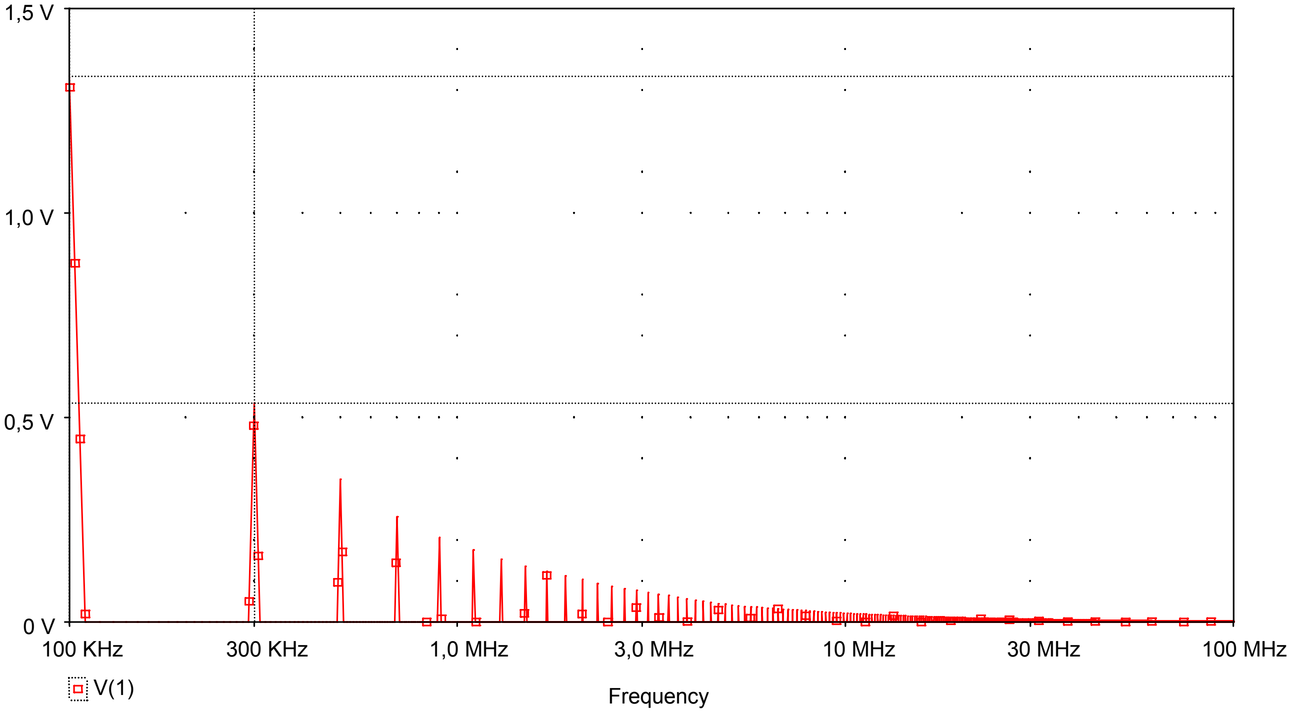


Figure E.3 – Periodic impulse voltage, rectangular waveshape with overshoot (see Figure 4)



B1:(100,005 K, 1,3338) B2:(300,002 K, 535,294 m) DIFF(B):(-199,997 K, 798,529 m)

Figure E.4 – Periodic impulse voltage, rectangular waveshape with overshoot, spectrum

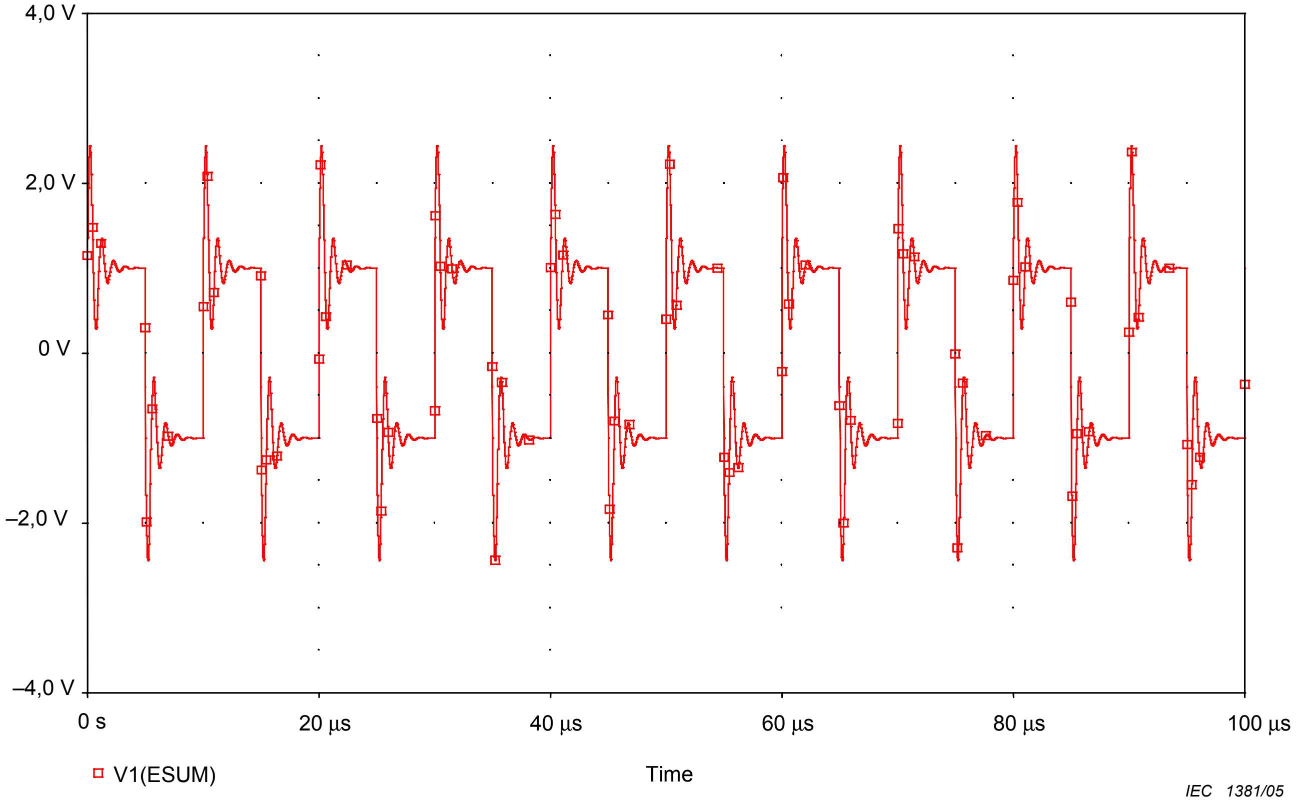


Figure E.5 – Periodic impulse voltage, rectangular waveshape with ringing (1 MHz)

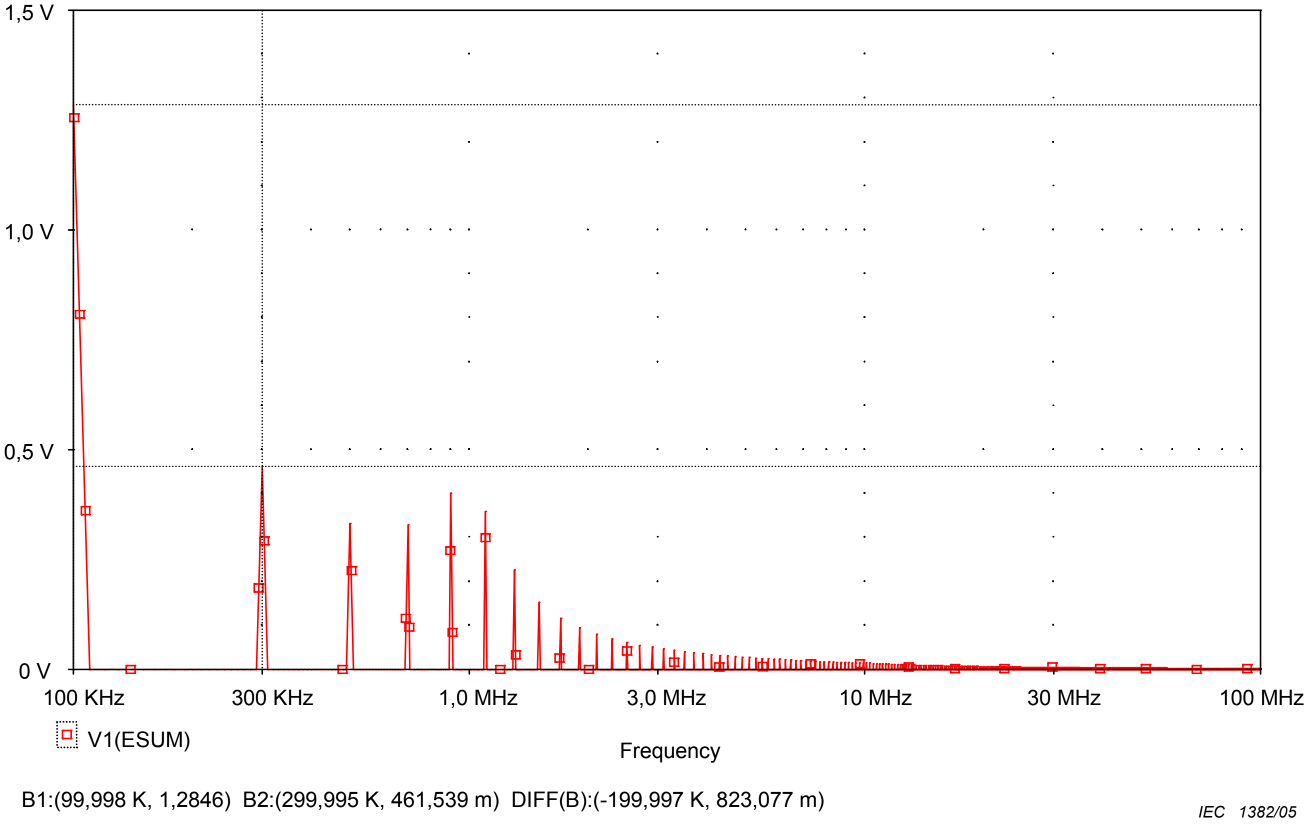


Figure E.6 – Periodic impulse voltage, rectangular waveshape with ringing (1 MHz), spectrum

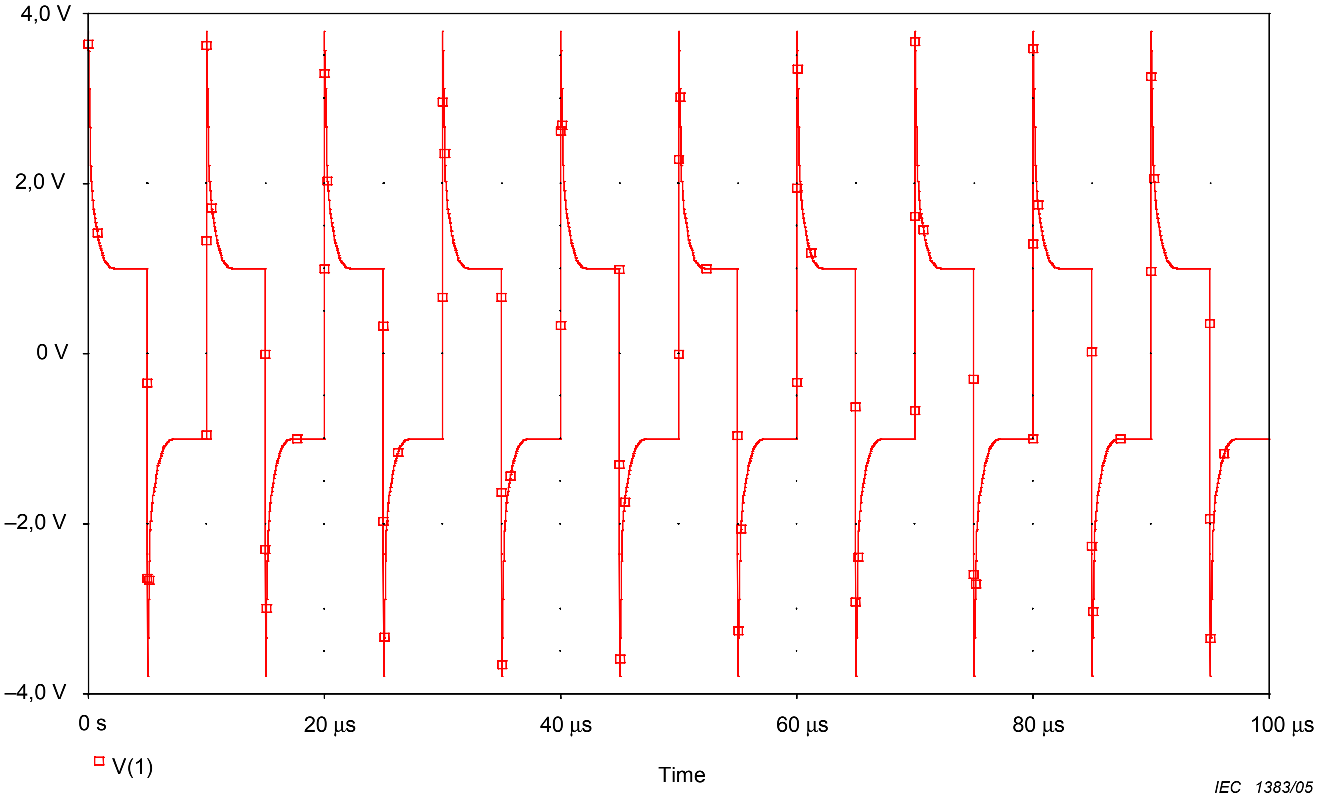


Figure E.7 – Periodic impulse voltage, rectangular waveshape with high overshoot

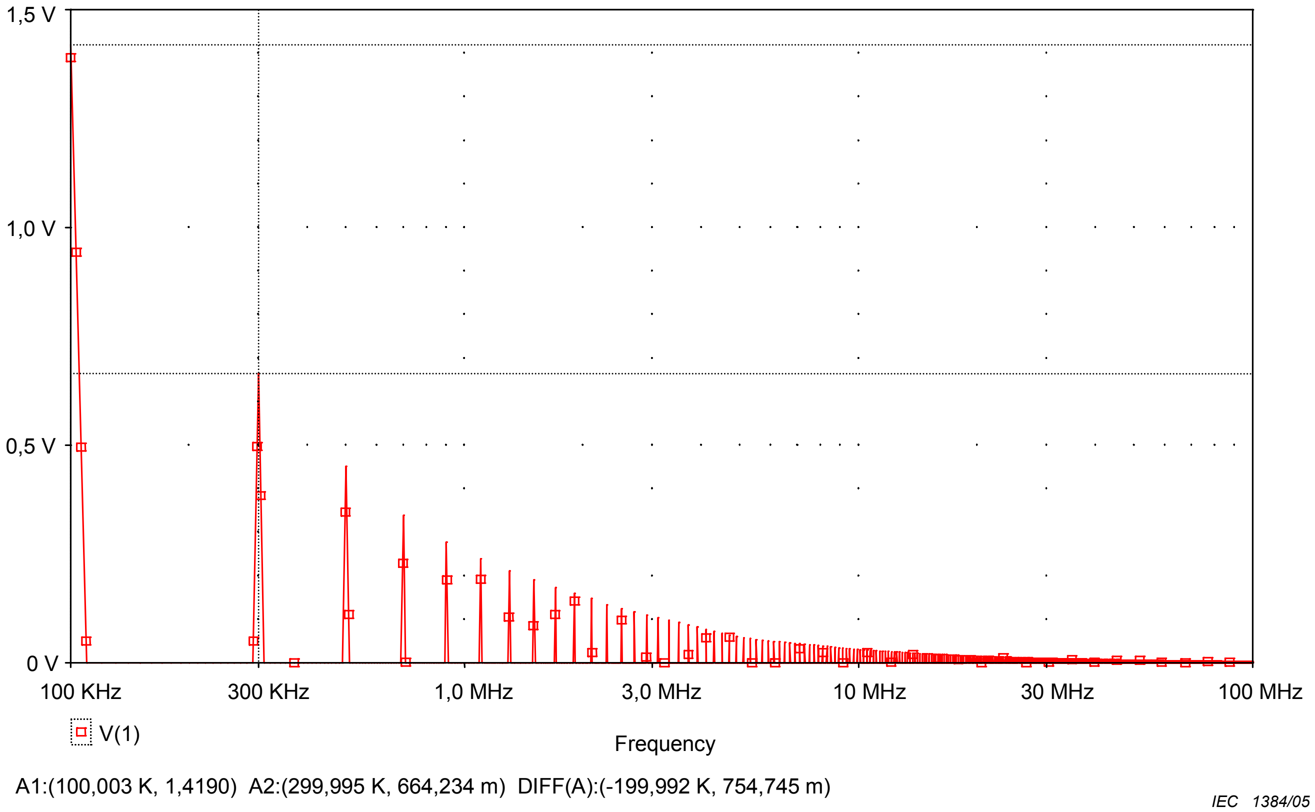


Figure E.8 – Periodic impulse voltage, rectangular waveshape with high overshoot, spectrum

Annex F

(informative)

Dimensioning diagrams

The following diagrams show the relationships between the factors influencing the dimensioning of clearances and creepage distances for insulation coordination. The diagrams highlight the major factors and are not intended to substitute for a full review of the relevant subclauses. In particular they do not take into account the homogeneous field situation (case B values), more precise dimensioning of clearances for frequencies between f_{crit} and f_{min} and dimensioning of solid insulation in order to avoid testing with HF-voltages.

It is to be noted that the dimensioning procedures for clearances and creepage are independent. Therefore, where a clearance and a creepage distance are coincidental over the same insulating surface, the larger of the clearance or the creepage distance is to be used.

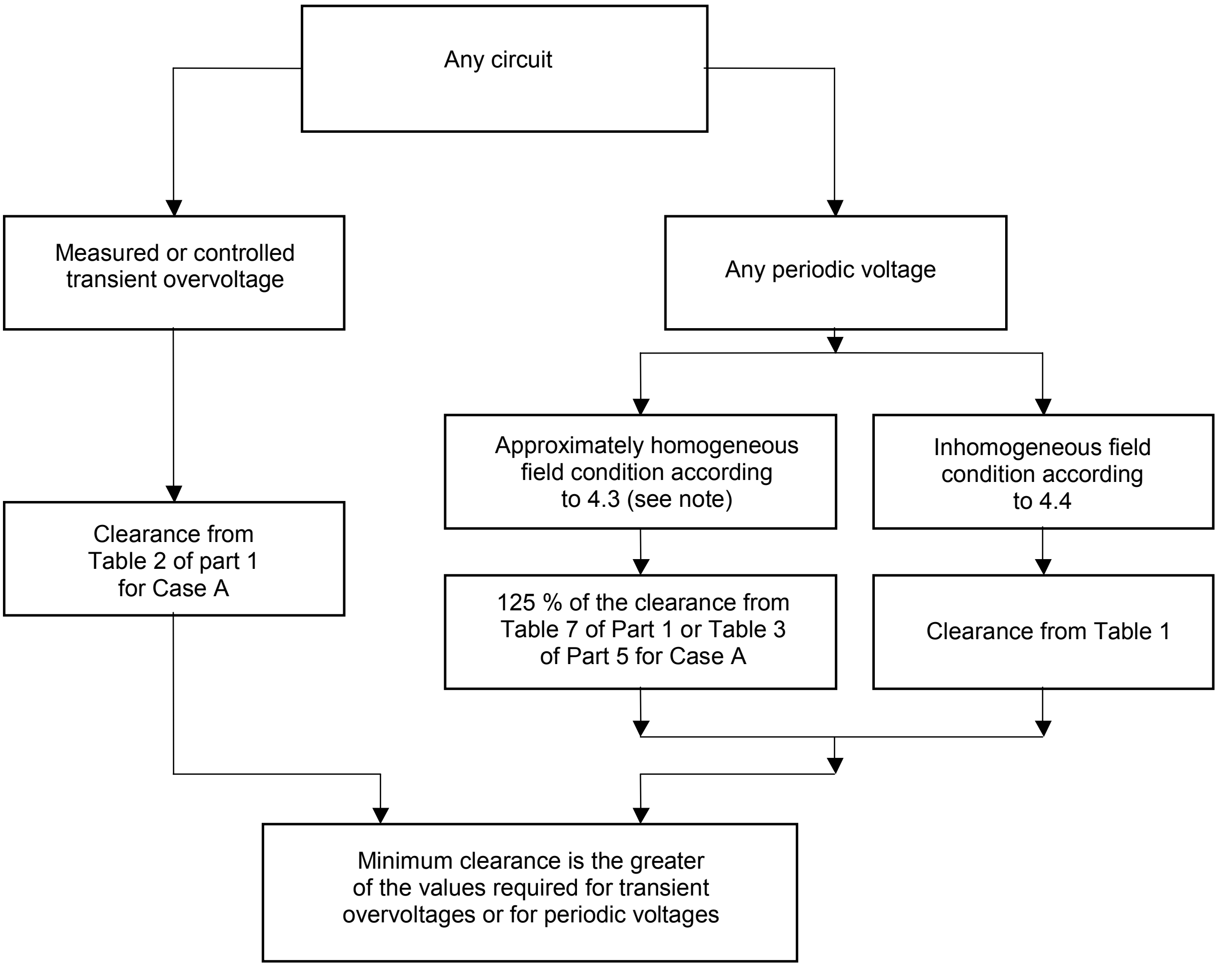


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Figure F.1 – Diagram for dimensioning of clearances

NOTE For frequencies exceeding 30 kHz, an approximately homogeneous field is considered to exist when the radius of curvature of the conductive parts is equal or greater than 20 % of the clearance. The necessary radius of curvature can only be specified at the end of the dimensioning procedure.

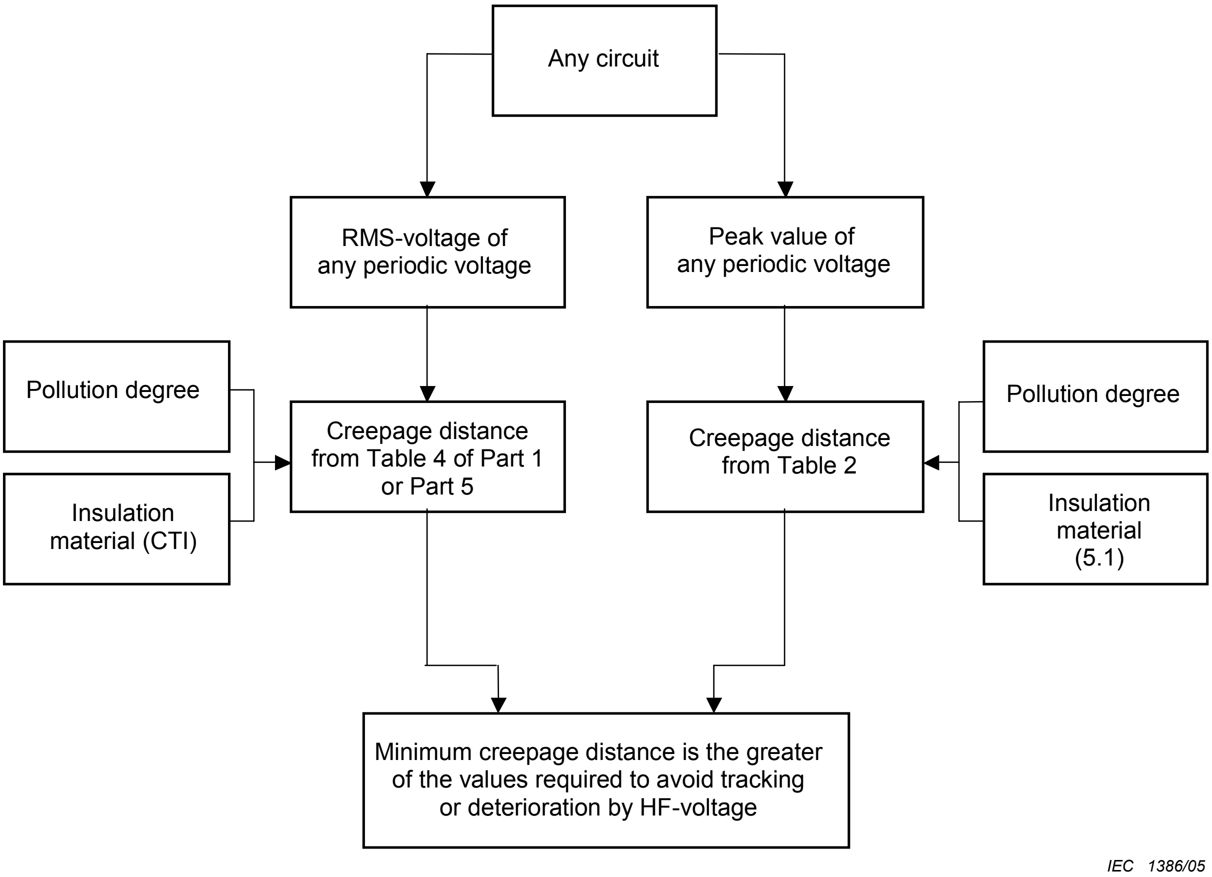

Figure F.2 – Diagram for dimensioning of creepage distances

For dimensioning of reinforced insulation additional requirements need to be fulfilled according to Part 1.

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The Committee has reviewed the provisions of the following international standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard.

International Standard	*Title*
IEC 60664-5 : 2003	Insulation coordination for equipment within low-voltage systems: A comprehensive method for determining clearances and creepage distances equal to or less than 2 mm
IEC Guide 104 : 1997	The preparation of safety publications and the use of basic safety publications and group safety publications

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

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 2022 ‘Rules for rounding off numerical values (*second revision*)’. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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Amendments Issued Since Publication

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