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TECHNICAL REPORT

Low voltage switchgear and controlgear – Partial discharge voltages and PD-level in low voltage switchgear and controlgear

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LOW VOLTAGE SWITCHGEAR AND CONTROLGEAR –

PARTIAL DISCHARGE VOLTAGES AND PD-LEVEL IN LOW VOLTAGE SWITCHGEAR AND CONTROLGEAR

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IEC TR 63434 has been prepared by subcommittee 121A: Low voltage switchgear and controlgear, of IEC technical committee 121: Switchgear and controlgear and their assemblies for low-voltage. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
121A/549/DTR	121A/556A/RVDTR

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

The language used for the development of this Technical Report is English.

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

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

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- withdrawn,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

INTRODUCTION

The application of this document is intended to provide awareness about partial discharge phenomena. Special emphasis is given to the electrical field stress through solid insulation as it relates to the risk of insulation failure.

IEC 60664-1[1] [1] is only providing requirements for partial discharge testing of solid insulation when the peak value of the operational voltage exceeds 700 V and the average field strength is higher than 1 kV/mm. However, in practice, partial discharge testing gives random results below 4 kV/mm, mainly because of the intrinsic fluctuation of PD inception voltage in gaps, the variations of the shape and size of the internal voids in solid materials, and the large influence of the temperature and humidity on the material characteristics. Therefore, this document is providing guidance related to the proper design of the insulation and the selection criteria of the material.

1 Numbers in square brackets refer to the Bibliography.

LOW VOLTAGE SWITCHGEAR AND CONTROLGEAR –

PARTIAL DISCHARGE VOLTAGES AND PD-LEVEL IN LOW VOLTAGE SWITCHGEAR AND CONTROLGEAR

1 Scope

This document is intended to provide awareness about partial discharge phenomena. This document gives guidance for some conditions when partial discharge can occur in low voltage switchgear and controlgear connected to networks of up to 1 000 V AC. Internal operational voltages can exceed these values. This document gives guidance on the design of conductors and dimensioning of insulation exposed to electrical fields.

This document explains the partial discharge phenomena considering electrical field stress, type of insulation material and other construction parameters, such as the voltage, frequency, temperature, humidity and the distances within the device.

This document does not cover:

- phenomena associated with semiconductor power switching by effects on equipment placed downstream of semiconductor power switching systems;
- partial discharge test procedures (see IEC 60270) [2];
- pure DC systems which are under consideration;
- selection of solid insulation material.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

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

3.1
homogeneous electric field
electric field which has an essentially constant voltage gradient between electrodes, such as that between two spheres where the radius of each sphere is greater than the distance between them

Note 1 to entry: The homogeneous field condition is referred to as case B in IEC 60664-1[1].

[SOURCE: IEC 60050-442:2014[3], 442-09-02]

3.2
inhomogeneous electric field
electric field which does not have an essentially constant voltage gradient between electrodes

Note 1 to entry: The inhomogeneous field condition of a point-plane electrode configuration is the worst case with regard to voltage withstand capability and is referred to as case A in IEC 60664-1[1]. It is represented by a point electrode having a 30 µm radius and a plane of 1 m × 1 m.

Note 2 to entry: 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.

[SOURCE: IEC 60050-442:2014[3], 442-09-03]

3.3
partial discharge
PD
electric discharge that only partially bridges the insulation between conductors

Note 1 to entry: A partial discharge may occur inside the insulation or adjacent to a conductor.

Note 2 to entry: Scintillations of low energy on the surface of insulating materials are often described as partial discharges but should rather be considered as disruptive discharges of low energy, since they are the result of local dielectric breakdowns of high ionization density, or small arcs, according to the conventions of physics.

[SOURCE: IEC 60050-212:2010[3], 212-11-39, modified — Addition of the synonym “PD”.]

3.4
partial discharge intensity
amount of partial discharge occurring under given conditions

Note 1 to entry: In practice the partial discharge intensity is usually expressed in picocoulombs or in joules.

[SOURCE: IEC 60050-212:2010[3], 212-11-40]

3.5
partial discharge inception voltage
U_i
lowest peak value of the test voltage at which the apparent charge becomes greater than the specified discharge magnitude when the test voltage is increased above a low value for which no discharge occurs

Note 1 to entry: For AC tests the RMS value may be used.

[SOURCE: IEC 60050-212:2014[3], 212-11-41]

3.6
partial discharge extinction voltage
U_e
highest voltage at which partial discharges are extinguished when the voltage applied is gradually decreased from a higher value at which such discharges are observed

[SOURCE: IEC 60050-212:2010[3], 212-11-42, modified – added abbreviation U_e]

3.7
impulse withstand voltage
U_{imp}
highest peak impulse voltage, of prescribed form and polarity, which does not cause breakdown under specified conditions of test

3.8
internal partial discharge
partial discharge inside an insulating material

[SOURCE: IEC 60050-212:2010[3], 212-11-43]

3.9
working voltage
highest RMS value of the AC or DC voltage across any particular insulation which can occur when the equipment is supplied at rated voltage

Note 1 to entry: Transient overvoltages are disregarded.

Note 2 to entry: Both open-circuit conditions and normal operating conditions are taken into account.

[SOURCE: IEC 60947-1:2020[4], 3.7.52]

3.10
recurring peak voltage
U_{rp}
maximum peak value of periodic excursions of the voltage waveform resulting from distortions of an AC voltage or from AC components superimposed on a DC voltage

Note 1 to entry: Random overvoltages, for example due to occasional switching, are not considered to be recurring peak voltages.

[SOURCE: IEC 60050-442:2014[3], 442-09-15]

3.11
temporary overvoltage
overvoltage at power frequency of relatively long duration

Note 1 to entry: A temporary overvoltage is undamped or weakly damped. In some cases, its frequency may be several times smaller or greater than power frequency.

[SOURCE: IEC 60947-1:2020[4], 3.7.53]

3.12
transient overvoltage
short duration overvoltage of a few milliseconds or less, oscillatory or non-oscillatory, usually highly damped

[SOURCE: IEC 60050-614:2016[3], 614-03-14, modified – "overvoltage with a duration" has been replaced with "short duration overvoltage" and the notes have been deleted.]

3.13
glow discharge
self-maintained gas conduction for which most of the charge carriers are electrons supplied by secondary-electron emission

[SOURCE: IEC 60050-121:1998[3], 121-13-13]

3.14
electric breakdown
abrupt change of all or part of an insulating medium into a conducting medium resulting in an electric discharge

[SOURCE: IEC 60050-614:2016[3], 614-03-15]

3.15
electric strength
quotient of the maximum voltage applied without breakdown, by the distance between conducting parts under prescribed test conditions

[SOURCE: IEC 60050-212:2010[3], 212-11-37]

3.16
glass transition
physical change in an amorphous material or in amorphous regions of a partially crystalline material from a viscous or rubbery condition to a hard one, or the reverse

[SOURCE: IEC 60050-212:2010[3], 212-12-28]

3.17
glass transition temperature
T_g
midpoint of a thermodynamic temperature range over which the glass transition takes place

[SOURCE: IEC 60050-212:2010[3], 212-12-29]

4 Basic information (physics)

4.1 Discharge phenomena

4.1.1 General

Partial discharges are well known in the field of high voltage applications and typical for inhomogeneous electrical field distributions.

Partial discharges in electromechanical switchgear can appear in different ways: through air directly (external PD), on surfaces of supporting parts (surface PD) and within voids of solid or liquid insulation components like phase separation walls (internal PD). Surface discharges in air have generally larger values than those inside of cavities of solid insulation [5].

NOTE In [6] a simulation is shown illustrating the potential locations of PD generation in a Motor Protection Switching Device (MPSD).

4.1.2 Homogeneous electric fields

The breakdown field strength or dielectric strength of an air gap of 1 mm distance with a homogeneous electric field – e.g. between parallel plane electrodes – is about 4 kV/mm (see Figure 4). In technical applications the size of the air gaps between electrodes and insulation material can be 1 mm or less.

NOTE For breakdown processes in homogeneous electric fields in air in general the Paschen-Law [7], [9] is valid.

The breakdown field strength $\hat{E}_d$ is depending on the temperature T. The temperature correction is done by using equation (1) with T_0 = 293 K and the worst case temperature coefficient α = 0,8.[[7], p. 169], see Figure 1.

$$\hat{E}_d = \hat{E}_{do} \left(\frac{p / p_0}{T / T_0} \right)^{\alpha} \quad (1)$$

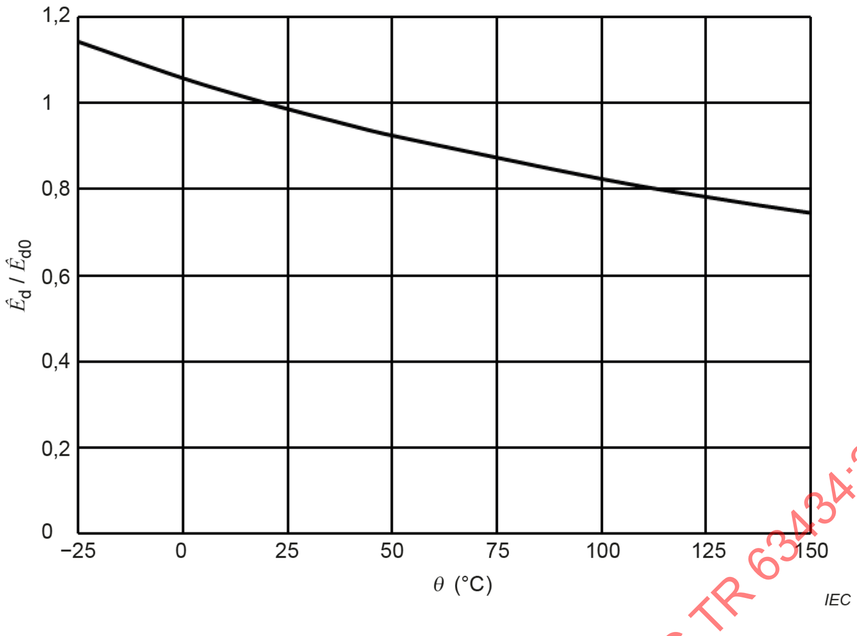


Figure 1 – Temperature dependent variation of the breakdown field strength $\hat{E}_d$ of air per Equation (1), α = 0,8, θ = 20 °C, $p = p_0$ = 1 013 mbar

For 130 °C this results in a dielectric strength of a 1 mm air gap with homogeneous field distribution $\hat{E}_d$ of 3,1 kV/mm (77,5 % of the 20 °C-value). This is the crest value of the field strength and related to the peak value of the applied voltage. The effective value of a corresponding sinusoidal voltage is reduced by the factor 1/√2.

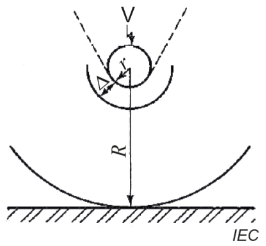
4.1.3 Inhomogeneous electric fields

The PD inception voltage is related to inhomogeneous electrode distribution – like point to plane electrodes – with a degree of homogeneity or utilization factor η lower as the limit of $\eta \approx 0{,}2$ [9]. This value gives the quotient of average field strength to maximum field strength for an electrode arrangement [5], [8]. Stable glow discharges in air can principally appear at field strength values of 2,5 kV/mm (see [9] and IEC 60664-1:2020, Figure A.1[1]). With a low utilization factor of 0,2 the PD inception peak voltage for an inhomogeneous electrode arrangement – like a point or edge electrode against a plane electrode – with an air gap of 1 mm is only about 800 V_{peak} or 566 $V_{RMS.}$ according to the tables in [7].

NOTE 1 Because, in practice, partial discharge testing gives random results below 4 kV/mm, the threshold of 2,5 kV/mm is considered only for initial analysis purposes.

The utilization factor η is dependent on the electrode distance R and the electrode radius r [5], [8]. A reference model in [8] shows the relation between radius r and inception voltage U_i, expressed in RMS, based on real dimensions (see Table 1 and [8]).

Table 1 – Relationship between electrode radius r and corona inception voltage $U_{i,RMS}$

$R \gg r$	r µm	$U_{i,RMS}$ V
	10	450
	50	1 000
	100	1 400
	500	3 500
	1 000	5 500
	5 000	15 000

Key

V – potential

r – electrode radius

R – distance to earth plane

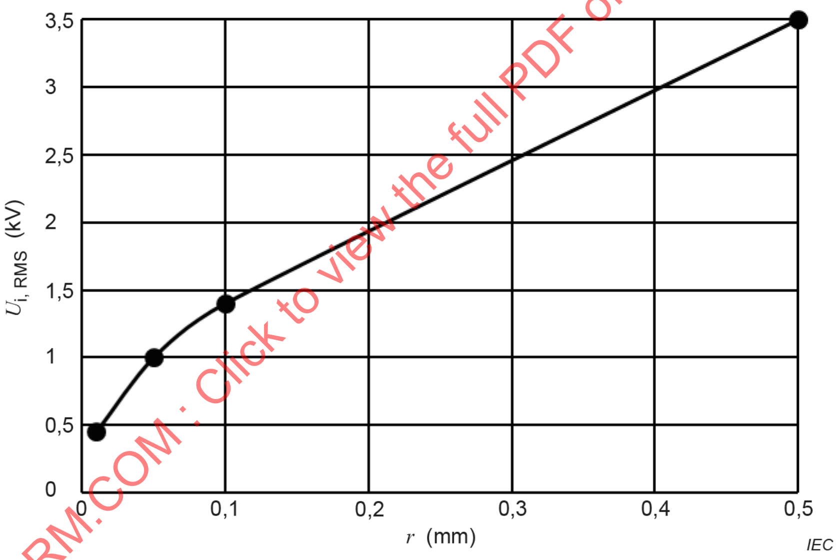


Figure 2 – Inception voltage $U_{i,RMS}$ depending on the electrode radius r, $R \gg r$

The graphical depiction of Table 1 up to a radius of 0,5 mm shows clearly that the inception voltage decreases more rapidly below r = 100 µm corresponding to an inception voltage of only 450 V with a radius of 10 µm.

The evaluation of FEM-simulations on a particular contact arrangement in Figure 3 also shows the progressive rise of the field strength once the edge radius is lower than 0,1 mm [10] and confirm the dependencies in Table 1 and Figure 2.

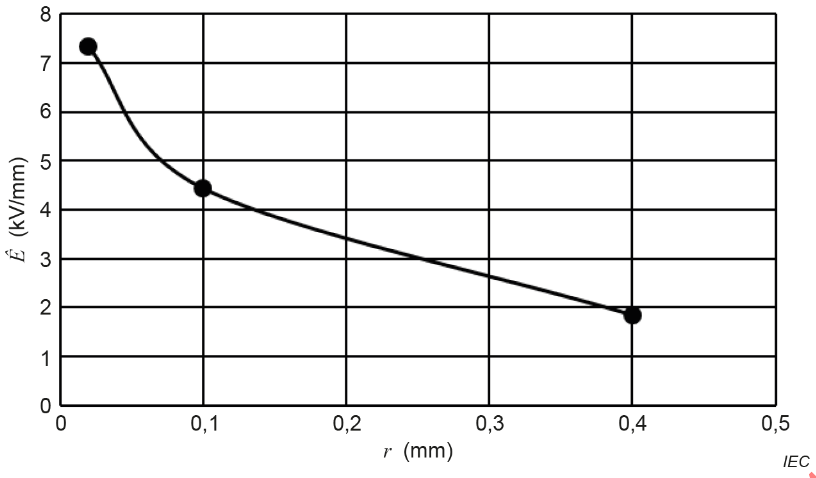


Figure 3 – Maximum electrical field strength $\hat{E}$ depending on the electrode edge radius r

In addition to the influence of the radius, the breakdown field strength in air (Paschen-curve Figure 4) needs to be considered.

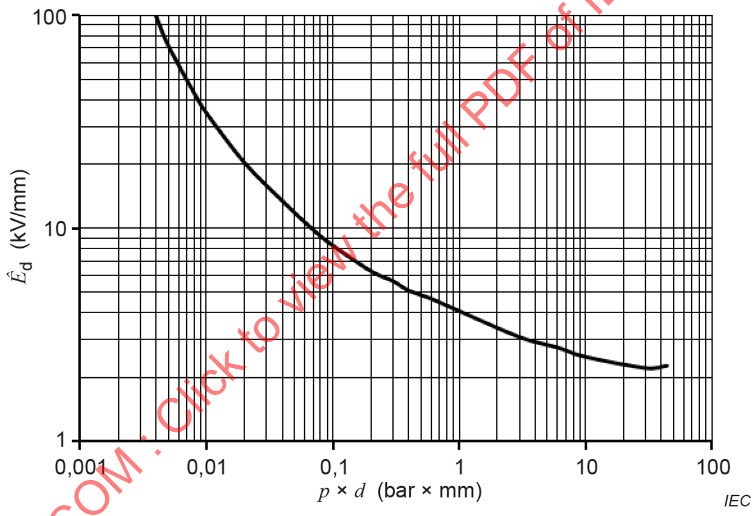


Figure 4 – Paschen curve $\hat{E}_d = f(p \times d)$ for air

For practical applications, in addition to the inception voltage, the extinction voltage is of relevance. Only if the permanent operational voltage remains below that value, a discharge initiated e.g. by a disturbance can extinguish. Persisting PD would not only destroy adjacent materials thermally or by UV radiation but also chemically for example through forming of nitric acid depending on the materials involved.

Field inhomogeneity also occurs when an electrode is mounted on a solid insulation or when a layer of solid insulation material is positioned in an air gap between electrodes. For the first situation the inception voltage in the wedge between electrode and support is roughly inverse proportional to the relative permittivity ε_r [7].

$$\hat{U}_i \propto \left(\frac{1}{\varepsilon_r}\right)^{\alpha} \quad (2)$$

With typical measured values α = 0,45...0,5.

The degree of relative permittivity variation over temperature is highly dependent on the glass transition temperature T_g and moisture uptake of the insulating material. For polyamides, with glass transition temperature close to room temperature in humid conditions the variation can be as high as factor 5 between 20 °C to 130 °C [6], [11]-[15], [16], [17], [18]. For other polymers with higher glass transition temperature or lower hygroscopic behaviour the variation can be comparatively low (e.g. by a factor 2).

Attention is drawn to the dependency of the relative permittivity in regard to temperature, frequency as well as the state of the material (dry or conditioned). Such data are often not available. IEC 60664-1[1] states that the insulation behaviour of the solid insulation is directly affected by its intrinsic material characteristics. Electrical, mechanical and other stresses which might affect the insulation behaviour over the lifetime of the product needs to be considered.

IEC 60664-1:2020[1] considers discharge phenomena at room temperature only. The following example shows how a calculation, considering a defined elevated operational temperature, reduces the electrical strength.

With the dependency as per Equation (2) and a change of the relative permittivity from ε_{r20} = 3,4 (relative permittivity at 20 °C) to ε_{r130} = 11 (relative permittivity at 130 °C), also the relation of the inception voltages at 130 °C and 20 °C in an air gap (wedge between electrode and support) would change to

$$\frac{\hat{U}_{i130}}{\hat{U}_{i20}} \propto \left(\frac{\varepsilon_{r20}}{\varepsilon_{r130}}\right)^{0,5} = 0,56 \qquad (3)$$

Both effects (air temperature see Equation (1) and change of the relative permittivity) would lead to a relation of

$$\frac{\hat{U}_{i130}}{\hat{U}_{i20}} \propto 0,56 \times 0,775 = 0,43 \qquad (4)$$

This corresponds to dielectric strength in a homogeneous field of a 1 mm air gap of $\hat{E}_{dmin}$ = 1,72 kV/mm (43 % of the 20 °C-value). For a specific electrode arrangement with inhomogeneous field (utilization factor of η = 0,5 [8],[12]), the dielectric strength is further reduced to a peak value of 860 V/mm, corresponding to an RMS value of about 600 V. This means that a device according to this example operated at 690 V would exceed the dielectric strength of the contact arrangement and partial discharges would occur at the assumed operational temperature, whereas at room temperature they would not occur.

NOTE 2 The utilization factor can vary due to the design and manufacturing process.

This example shows that the operational temperature can have a significant influence on the dielectric characteristics of the devices and therefore needs to be considered.

4.2 Dimensioning examples

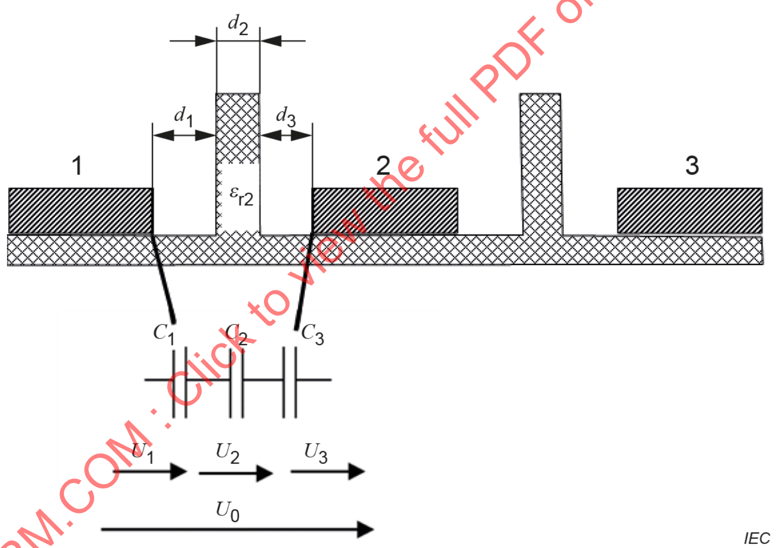
4.2.1 General

The following examples deal with the series connection of clearances and solid insulation as designed within the equipment. The dimensioning examples in IEC TR 60664-2-1[19] describe just one gap and one insulation layer. The example, including the Equations (5), (6) and (7), is valid for an ideal solid insulation layer (with no air voids). But a typical dimensioning task occurs at the terminals of multipole devices. In compliance with the example given in IEC TR 60664-2-1 [19] and [13], the following example is derived for a 3-pole device.

The intention of this example is to point out how the electric stress in the air gaps of an insulation construction is influenced and how it changes under the influence of operational temperature. In the example the full distance between the electrodes has been determined by the design. The objective is to optimize the distribution of this full distance into the thickness of the solid insulation material and air gaps to avoid partial discharge.

For AC voltage, the impedances of the series connected insulators are determined by their capacitances. Usually, for rather low frequencies as considered in IEC 60664-1[1], the dielectric losses are not considered for the calculation of the voltage distribution. However, the dielectric permittivity ε_r of the solid insulator has a decisive influence on the voltage distribution especially with regard to the values changing with temperature and/or humidity condition (see also Figure 17).

For an easy calculation and consideration of the capacitive voltage distribution, those capacitances are considered as plate-to-plate capacitors with a homogeneous field distribution first. This situation is described in Figure 5.



Key

1,2,3 phase poles

U_0 applied AC voltage

C_1, C_3 capacitance of the clearance

U_1, U_3 voltage across the clearance

C_2 capacitance of the solid insulation

U_2 voltage across the solid insulation

d_1, d_3 length of air gap

d_2 length of solid insulation wall

ε_{r2} permittivity of the solid insulation

Figure 5 – Principle terminal / contact arrangement of a 3-pole device, capacitive voltage divider

In order to prevent any deterioration of the solid insulation, the solid insulation is to be designed to withstand the entire operational voltage and the air gaps are to be designed to prevent inception of partial discharge under operational conditions.

For the following considerations and examples, it is defined that the overall distance between the phase poles ($d_1 + d_2 + d_3$ = 1,5 mm) is kept constant (design rules). This means that, as the thickness of the solid insulation decreases, the distance of the air gap gets bigger or vice versa.

Between 2 poles of the 3-pole configuration C_1, C_2 and C_3 form a capacitive voltage divider according to Figure 5 and the applied AC voltage U_0 is divided according to Equations (5), (6) and (7), and in the voltages U_1, U_2 and U_3. In symmetrical designs U_1 is equal to U_3.

$$U_1 = \left(\frac{d_1 / \varepsilon_{r1}}{d_1 / \varepsilon_{r1} + d_2 / \varepsilon_{r2} + d_3 / \varepsilon_{r3}} \right) \times U_0 \tag{5}$$

$$U_2 = \left(\frac{d_2 / \varepsilon_{r2}}{d_1 / \varepsilon_{r1} + d_2 / \varepsilon_{r2} + d_3 / \varepsilon_{r3}} \right) \times U_0 \tag{6}$$

$$U_3 = \left(\frac{d_3 / \varepsilon_{r3}}{d_1 / \varepsilon_{r1} + d_2 / \varepsilon_{r2} + d_3 / \varepsilon_{r3}} \right) \times U_0 \tag{7}$$

For symmetrical air gaps the capacitances $C_{1,3}$ and C_2 are given by Equations (8) and (9):

$$C_{1,3} = \varepsilon_0 \times \frac{A}{d_{1,3}} \tag{8}$$

$$C_2 = \varepsilon_0 \times \varepsilon_r \times \frac{A}{d_2} \tag{9}$$

where

A is the area of the plate-to-plate capacitors $C_{1,3}$ and C_2;

ε_0 is the dielectric constant of the air;

ε_r is the relative permittivity of the solid insulation.

For the voltage division, the capacitance ratio as given in Equation (10) is relevant.

$$C_1 = C_2 \times \frac{d_2}{d_1} \times \frac{1}{\varepsilon_r} \tag{10}$$

The breakdown field strength of the clearance ($\hat{E}_1$) can be calculated using the AC breakdown voltage and the corresponding clearance. For simplification, the examples given in this application guide are based on homogeneous field conditions first. The breakdown field strength of the solid insulation ($\hat{E}_2$) is specified by the manufacturer of the material ideally with long term temperature dependency.

A precise calculation or simulation of the voltage distribution is much more complicated to make and the above equations can only be considered as an approximation, assuming homogeneous field distribution. For small distances up to around 0,1 mm, this approximation is rather precise. For rather large distances, it is not directly appropriate but can be improved using a utilization factor η evaluated as per the method of Schwaiger [7], [12]. The factor depends on the overall shape but mainly on the two design parameters electrode distance d and radius r. A value of η = 0,5 or even 0,2 is an appropriate assumption in many cases [8], [13].

4.2.2 Influence of design and temperature on a series connection of clearances and solid insulation for AC voltage

4.2.2.1 General

For AC voltage, the voltage distribution is calculated according to the relevant capacitances. The following examples are based on Figure 5, which shows a simplified common design with a clearance and a layer of solid insulation in series. The dimensions chosen for the examples are derived from typical circuit-breakers or contactors in the range of up to 20 kW at 400 V.

4.2.2.2 Example showing the distribution of the electrical field at room temperature

This example shows that in an insulation configuration of a solid wall with two adjacent gaseous (e.g. air) gaps between two phase poles, a considerable electrical field stress can occur in the air gaps. Depending on the utilization factor η this can initiate partial discharges even at room temperature. Considering the following list of parameters

$d_{1,3}$ = 0,2 mm,
d_2 = 1,1 mm
ε_{r2} = 4 (at room temperature)

Application of Equation (10)	results in:	$C_1 = 1{,}375\ C_2$
Application of Equations (5) and (7)	results in:	$U_{1,3} = 0{,}297\ U_0$
Application of Equation (6)	results in:	$U_2 = 0{,}408\ U_0$

the result is that about 30 % of the full voltage drops across each clearance. Assuming that U_0 = 690 V_{RMS} and the utilization factor η = 0,5, the peak electrical field strength in the air gaps is approximately 2,9 kV/mm, which exceeds the threshold for glow discharges. In case of flashover of the clearances, however, the full voltage is applied to the solid insulation.

4.2.2.3 Example showing the distribution of the electrical field at a high operational temperature

This example shows how a considerable change in operational temperature (from 20 °C to 130 °C) increases the electrical stress on the gaseous (air) gaps in the vicinity of a solid insulation wall.

Since the relative permittivity can be strongly temperature dependent the results using a ε_{r2} = 15 would change to

Application of Equation (10)	results in:	$C_1 = 0{,}367\ C_2$
Application of Equations (5) and (7)	results in:	$U_{1,3} = 0{,}424\ U_0$
Application of Equation (6)	results in:	$U_2 = 0{,}152\ U_0$

In this case about 40 % of the whole voltage is applied across each clearance. Assuming the same conditions as for Example 1 (see 4.2.2.2) the electrical field strength in the air gaps then is even approximately 4,1 kV/mm which is close to the breakdown condition. In case of flashover of the clearances, however, the full voltage is applied to the solid insulation which has also a reduced electrical breakdown strength caused by the rise of the relative permittivity.

Temperature dependent values of dielectric strength are not generally available from the manufacturers or from literature. Same is valid for long term degradation. Usually designers refer to RTI (Relative Temperature Index) ratings as suitability criteria to select materials for the intended operational temperatures. These values do include some uncertainties related to the evaluation methods and they also imply that the relevant property has declined to 50 % of the initial value. For higher temperatures, this condition is reached in shorter time. As per the Arrhenius law a change to 10 K higher temperature results in 50 % of their useful lifetime.

4.2.2.4 Description for the distribution of the electrical field for different dimensions and temperatures

4.2.2.4.1 General

A more general description of the influence of the design parameters air gap and solid insulation dimension is given in the Figure 6 to Figure 9 and are expressed in field strength $\hat{E}$ [kV/mm] for the different cases of inhomogeneous field with utilization factor η = 0,5 in cold state (see Figure 6 and Figure 7) and warm state (and Figure 9). The total distance between two phase poles is kept constant. As reference lines the limit above which stable glow discharges can occur in the air gap (2,5 kV/mm) [9] or the field strength value for solid insulation as given in IEC 60664-1[1] (1 kV/mm) are marked as dashed line.

Field strength in "cold state" Figure 6 shows the field strength $\hat{E}_{1,3}$ in the air gaps depending on the size $d_{1,3}$ of the air gap. Furthermore, the characteristics are shown for different conventional operational voltages from 400 V up to 1 000 V.

The higher the operational voltage is, the larger the clearance and creepage distances (air gap) need to be dimensioned, as a trend, to withstand the power frequency voltage to avoid PD occurrence.

The example illustrated in Figure 6 to Figure 9 with $d_{1,3}$ = 0,1 mm and d_2 = 1,3 mm appears to be at or above the limits of the dimensioning criteria of IEC 60664-1[1] when operated with 690 V or higher.

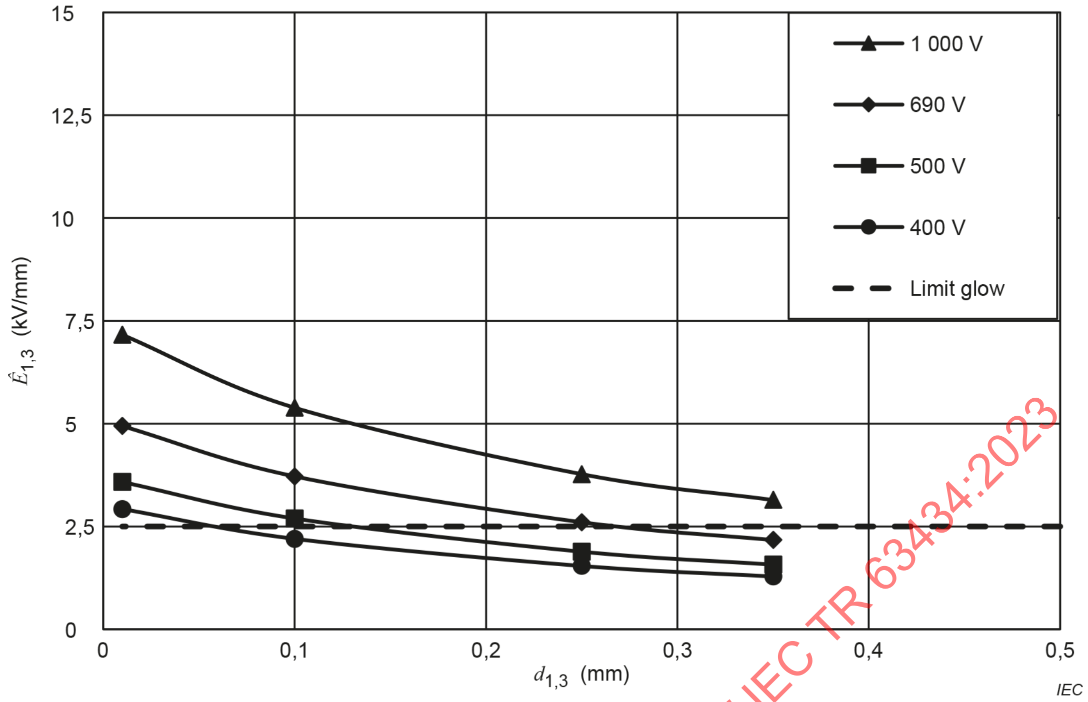


Figure 6 – Field strength in the air gap, inhomogeneous, η = 0,5 , ε_{r2} = 4, cold state

Figure 7 shows the field strength $\hat{E}_2$ in the solid insulation. The marked 1 kV/mm criterion as given in IEC 60664-1[1] for solid insulation appears to be uncritical for operational voltages up to 500 V. Above that value more detailed examinations are required.

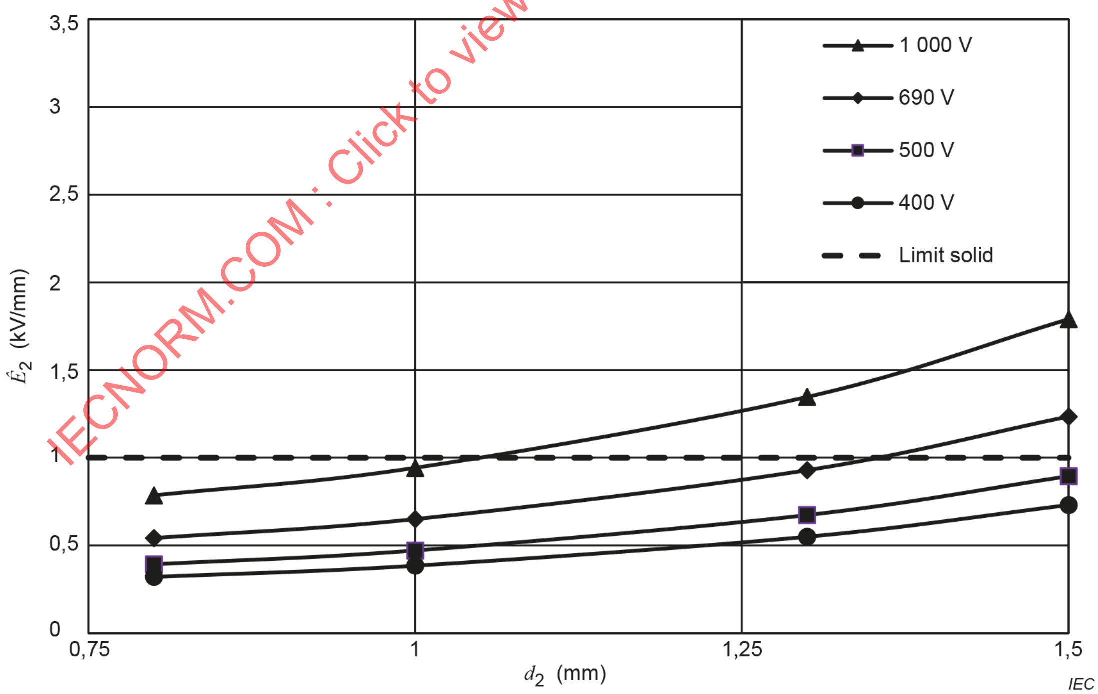


Figure 7 – Field strength in the solid insulation, inhomogeneous, η = 0,5, ε_{r2} = 4, cold state

The example illustrated in Figure 6 and Figure 7 with $d_{1,3}$ = 0,1 mm and d_2 = 1,3 mm appears to be at or above the limits of the dimensioning criteria of IEC 60664-1[1] already at room temperature when operated with 690 V or higher.

4.2.2.4.2 Field strength at elevated operational temperature

Figure 8 shows the field strength $\hat{E}_{1,3}$ in the air gaps depending on the size $d_{1,3}$ of the air gaps at operational temperature (e.g. 130 °C).

At all voltages of 400 V and higher the limit of 2,5 kV/mm for glow discharges is exceeded for d_1 < 0,3 mm. This would raise the probability of the occurrence of partial discharges in the air gaps.

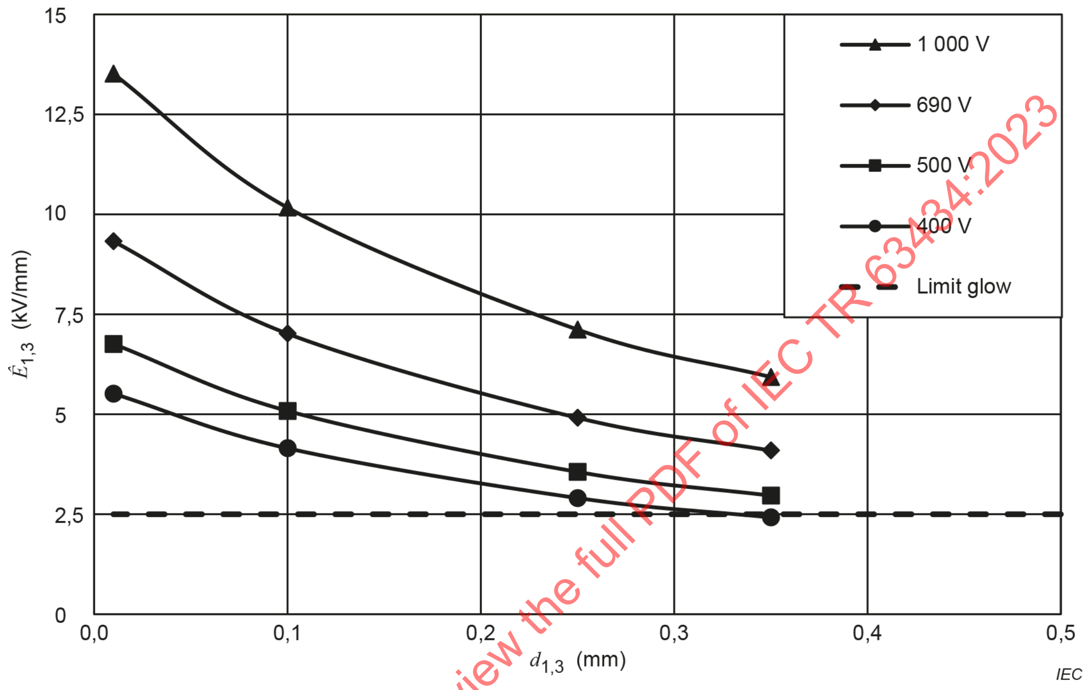


Figure 8 – Field strength in the air gap, inhomogeneous, η = 0,5, ε_{r2} = 12 at 130 °C operational temperature

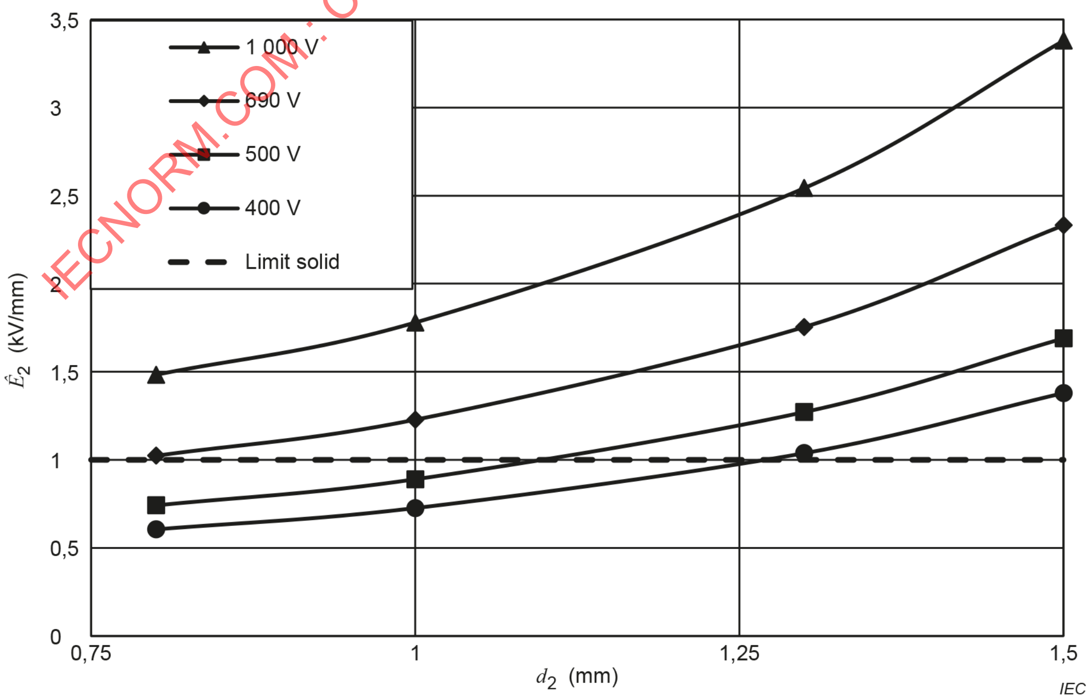


Figure 9 – Field strength in the solid insulation, inhomogeneous, η = 0,5, ε_{r2} = 12 operational temperature

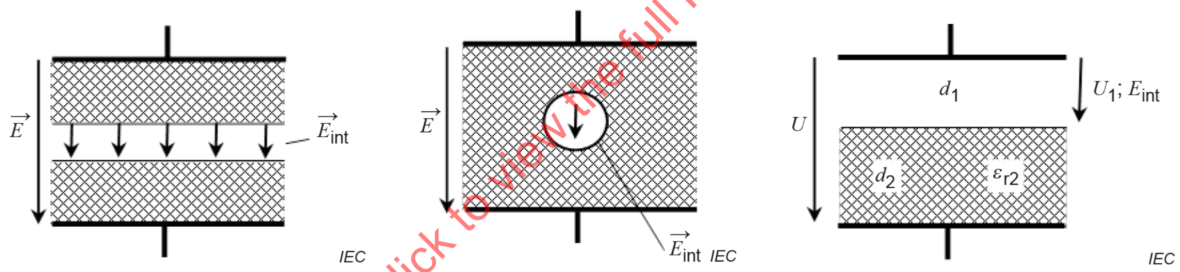
Figure 9 shows that as higher the operational voltage is, the larger the solid insulation is dimensioned, as a trend.

Figure 9 shows the field strength $\hat{E}_2$ in the solid insulation at operational temperature. An electrical field strength of 1 kV/mm peak can be reached for thicknesses below 1,25 mm for 400 V or below 1,1 mm up to 500 V. For higher voltages more detailed examinations are required, e.g. FEM-simulation of the electrical field strength and the material qualification for long term withstandability at the intended operational temperature. Thin insulation walls of e.g. 0,8 mm, as sometimes permitted by material ratings, however, need excellent injection mold quality as a precondition.

The examples illustrated in Figure 8 and Figure 9, with $d_{1,3}$ = 0,1 mm and d_2 = 1,3 mm, appear to be at or above the limits of the dimensioning criteria of IEC 60664-1[1] when operated with 700 V peak (500 V_{RMS}) or higher. As pointed out before the degree of homogeneity (utilization coefficient η) plays an important role in the result and can be influenced by design of electrode shapes and edge or corner sharpness and finally help to achieve the intended ratings under operational temperature as well.

4.2.2.5 Influence of gaps and voids in a solid or combined solid / gaseous insulation on partial discharge

In literature, the following examples are often referred to in order to describe partial discharges.



a) **Plane gap perpendicular to $\vec{E}$** b) **Sphere or perpendicular cylinder** c) **Plane adjacent gap**

Key

$\vec{E}$	applied external (leading) field strength	d_1	distance of the air gap
$\vec{E}_{int}$	resulting internal field strength in the void	d_2	thickness of the solid insulation
U	total voltage across the insulation	ε_{r2}	permittivity of the solid insulation
U_1	voltage across the air gap		

Figure 10 – Gaps and voids in a solid and combined solid / gaseous insulation [7]

In case of gaps and voids in the insulation walls the electrical stress and the probability of internal partial discharges would change with temperature per Equations (1) and (2) [7].

The electrical field strength $\vec{E}_{int}$ in gaps or in voids of a solid insulation depends on the local external field strength $\vec{E}$ and the relative permittivity ε_r of the surrounding material and can be calculated for different configurations [7], [9].

As per Equation (11), the plane gap within an insulation material (Figure 10 a)) gives the highest internal field strength $\vec{E}_{\text{int}}$.

$$E_{\text{int}} = \varepsilon_{\text{r}} \times E \tag{11}$$

The other shapes can be calculated as follows and give comparatively lower values:

– Perpendicular cylinder (Figure 10 b))

$$E_{\text{int}} = \frac{2\varepsilon_{\text{r}}}{1+\varepsilon_{\text{r}}} \times E \tag{12}$$

– Sphere (Figure 10 b))

$$E_{\text{int}} = \frac{3\varepsilon_{\text{r}}}{1+2\varepsilon_{\text{r}}} \times E \tag{13}$$

For the plane adjacent gap (Figure 10 c)) see Equation (5) to be used analogously for one gap only.

Based on ε_{r} = 4, the ranking of the internal field strength E_{int} in the differently shaped gaps is given in Table 2.

Table 2 – Ranking of the internal field strength of different gap and void shapes [7]

Shape	Plane gap (a)	Cylinder (b)	Sphere (b)	Plane adjacent gap (c)
E_{int} (%)	100	40	33	≲ 100 f (d_2, ε_{r2})

As per Equation (14)

$$\frac{E_{\text{int,130°C}}}{E_{\text{int,20°C}}} = \frac{\varepsilon_{\text{r130°C}}}{\varepsilon_{\text{r20°C}}} \tag{14}$$

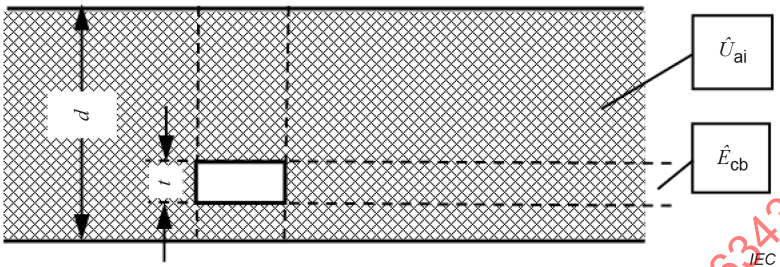
the field strength E_{int} across a gap within the solid insulation in high temperature condition (ε_{r} = 11) would be 2,75 times as high as compared to the cold state (ε_{r} = 4).

In the example b) of Figure 13 (sphere) using Equation (15)

$$\frac{E_{\text{int,130°C}}}{E_{\text{int,20°C}}} = \frac{\varepsilon_{\text{r130°C}}}{\varepsilon_{\text{r20°C}}} \times \frac{\left(1+2\varepsilon_{\text{r20°C}}\right)}{\left(1+2\varepsilon_{\text{r130°C}}\right)} \tag{15}$$

the internal field strength E_{int} then is 1,076 times the leading field strength E. Assuming that the breakdown field strength of the warm air in the void follows Equation (1), a temperature factor of 0,79 would apply. The internal electrical field strength level in the void would be raised to 163 %.

Examples a) and b) in Figure 10 are simple and independent of the solid insulation thickness. Another explanation of the PD inception in an enclosed cavity including an insulation wall thickness and the size of a void is given in Figure 11[20].



Key

$\hat{U}_{ai}$ voltage across insulation for inception in the void

$\hat{E}_{cb}$ breakdown strength of the void

d thickness of the solid insulation

t diameter of the void

ε_r permittivity of the solid insulation

Figure 11 – Model of a void of thickness t in an insulation wall of defined thickness d [20]

The corresponding equation for the voltage across the insulation at which PD inception in the void is reached is Equation (16):

$$\hat{U}_{ai} = \hat{E}_{cb} \times t \left[1 + \frac{1}{\varepsilon_r}\left(\frac{d}{t} - 1\right)\right] \tag{16}$$

As an example, with t = 0,1 mm, d = 1 mm, ε_r = 4 and $\hat{E}_{cb}$ = 8,6 kV/mm for air, $\hat{U}_{ai}$ results in 2,8 kV in cold state.

Assuming an operational temperature of 130 °C, ε_r = 15, a temperature coefficient of 0,77 as per Equation (1) and as per the examples in 4.2.2.3 $\hat{U}_{ai}$ results in only 1,06 kV.

This means that in case of a flashover (PD) in the air gaps next to the insulation wall, this value could be reached with the peak values of the operational voltage of 690 V_{RMS} (homogeneous field distribution).

Reduction of the relative permittivity to 8 leads to $\hat{U}_{ai}$ = 1,41 kV (homogeneous field distribution) but considering an inhomogeneous field distribution (with utilization coefficient e.g. of η = 0,5) a PD inception voltage of $\hat{U}_{ai}$ = 0,7 kV is reached.

Plane adjacent gap (Figure 10 c)) gives the internal field strength

$$E_{int} = \frac{1}{d_1 + \frac{d_2}{\varepsilon_{r2}}} . \qquad (17)$$

This shape is representative for the current paths of multipole switchgear and in that case additionally depends on the distance d_3 (Figure 12).

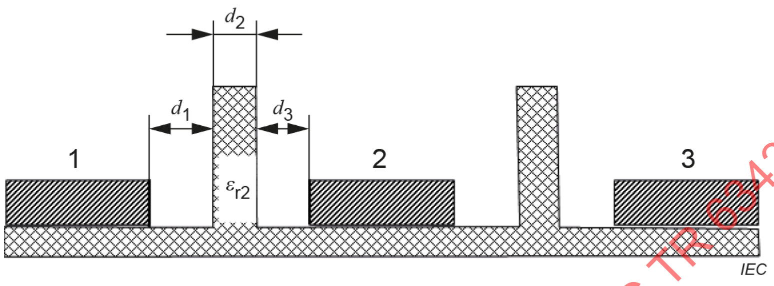


Figure 12 – Principle arrangement of electrodes and insulation walls of a 3-pole device

Depending on the combination of these parameters, the field strength in the air gaps can be either higher or lower compared to the shape of Figure 10 a)).

During temperature rise from cold state to operational temperature, the electrical stress across the air gaps rises whereas the internal electrical stress on the solid insulation diminishes, however, its electrical strength is also reduced.

Assuming that the field strength is sufficient to start partial discharges (especially in voids less than 1 mm), this can also be understood in the way that during heating up at first internal discharges within the solid insulation occur which then diminish with temperature rise (E-field in the air gap rises, while E-field in the solid insulation declines). The possible discharges in the air gaps increase with rising temperature and lead to erosions on the insulation wall from their surface.

In order to quantify the impact of the partial discharges the charge value in pC and the repetition rate (up to several 100 000 events / 60 s test period) of the occurring partial discharges can be measured and interpreted, compare Annex A (Figure A.1).

4.2.3 Series connection of clearances and solid insulation by design for DC voltage

Under consideration.

4.2.4 Solid insulation – dimensioning – material characteristics

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. In IEC 60664-4 [21] for thick layers of solid insulation of $d_1 \geq 0{,}75$ mm the peak value of the field strength E is 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 is equal or less than 10 kV/mm. For $d_1 > d > d_2$ Equation (18) is for interpolation for a certain thickness d (see also Figure 13):

$$E = \left(\frac{0{,}25}{d} + 1{,}667\right)\frac{\text{kV}}{\text{mm}} \tag{18}$$

It applies for a maximum fundamental frequency of the voltage of 10 MHz.

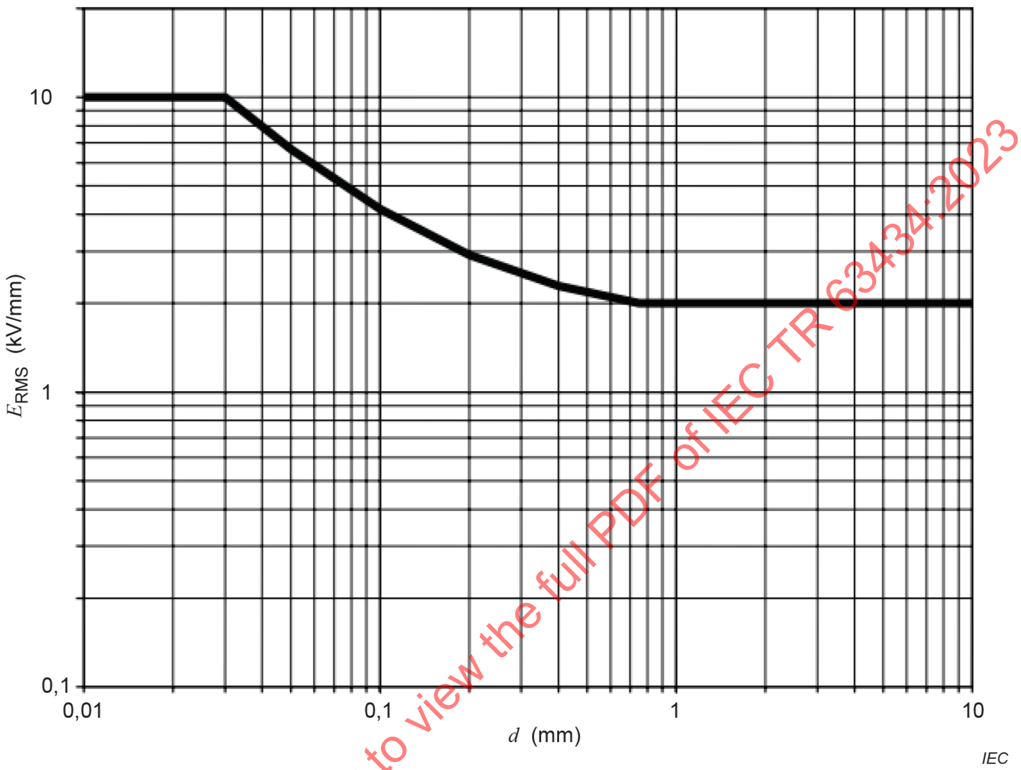


Figure 13 – Permissible field strength for dimensioning of solid insulation according to Equation (18)

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.

This approach differs from IEC 60664-1[1], as it shows permissible peak values of 2 kV/mm up to 10 kV/mm depending on the thickness of the solid insulation, instead of 1 kV/mm stated in IEC 60664-1[1] independent of the thickness. In addition, during real life applications it needs to be considered, that all stresses and their damaging effects that occur during the lifetime of the equipment are cumulative. Electrical, thermal [22] and also mechanical stresses are superimposed.

These stresses influence the occurrence of partial discharges and their damaging effect combined with dielectric heating cause a drastic reduction of the breakdown strength.

Annex C of IEC 60664-4:2005 shows some experimental results for such a behavior. In Figure 14 the dependency of the electrical field breakdown voltage (RMS) for different materials is shown. At 50 Hz, the breakdown voltage is at a very high level (approximately 10 kV/mm RMS). However, this changes with the influence of long-time storage under high humidity conditions (see Figure 15).

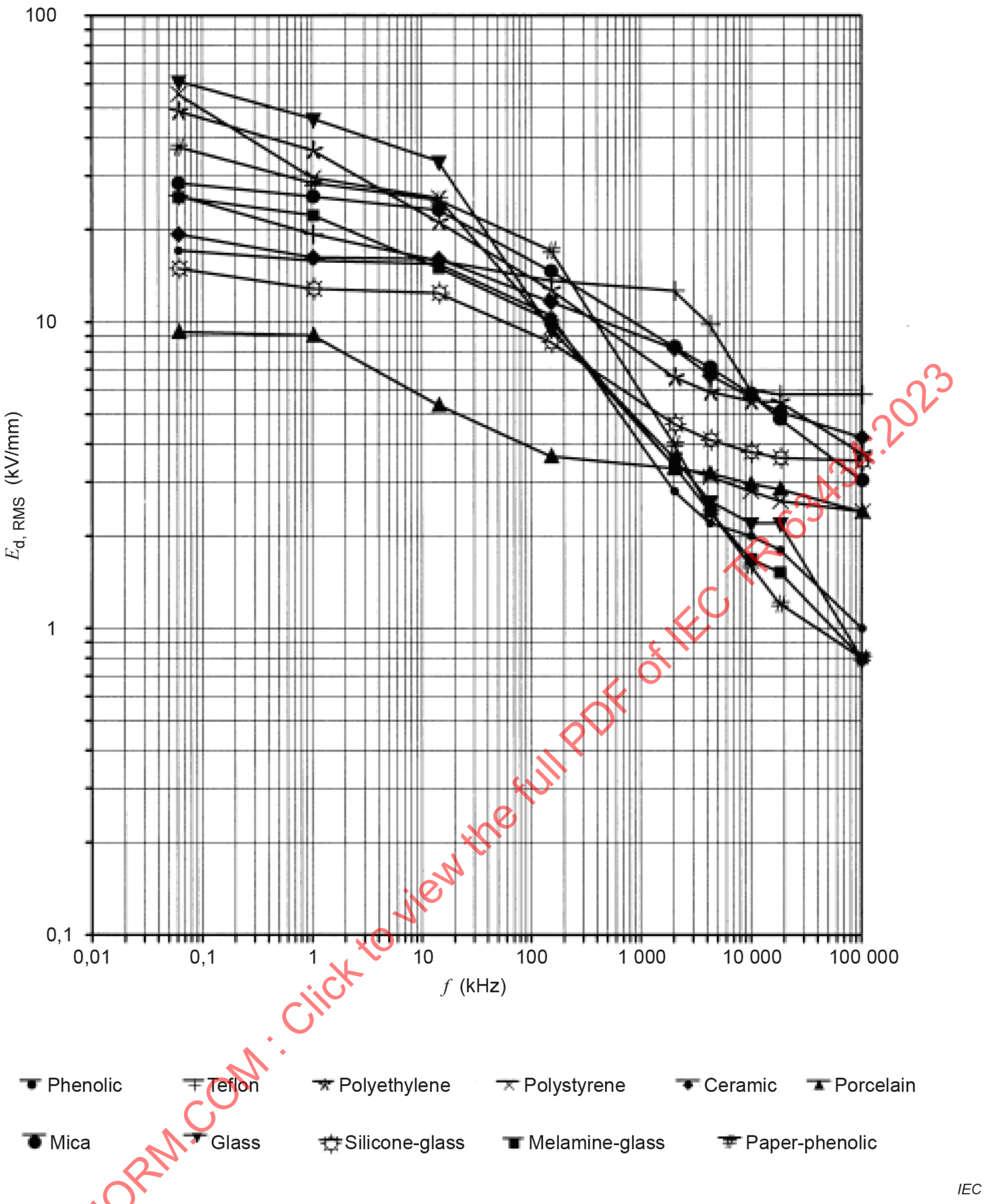


Figure 14 – Breakdown at high frequency, solid insulation; d = 0,75 mm [23]

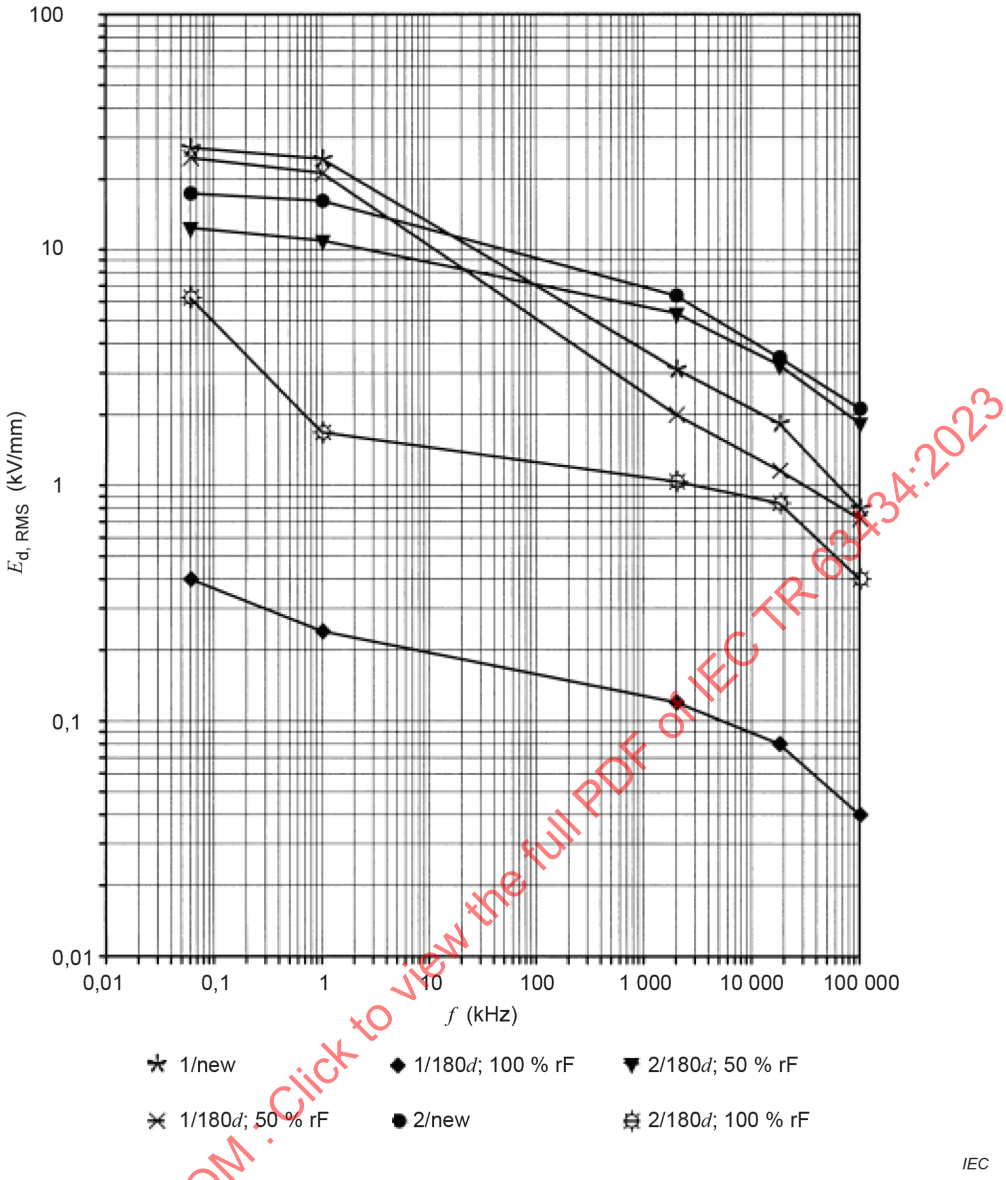
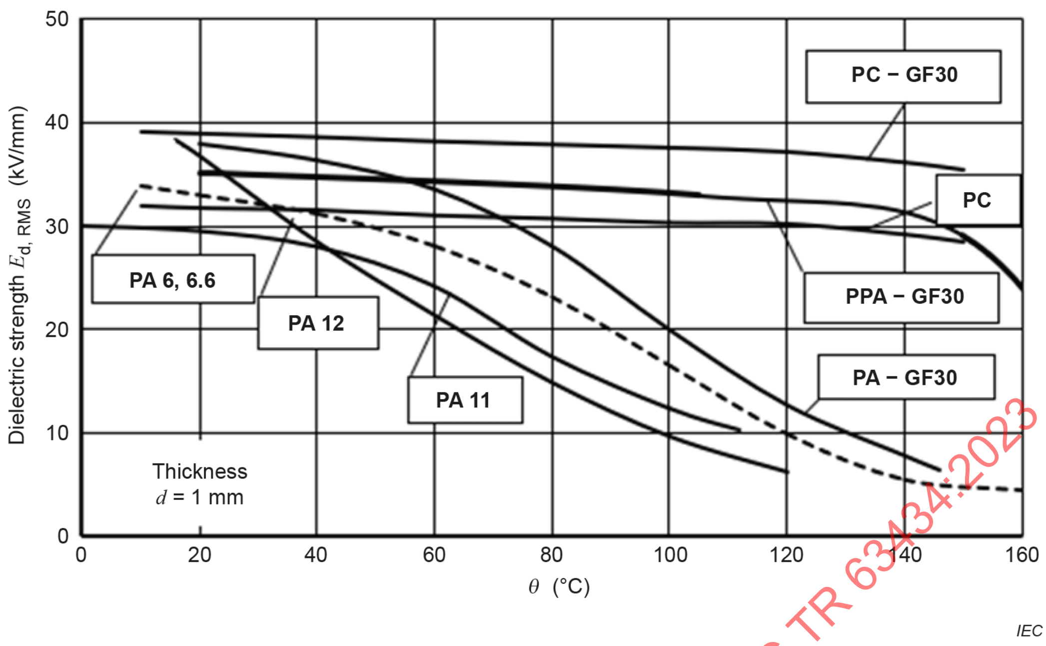


Figure 15 – Breakdown at high frequency, solid insulation, influence of humidity; conditioning at 50 °C; 1: mica-filled phenolic, d = 0,75 mm; 2: glass-silicone laminate, d = 1,5 mm [24]

Besides the frequency, temperature and humidity have a high impact on the breakdown voltage. Figures above refer to materials which are not state of the art. Figure 16 shows some examples of materials used today.

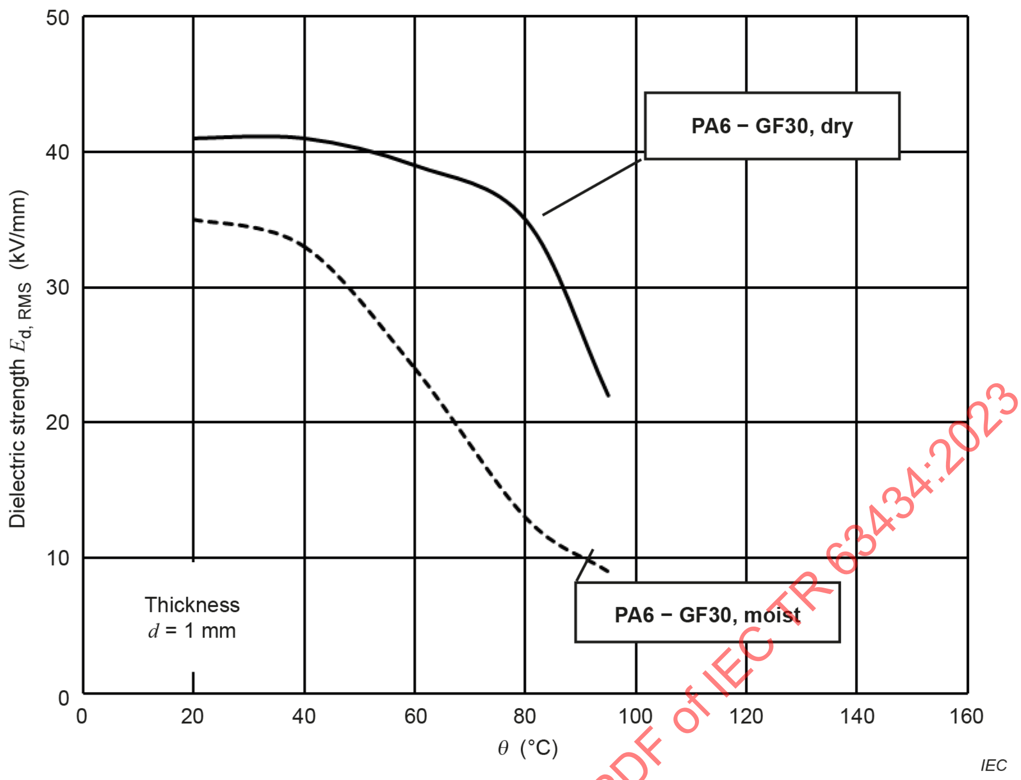


SOURCE: reproduced and published with the permission of the authors [25], [26].

Figure 16 – Dielectric strength $\hat{E}_d$ of different types of thermoplastic insulation material depending on the temperature

More modified and temperature stabilized materials based on PPA are offered [27]. One PPA-GF30 example is referenced in Figure 16 [25], [26].

It needs to be noted that humidity as well as thermal aging has a significant influence on the breakdown voltage. In addition, coloured materials can have lower dielectric strength compared to natural colour. As an example, the influence of humid vs. dry condition depending on the temperature is given in Figure 17.



SOURCE: BASF, published with the permission of the author [26].

Figure 17 – Dielectric strength $E_{d,RMS}$ of PA6-GF30 in dry and moist condition (equilibrium moisture content at 23 °C/50 % RH) depending on the temperature θ (°C)

Furthermore, the dielectric strength of inappropriate thermoplastic materials can be considerably reduced within a timeframe of only several thousand hours under thermal aging conditions especially with relatively high temperature [28], [29].

The above examples show that the electrical field breakdown voltage depends highly on the material used, the inhomogeneity of the electrical field and the application of the product.

5 Application rules

5.1 General

Partial discharge events can be internal or external. To avoid external partial discharges in air, the local field strength in air can be limited to a value below the air ionization threshold of 2,5 kV/mm. The evaluation (effect) of the local electrical field needs to consider material capabilities e.g. relative permittivity, breakdown electric strength for the intended operating temperature and humidity.

The local electrical field should be considered

- at the highest steady-state voltage;
- at the long-term temporary overvoltage;
- the working voltage,
- as well as at the recurring peak voltage.

5.2 Partial discharge considerations

Partial discharge does not to be considered when the following applications and design parameters apply:

– The highest steady-state voltage, the long-term temporary overvoltage, the working voltage, as well as at the recurring peak voltage does not exceed 700 V_{peak} equivalent to 500 V_{RMS} and

– the clearances given in Table F.9 of IEC 60664-1:2020[1] are maintained, and

– the local electrical field strength in air does not exceed 2,5 kV/mm, and

– the suitability of the insulating material in regard to electric strength e.g. as given in IEC 62631 series [32].

The resulting impulse withstand voltage U_{imp} according to the overvoltage category only considers transient overvoltages and not recurring peak voltages, steady state withstand voltages and temporary overvoltages which according to IEC 60664-1[1] require larger clearances. Therefore, even when the above criteria are met, detailed considerations can be required for specific design or application aspects e.g.:

- to ensure safety and to avoid functional distortions, it is essential to select qualified material and manufacturing process for all SELV/PELV related circuits;
- for some built-in components, e.g. power supply transformers or current transformers, specific PD requirements and limits need to be followed.

5.3 Measures to prevent/reduce the probability of partial discharges

Several measures are available to prevent or reduce partial discharge events, depending on their origin. In most cases, changing the design can help prevent the formation of locally higher electric fields, which are the primary cause of partial discharge [31].

The following application rules help to prevent/reduce the probability of partial discharges:

- rounding sharp tips and edges (field homogenization) to prevent the concentration of field lines (see 4.1.3). There is a progressive rise of the field strength once the edge radius is lower than 0,1 mm [11] (see Figure 2 and Figure 3);
- prevent contamination (conductive deposits, entrapped air or moisture) of insulation material (excellent injection molding quality);
- increase clearance and creepage distances to reduce the field strength;
- increase the thickness of the insulation;
- avoid large difference of ε_r when using more than one dielectric;
- use material with RTI / CTI suitable for the temperature to which the component is continuously exposed;
- prevent deposits from operation (arcing, sliding contacts);
- use insulating material with higher insulation rating (higher thermal stability);
- observe the minimum permissible bending radii of conductors in regard to the stress on the insulation material and/or field strength (e.g. see DIN VDE 0298-3, [33]);
- thorough potting (free of voids or bubbles);
- using coats of PD-resistant insulating varnish on PCBs;
- determining air gaps and creepage distances based on the application area (height above mean sea level (AMSL));
- reduce external voltage distortions (rise time of switch mode supplies).

Conclusions from research are described in Annex A.

Annex A
(informative)

Research on partial discharge in low-voltage switchgear and controlgear

A.1 General

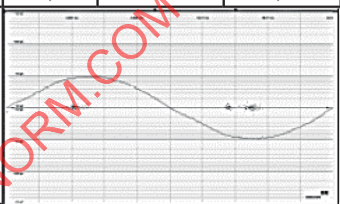
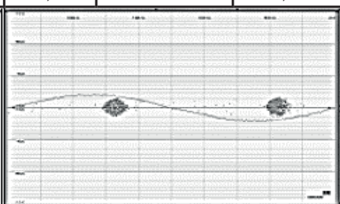
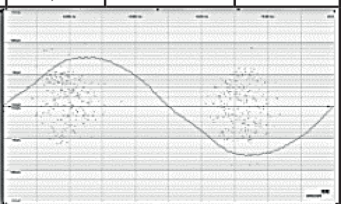
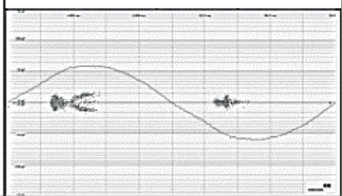
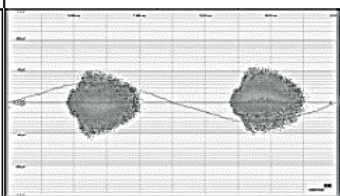
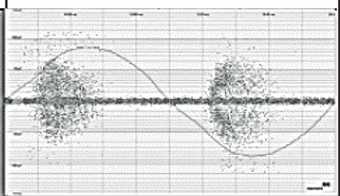
Different types of switchgear are not susceptible to PD in the same degree. Those without additional thermally active parts (e.g. bimetal trip units, fuse-links etc.) run rather cool and are less affected except in higher ambient temperatures. Those with thermally active parts run rather hot and are more susceptible.

A.2 Investigations on switchgear

Generally (gap) dimensions in the mm-range are typical for low voltage switchgear and devices. With regard e.g. to manual motor starters (MPSD) it had been found that due to sharp edged (punched) electrodes homogeneity degrees of η = 0,5 and below can easily be found [28]. This corresponds to edge radii of 0,1 mm or less. Maximum field strengths reported there reached or exceeded the value of 2,5 kV/mm (related to operational voltage of 690 V_{RMS}).

Test methods like phase-resolved measurement of partial discharges produce typical patterns which can be interpreted accordingly [9]. The PD measurement device records the number and value of the discharges, the graph displays the events related to the AC voltage trace [18].

As an example, typical phase-resolved test records of a motor protection switching device (MPSD) with thermos-bimetal trip units, rated 690 V AC, is given in Figure A.1 below [15]. Three measurements were done in sequence following the IEC 60270 [2] procedure in principle: At room temperature (RT), operational temperature (130 °C) and again room temperature.

Temperature	RT 20 °C			130 °C			RT 20 °C		
Sample C Rating 690 V	U [kV]	$n_{discharges}$	q_a [pC]	U [kV]	$n_{discharges}$	q_a [pC]	U [kV]	$n_{discharges}$	q_a [pC]
	0,7	none	no PD	-	-	-	0,7	none	no PD
U_i [kV]	0,9	226	1,7	0,4	4 173	2,1	1,4	584	90
									
U_n [kV]	1,1	3 242	2,5	0,6	231 290	18	1,6	27 166	200
									
U_e [kV]	0,7	none	no PD	0,4	none	no PD	1,3	none	no PD

IEC

SOURCE: Reproduced and published with the permission of the authors [15].

Figure A.1 – Example of phase resolved partial discharge measurement on a MPSD at room temperature and at elevated operational temperatures

The test procedure for voltage application is given in Figure A.2:

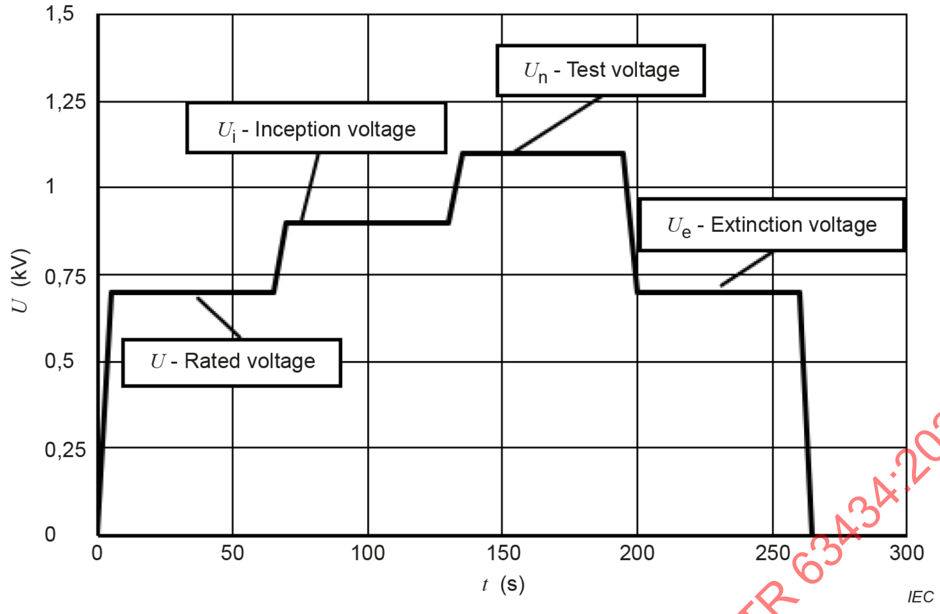


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Figure A.2 – PD Testing (690 V, basic insulation, 20°C)

The values given in Table A.1 and Table A.2 apply as per Figure A.1:

Table A.1 – Inception U_i and extinction U_e voltage depending on the temperature as per Figure A.1 and Figure A.2

Temperature	θ	20	130	20	°C
Initial voltage	U	0,7	0,4	0,7	kV
Inception voltage	U_i	0,9	0,4	1,4	
Test voltage	U_n	1,1	0,6	1,6	
Extinction voltage	U_e	0,7	0,4	1,3	
Max. apparent discharge at U_n	q_a	2,5	18	200	pC
Number of discharge events	n	3 242	231 290	27 166	-

Table A.2 – Maximum discharge values and number of events observed at the test voltage as per Figure A.1 and Figure A.2

Temperature	θ	20	130	20	°C
Test voltage	U_n	1,1	0,6	1,6	kV
Maximum value of apparent discharge	q_a	0,7	0,4	0,7	pC
Number of discharge events	n	0,9	0,4	1,4	-

The final valuation of these measurement results requires the specification of the insulation level to be achieved, e.g. basic insulation. With application of the correction factors described in Annex B at least at room temperature the inception voltage of 1 139 V and the extinction voltage of 911 V needs to be reached. As the extinction voltage was only about 700 V this sample would be suitable for a 500 V rating only (see Table B.1).

At operational temperature the extinction voltage is way too low even for that. In addition, the discharge values and also the number of events increase considerably with temperature. After cooling down voltages and discharge level raised again, this effect is reported as well in literature.

Investigations on different designs of motor protection switching devices (MPSD) as per IEC 60947-4-1, rated currents of 2,5 A to 25 A, maximum rated voltage 690 V, have been carried out at both room temperature (20 °C) and maximum operational temperature of the bimetal trip units (130 °C) [15].

Although the investigated devices are of similar design some types operate at slightly lower temperatures. For comparison all were tested at elevated temperature of 130 °C. Samples C and E were additionally tested at 100 °C.

At room temperature the inception voltage of all samples was higher than the maximum voltage rating of 690 V (U_i = 0,9 kV to 1,9 kV), the extinction voltage was higher or equal to the maximum voltage rating (U_e = 0,7 kV to 1,7 kV). No partial discharges were recorded under these conditions. So all types had passed the requirements of the existing document requirements.

The test results at elevated temperatures are summarized in Figure A.3. At 130 °C the range of inception voltage is U_i = 0,4 kV to 0,6 kV that of the extinction voltage is U_e = 0,3 kV to 0,5 kV. When tested at 100 °C ambient temperature the samples C and E achieved a 200 V higher inception voltage and 100 V higher extinction voltage but still not enough for a 690 V rating.

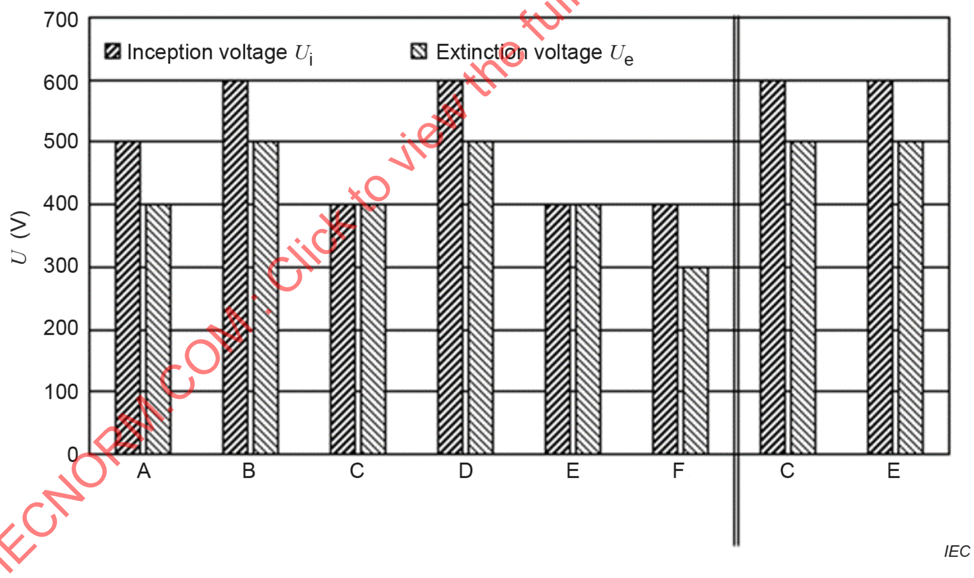

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Figure A.3 – Inception (U_i) and extinction (U_e) voltage during partial discharge measurements on motor protection switching devices (MPSD) at elevated temperatures

At 130 °C the ratio between extinction and inception voltage is between 1 and 0,75, at 100 °C it is 0,83. Literature [8] states that the extinction voltage is typically 10 % to 35 % lower than the inception voltage. In this case the deviation observed is up to 25 % accordingly.