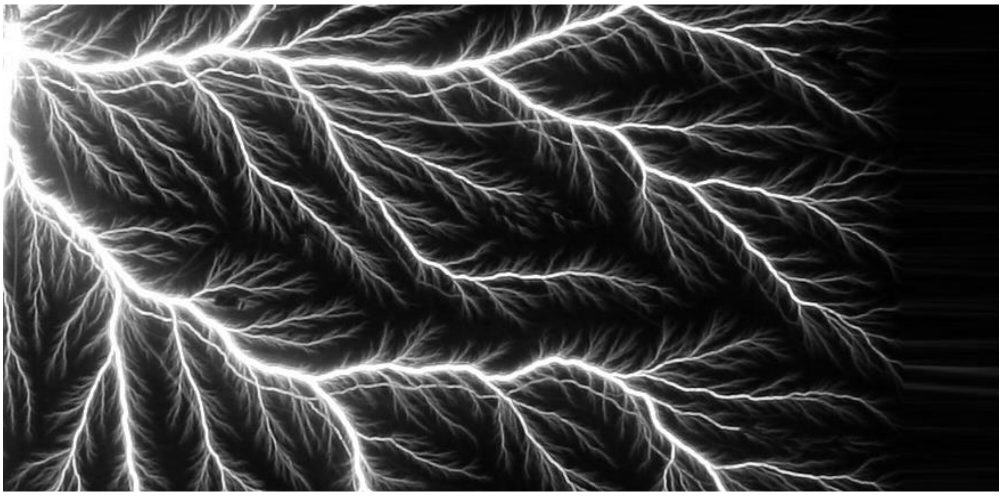
Guideline

Measurement and diagnosis of partial discharges in low voltage applications ≤ 1000 volts



Electrical Winding & Insulation Systems Division

Legal notice

Measurement and diagnosis of
partial discharges in
low voltage applications ≤ 1000 volts

Published by:
ZVEI - German Electrical and
Electronic Manufacturers' Association
Electrical Winding & Insulation Systems Division
Lyoner Str. 9
60528 Frankfurt am Main, Germany

Responsible:
Dr.-Ing. Rolf Winter

Phone: +49 69 6302-402
Fax: +49 69 6302-407
Email: winter@zvei.org
www.zvei.org/ewis

Authors:
Aumann, Sebastian – Isovolta
Becker, Stefan – Sekels
Berton, Dr. Farhad – Vacuumschmelze
Friederici, Gerald – CMC Klebetechnik
Gauer, Dr. Mario – Ephy-Mess
Jovalekic, Mark – Pucaro Elektro-Isolierstoffe
Kohlhof, Jens – Ephy-Mess
Kübler, Frank – Krempel
Radbruch, Jens – TMC Sensortechnik
Winter, Dr.-Ing. Rolf – ZVEI

January 2017

Contents:

1. Introduction

Developing highly powerful electrical components and equipment in increasingly compact designs always involves improving the properties of insulation systems, especially with regard to electrical, thermal, chemical and mechanical stress. Insulating materials used in electrical components and equipment come in a wide variety of forms and can be a solid, a liquid or a gas depending on the relevant application. Solid insulating materials include organic and inorganic materials as well as plastic materials (e.g. polymers). Mineral-filled and glass-fiber reinforced plastics are classified as compound or composite materials and are made from two or more constituent materials: matrix-forming organic polymers and inorganic fillers or reinforcing materials.

Energy efficiency requirements for electrical equipment and the speed control of electric drives increasingly calls for the use of switch power supplies and frequency converters. The enameled wire insulation of asynchronous motors is stress-tested with double DC-link voltage. One of the causes of damaging voltage overshoot is the superposition of the reflected voltage wave with the supply voltage due to the impedance difference between cable and machine. The square-wave operating voltage with high switching rates creates high peak levels and steep rising edges (du/dt), which together can trigger partial discharges and accelerated ageing of insulation systems.

The measurement and diagnosis of partial discharging also plays an increasingly important role in routine and type testing, as well as in assessing the lifespan of insulation systems, when monitoring product quality during production [1-4]. Rising demands placed on solid insulation systems for compact electronic and electrical components or operating equipment with higher switching frequencies of semiconductors (IGBT, silicon carbide (SiC) or gallium nitride (GaN) power MOSFET) require the use of insulation materials or composite materials that are partial-discharge-free or resistant to partial discharge. This is particularly true for electrical components in speed-adjustable drives for trains, electric vehicles or energy technology applications, e.g. solar farms and especially offshore wind farms.

This guide offers an initial insight into this complex subject matter.

2. Definition of partial discharging

DIN EN 60270 and VDE 0434 define partial discharge (PD) in section 3.1 as follows: “Localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor” [1].

Short-time PD measurements can be used as non-destructive testing methods for controlling the quality of insulation systems in electronic and electrical components.

Partial discharges may also occur in low voltage applications (transformers, electric motors, sensors, voltage converters and current transformers). These are mainly internal partial discharges (gas discharges inside solid insulating materials) that accelerate ageing as a result of the continuous disintegration of the insulating material, thereby weakening the insulation system or even causing it to fail.

The following three conditions must be fulfilled for generating partial discharges:

- sufficiently high electrical field strength to produce ionization
- availability of a start electron
- feedback mechanism that maintains the avalanche effect

Partial discharge is a physical value that can be measured with different methods as described below:

- traditional electrical PD measurement according to EN 60270, measurement within the frequency range
- analysis of PD peak value, time-domain integration
- waveform analysis of pulse response in impulse voltage tests
- UHF electromagnetic wave detection
- acoustic PD detection
- radio interference method (outdated)
- measurements with ultrasonic sensors

The traditional PD measurement method as specified in EN 60270 is generally used for the applications referred to in this guide. UHF wave detection is preferably used for state monitoring and localizing PD events in gas-insulated switchgears, large transformers and generators. It is not yet suitable for acceptance and PD testing of components and motors in the low voltage range.

3. What types of partial discharge events exist?

Partial discharge events are classified into two main groups:

1) External and surface partial discharges

External and surface discharges include corona, glow and sliding discharges, pulse-free partial discharges, Trichel pulses to electrodes with sufficiently high curvature radius, both in gases as well as on the surface of solid dielectrics. Although external partial discharges can occur in the insulation systems of low voltage applications, for design reasons they are rather rare.

2) Internal partial discharges

Internal partial discharges are cavity discharges or gas discharges that occur in solid and/or liquid dielectrics. In most cases, the insulation system of electrical devices consists of several dielectric substances. This is why it is necessary to increase the field strength in the insulating material with low dielectric constant (also referred to as “field displacement”) when determining/dimensioning the insulation system [2].

Partial discharges occurring in electrical equipment are usually a combination of different discharge types. It is possible to simulate the individual PD types with different experimental setups in order to analyze and understand their effects. This helps detect and assign real error patterns to the relevant causes.

These experimental setups are:

i) needle-to-plate (corona discharge)
ii) needle-dielectric-plate (surface discharge)
iii) cavity
  a) in a dielectric material
  b) adjacent to an electrode
iv) needle in solid dielectric (electrical tree discharge) [7]

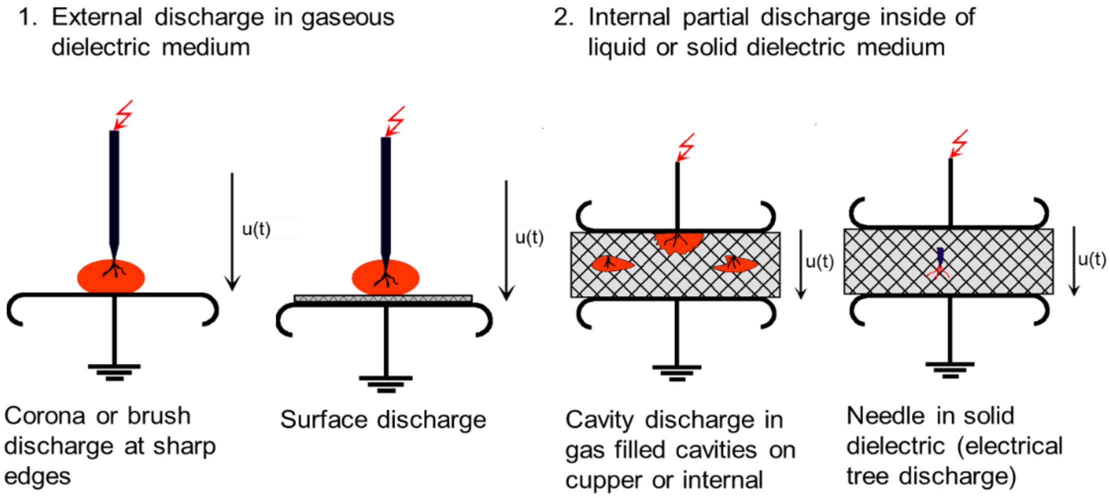


Figure 1: Setups to simulate external and internal partial discharges [4]

4. What measurement parameter is used for PD tests?

The apparent charge ($q_a = i_{TE\_s}(t)*dt$) of PD pulses has become internationally accepted for measuring partial discharges. According to EN 60270, it is defined in essence as: The charge that, if injected within a very short time between the terminals of the test object, would change the voltage across the terminals by an amount equivalent to the PD event [1].

Besides the apparent charge, the partial discharge **I**nception voltage U_i and partial discharge **E**xtinction voltage U_e are also important for analyzing the PD measurement. Partial discharge inception voltage U_i is the lowest voltage at which partial discharges occur in a test circuit when the test voltage is gradually increased from a lower value. Partial discharge extinction voltage U_e is the voltage at which repetitive partial discharges cease to occur when the test voltage is gradually decreased from a value higher than the inception voltage.

In practice, the PD level is determined according to the individual application. In other words: When increasing the voltage, the voltage reaching this PD level first is referred to as PD inception voltage U_{PDIV} (or U_i). The voltage level at which the PD activity stops (e.g. PD level < 10pC) is called PD extinction voltage U_{PDEV} (or U_e) [1].

Discourse on the test setup and execution of PD measurements:

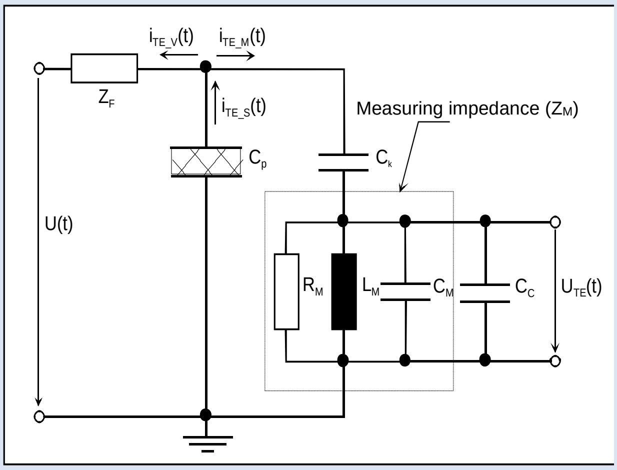


Figure 2: Simplified schematic of a PD measuring circuit with $R_M L_M C_M$ measuring impedance.

Figure 2 shows a simplified diagram of a PD measuring circuit where the measuring impedance Z_M consists of an $R_M L_M C_M$ circuit connected in parallel. The purpose of the measuring impedance is to decouple the high-frequency PD pulses superimposing the test voltage from the high-voltage test circuit and feed them to the PD measuring device. The test voltage is U(t), the impedance of the high-voltage filter is Z_F, the capacitance of the test is C_p, the coupling capacitance is C_k, the capacitance of the measuring cable is C_c and the measuring impedance of the four-terminal coupling circuit is Z_M. The high-voltage filter Z_F reduces background noise from high-voltage supply. The test object is shown as the capacitor C_p to simplify matters. The PD pulses are transferred from C_p via the coupling capacitor C_k to the measuring impedance Z_M [7]. Ignoring the influence of parasitic capacitance and ground capacitance, the apparent PD pulsed current $i_{TE\_s}(t)$ splits into two components.

The first component is the PD pulse current $i_{TE\_M}(t)$ flowing out through the measuring impedance that can be actually measured and the second component is the leakage current $i_{TE\_V}(t)$ flowing out through the impedance Z_f. Since the measuring cable is not usually fitted with a surge arrester, the capacitance of the measuring cable C_C must be taken into account when determining the transfer function. With regard to the actually measurable PD pulse current $i_{TE\_M}(t)$, the capacitance C_k and C_p forming the equivalent capacitance C_R are connected in series. The equivalent capacitance is connected in parallel to the measuring capacitance C_M and cable capacitance C_C.

5. How can PD measurements be interpreted?

Performing PD measurements and interpreting the test results requires sound knowledge of PD test technology. Even ambient temperature and relative humidity significantly influence the results.

The measured amplitude of a PD signal plays only a minor role in the fault diagnosis. Key parameters include phase angle, polarity, pulse frequency and regularity of the discharge pattern, voltage or time difference between two successive partial discharges, intensity changes associated with voltage changes and the relationship between PD inception and PD extinction voltage.

There are several approaches to interpreting partial discharges [3]. The following methods are frequently used:

- traditional physical approach (physical processes at the point of discharge) *Note: Appendix 3 provides examples of sine wave phase diagrams and their relevant interpretation*
- statistical approach (distribution function)
- neural networks (correlation between discharge parameters and error types using neural networks)
- analysis of PD pulse shape (time resolved analysis)
- expert systems for PD analysis, different approaches (fuzzy logic)

Measuring partial discharges is particularly important in type and routine tests of electrical equipment. The standard EN 61800-5-1:2008, for instance, specifies requirements for drive systems and their components with respect to electrical, thermal and energy safety considerations. It places special focus on insulation systems, air gaps and creepage distance and the relevant test and validation conditions.

Partial discharge measurements are rated as one of the key tests to ensure product quality.

EN 61800-5-1:2008 and EN 60664-1:2008 basically define the performance and evaluation of partial discharge tests for double or reinforced insulation as follows: The AC test voltage is increased from zero to a voltage value of $1.875*U_{PD}$ (applies to reinforced insulation) and held there for a maximum time of 5 s. The AC test voltage is then decreased to $1.5*U_{PD}$ and held at this level for a maximum time of 15s. The test object is considered to have passed the PD test if the mean value of the PD level is less than 10 pC during these 15 s. The voltage U_{PD} is the maximum recurring voltage peak occurring in the operating equipment.

According to EN 61800:5-1:2008, partial discharge testing is required for double and reinforced insulation if the recurring peak working voltage across the insulation is greater than 750 V and the voltage stress on the insulation is greater than 1 kV/mm.

In addition to test conditions for reinforced insulation, EN 60664-1:2008 also provides information on differing test conditions for basic insulation.

Important note on embedded sensors in insulation systems:

The insulation system of integrated components such as temperature sensors or bimetallic switches must also be free of partial discharge. However, the internal design of these components can falsify the results of the PD measurement. If such an electrical component is fitted with a potential-free metal housing to ensure pressure resistance and protect the sensitive sensor, electrical discharges may occur between the potential-free housing and electrical connection when performing tests inside the housing.

These discharges in air gaps do not damage the insulation system; they superimpose the PD test values and lead to a higher PD level. However, they falsify the measurement since they are no indication of the partial discharge resistance of the insulation system. In this case, additional comparative measurements must be performed using a potential-free sensor to avoid misinterpretation.

6. What are the causes of partial discharges?

Partial discharges occur when the breakdown field strength of the dielectric is locally exceeded due to varying local field intensity or varying local voltage resistance, resulting in the partial breakdown of the insulation system. To start partial discharging, the voltage must lie above the level of the relevant PD inception voltage (U_{PDIV}).

Since applications usually use a combination of insulating materials with different dielectric constants, there is not normally a homogenous field of distribution.
Causes of partial discharges include the presence of voids (cavities) in insulation systems, the ageing of the insulation system or significant electrical field inhomogeneities due to the system configuration. In addition to poor impregnation, cavities may form due to improperly degassed impregnating or cast resin insulation, or due to side reactions occurring in the presence of moisture. Mechanical tension or brittleness can promote detachment of the insulation from the wire and also lead to insufficient adhesion [2].

Contamination of any kind, introduced either during production or during field operation, may also result in partial discharges. Such contamination incidents can be associated with conductive particles such as carbon particles, dust and salt deposits (offshore) that form conductive coatings, especially when combined with moisture. This can then lead to partial discharges and, at worst, even to electrical breakdown.

Voltage pulses produced by a converter are another source of partial discharge. These can run as travelling waves through the cables connecting the converter and motor. Since they are reflected from the motor winding, voltage overshoots, e.g. at the motor terminals, can occur subject to the cable length.

7. PD and secondary factors influencing insulation system life

Secondary factors have a significant impact on accelerated ageing caused by partial discharges:

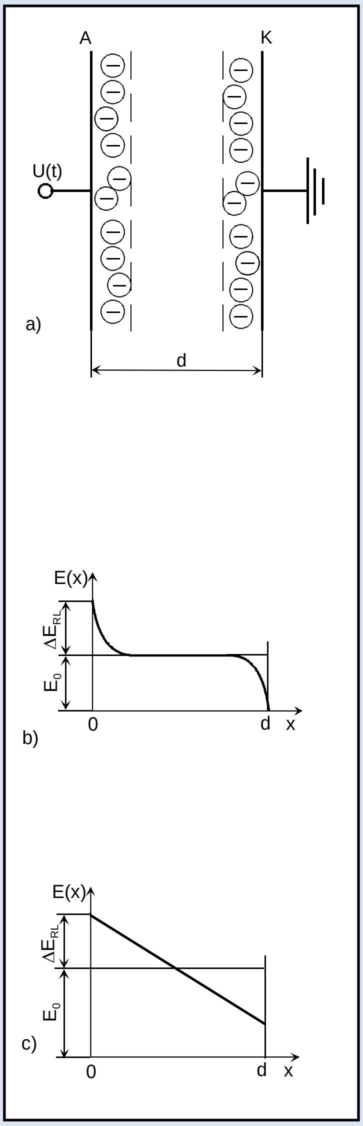
- voltage overshoots (spikes, reflections, etc.)
- ambient temperature
- Voltage gradient du/dt
- switching frequency of voltage
- moisture
- tracking
- UV stress due to PD
- ozone formation due to PD

In the presence of partial discharges, temperature increases have a catalyzing impact and accelerate ageing (e.g. brittleness) of the insulation system, leading to the premature failure of the operating equipment. Practical experience has shown that increasing the temperature by 10 K will halve the life of the insulation system (e.g. of film capacitors). By contrast, it is not always possible to double the life by reducing the operating temperature by 10 K due to several other influencing factors. The ageing of the insulating material is accompanied by decreasing dielectric strength. At worst, it may fall as low as the PD inception voltage limit, leading to continuous partial discharges and thus the failure of the insulation system.

In addition to the primary electrical requirements, the influence of environmental conditions on insulation performance must also be considered when developing a device. The principles of insulation coordination for operating equipment in low voltage systems are specified in EN 60664-1.

Discourse: Role of space charges in PD processes

When applying DC voltage and exceeding specific field strengths, electrons from the cathode are injected into and trapped in the insulating material (especially in solid and liquid insulating materials) in the negative voltage half-wave. In the positive half-wave, part of the injected and trapped electrons is freed and drifts back to the electrode. The other part remains in the dielectric. This results in the accumulation of fixed negative space charges before the electrodes. When applying DC voltage, the presence of space charges always has a cumulative impact on the field strength since in one of the two half-waves of the load voltage, the field strength $\Delta E_{RL}(t)$ *caused by the space charges has the same polarity as the local field strength* $E_0(t)$ *caused by the external voltage. As a result, the field strength* $E(t)$ *increases near electrodes. Figure 3a) shows the simplified model of a parallel-plate capacitor with space charge build-up on both sides that has a density of* $(-\rho)$*. Figure 3b) and 3c) show the field strength curves after short and long load periods, assuming that a long load period will result in homogenous space charge distribution [4].*



$$E(t) = E_0(t) \pm \Delta E_{RL}(t)$$

The field strength ΔE_{RL} *produced by space charges can be calculated for simple geometric setups using Poisson's equation.*

$$\Delta\Phi = -\frac{\rho}{\varepsilon_0\varepsilon_r}$$

The electrical field strength is obtained from

$$E = -\mathrm{grad}\Phi$$

For a parallel-plate capacitor setup, the equation for a space-dependence specified in x-direction reads as

$$\frac{d^2\Phi}{dx^2} = -\frac{\rho}{\varepsilon_0\varepsilon_r}$$

and for the electrical field strength as

$$E(x) = -\frac{d\Phi}{dx}$$

Solving this differential equation for a space-dependent homogeneous space charge yields a field strength of

$$E(x) = \frac{U}{d} + \frac{\rho}{\varepsilon_0\varepsilon_r}\left(\frac{d}{2} - x\right)$$

Figure 3: a) Parallel-plate capacitor with negative space charges at the electrodes

b) Field strength after short load period

c) Field strength after sufficiently long load period (and homogeneous space charge)

8. How can partial discharges be prevented?

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 PD. The following measures have proved to be useful:

- Preventing decontamination of insulation material during production (conductive deposits, swarf, entrapped air or moisture)
- Rounding sharp tips and edges (field homogenization) to prevent the concentration of field lines
- Observing the minimum permissible bending radii of wires
- Optimizing the winding head shape (higher filling level without damaging the wires by pressure or wire tension)
- Increasing air gaps and creepage distances (e.g. in the event of sliding discharges) to reduce the field strength (voltage drop per distance)
- Thorough potting (free of voids or bubbles, e.g. under vacuum and by using inert gas, pipette filling from bottom to top, ascending potting compound)
- Increasing the insulation layer thickness
- Avoiding large ε_r jumps when using two dielectrics
- Using materials that have a higher creepage current resistance (higher CTI value) or that are less prone to damage from partial discharge (e.g. mica)
- Field control by using partially conductive coatings (e.g. semi-conductive surface insulating materials, paints acting as voltage controlled resistor VCR)
- Preventing deposits from brush arcing/sliding contacts
- Using coats of PD-resistant insulating varnish on PCBs
- Determining air gaps and creepage distances based on the application area (height AMSL) (see Appendix 1)

Appropriate measures in the design of circuits (controlling power semiconductors, using line filters) can help prevent PD in component parts. Special high-frequency filters can dampen electrical power interferences (surge voltage caused by non-galvanic, inductive coupling in control lines) and harmonics.

9. Practical example illustrating the complexity of PD measurements

Partial discharge testing is often part of the final acceptance process of electrical machines.

For instance, with an electrical machine which is operated with a temperature sensor (Pt100) that is connected to its evaluation electronics, the electronics are usually connected to ground. This ground connection can be responsible for the production of PD pulses during operation, e.g. via the insulation of the connecting wire. It is therefore recommended to perform final acceptance tests of electrical machines with integrated sensors as described below:

a) All poles of the sensor must be connected to the test voltage/ground potential during PD testing. The partial discharge to the motor ground created by the sensor is thus also recorded. It must also be ensured that the test voltage does not exceed the dielectric strength of the sensor.
b) Since the PD level of the sensor superimposes that of the machine, it is essential to first determine the PD level of the individual sensor to enable proper analysis of the test results.
c) By contrast, in the event of surge voltage testing (to be performed before PD measurements according to standard recommendations), the voltage levels occurring during the test would inevitably destroy the insulation of the sensor, if the sensor was incorrectly connected. It is essential that all poles of the sensor are galvanically isolated to ensure it has no electrical impact on the measurement.

When potting a winding with integrated sensors, care must be taken to ensure that cavities caused by protective sleeves or other additional sensor insulation are also potted (see also Appendix 2).

10. Summary / conclusion

In addition to defining partial discharge, this guide provides descriptions of the different types of partial discharge. It explains the role of apparent charge as a PD measurement parameter, PD inception and extinction voltage, and the influence of space charge on partial discharges. Partial discharge measurements and the interpretation of test results based on PD examples for common types of voids are discussed and best practices presented to prevent partial discharge in insulation systems.

Partial discharge has multiple causes that can significantly vary depending on the design of the insulation system within an electrical device. In the long term, partial discharges can result in the premature failure of the insulation system and hence device. Its main causes include “voltage levels”, environmental conditions and many other factors.

Given the complexity of this topic, it is difficult to make general recommendations about the prevention of partial discharge in low-voltage appliances. However, the basic aspects presented above can help develop new devices that are specifically designed to be free from partial discharge. Furthermore, where partial discharge cannot be avoided, appropriate engineering and design measures can ensure that devices enjoy a longer lifespan.

The companies of the EWIS Division will be happy to answer any additional question and assist you with the implementation of your next topic.

11. References

[1] IEC 60270, VDE standard 0434:2001-08: High-voltage test techniques, partial discharge measurements. VDE-Verlag GmbH, Berlin Offenbach, 1983

[2] König, D.; Rao, Y.N.: Partial discharges in electrical power apparatus. VDE-Verlag GmbH, Berlin Offenbach, 1993

[3] Küchler, A.: Hochspannungstechnik, Grundlagen – Technologie – Anwendungen. VDI-Verlag, Düsseldorf, 1996

[4] Berton, F.: Entwicklung und Anwendung eines DSP-gesteuerten TE-Messgerätes zur Teilentladungsdiagnostik von Isolationssystemen, Shaker Verlag, Aachen, 2003

[5] Peil, S.; Koziel, R.; Weidner, J.: Neue Entwicklung bei der Online-Überwachung von Generatoren. VDE Conference, Frankfurt, 2001

[6] Bergmann, A.; Facklam, Th.: Teilentladungsprüfung an Bauelementen der Niederspannungstechnik. Teilentladungen in Betriebsmitteln der Energietechnik, VDE-Verlag, 1993

[7] Berton, F.; Bonfig, K. W.; Patsch, R.: Teilentladungsmesstechnik in elektrischen Betriebsmitteln der Energie- und Automatisierungstechnik. 9. Symposium „Sensoren und Messdatenverarbeitung″, Technische Akademie Esslingen, 2002

[8] Porzel, R.; Neudert, E.; Sturm, M.: Diagnostik der elektrischen Energietechnik. Expert-Verlag, Renningen, 1996

[9] F.H. Kreuger; Industrial High Voltage I and II; Delft University Press, 1991 and 1992

12. List of relevant standards (the list is by no means exhaustive)

IEC 60270:2000 High-voltage test techniques – Partial discharge measurement; German version EN 60270:2001

IEC 60664-1: 2007 Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests; German version DIN EN 60664-1:2008-01 (VDE 0110-1)

IEC 61800-5-1:2007 Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy; German version DIN EN 61800-5-1:2008

IEC 62068:2013 Electrical insulating materials and systems – General method of evaluation of electrical endurance under repetitive voltage impulses; German version DIN EN 62068:2013

IEC/TS 61934:2011 Electrical insulating materials and systems – Electrical measurement of partial discharges (PD) under short rise time and repetitive voltage impulses; German version DIN/TS 61934:2012

IEC 60730: Automatic electrical controls for household and similar use – Part 1: General requirements – Part 2-9: Particular requirements for temperature sensing controls (IEC 72/779/CD:2009); German version DIN EN 60730-2-9:2011

IEC 61000-4-3:2010 Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test

Appendix 1: Paschen's Law

Paschen's Law states that the breakdown voltage U_d in an electric field is a function of the product of the gas pressure p of the insulating gas and the electrode gap (gap length) d between the live electrodes/conductors. The dependence $U_d = f(p*d)$ applies only to a specific temperature and only for as long as the density of the insulating gas is a linear function of the pressure. Deviations from this rule occur when gaps are very small (e.g. d = 5 cm) and densities are higher (p = 10 bar).

Paschen's Law and the Townsend mechanism provide a basic explanation of the breakdown mechanism in gases. Since the ionization coefficient (number of ion pairs generated in the air per cm path length) is a function of the air pressure, the breakdown strength and breakdown voltage are also dependent on it. This law also applies to the inhomogeneous field if the radius of curvature of the electrodes also changes proportionally to the distance (Toepler's Law of Similarity). The qualitative course of the Paschen curve is shown in Figure 4.

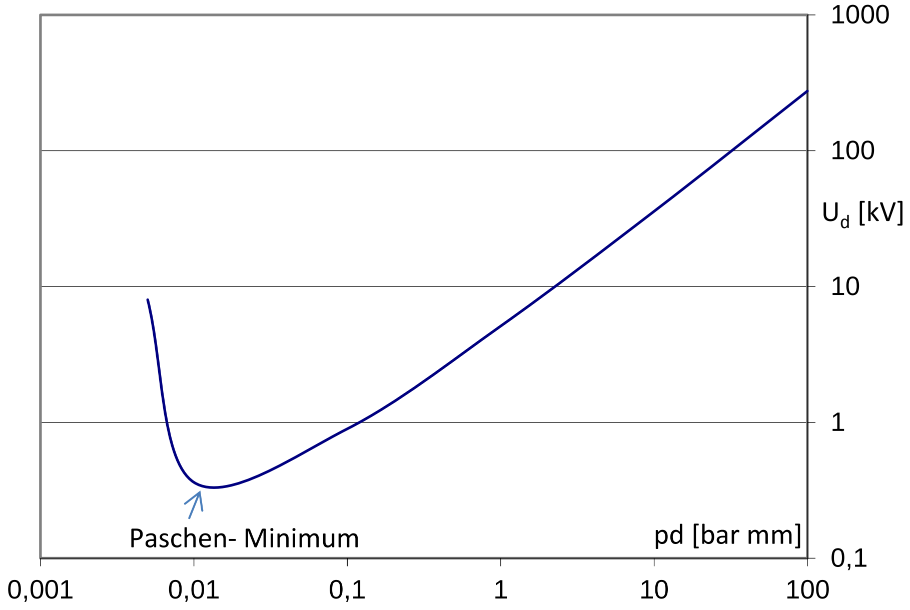


Figure 4: Qualitative course of the Paschen curve

$$U_d(pd) = \frac{B * pd}{\ln(A * pd) - \ln(\ln\left(1 + \frac{1}{\gamma}\right))}$$

whereby
p = gas pressure
d = electrode gap
γ= 2nd Townsend coefficient
A and B = constants

The constant factors for air as the insulating gas at 20 °C are:
$A = 1130\ \text{mm}^{-1}$, $B = 27.4\ \text{kV/mm}$
γ= 0.025 dimensionless material coefficient for copper electrode surface in air

As can be seen from the formula, the breakdown voltage is a function of the product of pressure and electrode gap.

For measurements to be comparable, they must be conducted at the same pressure. Since gas density (and thus ionization) is also dependent on temperature, temperature influences the measurements indirectly. Breakdown field strength decreases as temperature rises.

The gas density is critical for ionization. For this reason, the comparative pressures must always relate to the same temperature. Particular attention must be paid to this density dependence in high-voltage systems engineering. The mean air pressure is known to decrease by 1h Pa with every +8 m increase in altitude (above sea level), and the mean temperature similarly falls by 0.3…0.5 °C. Therefore, the air density falls by 125hPa on average with every +1000 m increase in altitude (barometric formula).

When designing the insulation system of electrical components intended for use above 2000 m above sea level, larger gaps must be allowed for to take account of corona and surface discharges (altitude factor).

The altitude of 2000 m above mean sea level (AMSL) is typically used to indicate the standard installation height for electrical equipment. Above this altitude, air becomes an increasingly poor insulator and so air gaps and creep distances must be increased by way of compensation. This means for an installation height of 5000 m, the gap needs to be 48 percent wider than for the reference altitude of 2000 m, and still 29 percent wider for an altitude of 4000 m (DIN EN 60664-1, Table A.2 altitude correction factor).

This influence can be demonstrated by comparison with standard conditions (T0 = 293°K and p0 = 1013 hPa) at sea level.

Example:

Mean sea level (MSL): $p_0 = 1013{,}25$ hPa $T_0 = 293$ °K $U_{d0} = 1000$ V *(selected)*

At 4000 m AMSL: $p_1 = 616.45$ hPa $T_1 = 282$°K U_{d1} = *is sought*

whereby:

$$U_{d1} = U_{d0} * \frac{p_1 * T_0}{p_0 * T_1}$$

It thus follows:

$$U_{d1} = 1000\ V*(616.45\ hPa *293°K) / (1013.25\ hPa *282°K)$$

$$= 1000\ V*0.63 = 630\ V$$

The temperature and air pressure data is based on the barometric formula.

In this example, it is clear that the dielectric strength decreases in line with decreasing air density.

Paschen minimum: Partial discharges can theoretically occur in air when peak voltages exceed 300 V AC. In practice, however, they are unlikely to occur below 500 V.

Appendix 2: Requirements on withstand voltage and safe separation

Safe separation means systematically protecting the user of an electrical appliance from electric shock. This requires several framework conditions to be observed, which are becoming increasingly complex due to technological developments.

Safe separation of all interfaces between different electric circuits is essential, with at least one voltage level above the extra-low voltage. An example of this is the separation between an SELV circuit (safety extra-low voltage) and an electric circuit with normal mains voltage. Safe separation means that electricity cannot cross over from one electric circuit to another, thereby endangering the user of the electrical appliance.

The following types of electrical insulation between such electric circuits are described in the relevant standards (e.g. DIN EN 60664-1 / VDE 0110):

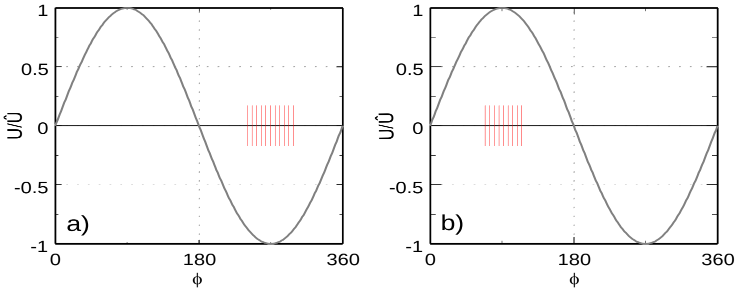
Functional insulation:	This type of insulation is necessary for the proper functioning of the circuit, but does not provide protection against electric shock.
Basic insulation:	Basic insulation provides basic protection against electric shock.
Supplementary insulation:	Supplementary insulation provides a second level of protection in the event that the basic insulation fails.
Double insulation:	The term used to describe a two-level system comprising two separate layers; basic insulation plus supplementary insulation. Each layer provides basic protection against electric shock.
Reinforced insulation:	Insulation consisting of a single-insulation system which provides protection equivalent to double insulation. Where it comprises several layers (multi-layer laminates), these layers are inseparably bonded and cannot be individually tested.

Air gaps and creep distances naturally act as insulation paths as well. They are defined in standards according to the voltage level, degree of contamination and material characteristics. Multi-layer double insulation systems must always be critically examined with respect to partial discharge resistance. The loads generated by ever-higher voltages, non-sinusoidal voltage characteristics, transients and other phenomena can lead to partial discharges. This can damage the insulating materials, especially at the interfaces between individual layers. Furthermore, it is technically demanding to encapsulate separably bonded multi-layer foils without entrapping air.

If partial discharges are expected to occur due to the operating conditions, reinforced insulation should be used in preference to double insulation. The multi-layer laminates used in reinforced insulation systems can in most cases be manufactured without air entrapment. In addition, it is easier to embed them in the potting compound without massive dielectric jumps (e.g. air pockets).

Appendix 3: Phase diagrams – interpretation guide [3] and [9]

Corona discharges in gas

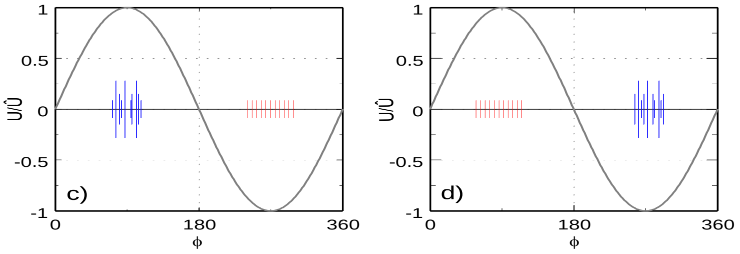


a) High-voltage peak

b) Earth peak

Discharges accrue in the other half-wave at higher voltages.

Corona discharges in oil

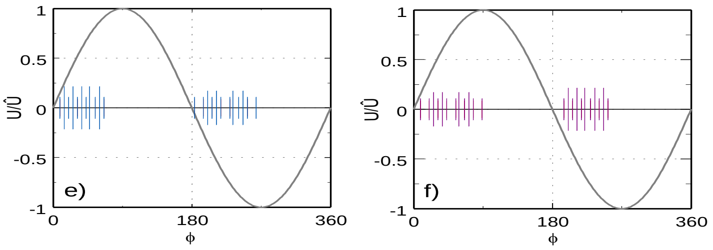


c) High-voltage peak

d) Earth peak

Frequency increases with voltage.

Cavity and surface discharges

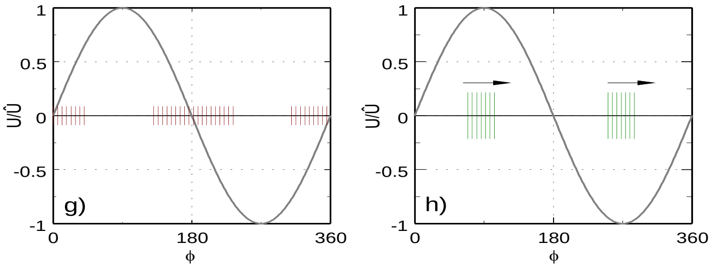


e) Electrode at high-voltage

f) Electrode at earth

The amplitudes of the two half-waves differ by at least a factor of 3.

The distribution of discharges in a cavity without contact to an electrode looks similar to diagrams e) and f) but the amplitudes of the two half-waves differ by no more than a factor of 3.



g) Contact noise

h) Discharges of electrodes at free potentials

Photo credits:

Front cover:	Treeing – electrical pre-breakdown in solid insulation, Gerald Friederici, CMC Klebetechnik
Figure 1 – 3:	Dr. Farhad Berton
Figure 4:	Jens Kohlhof, EPHY-Mess
Figures in Appendix 3:	Dr. Farhad Berton

ZVEI – German Electrical and Electronic
Manufacturers' Association
Lyoner Straße 9
60528 Frankfurt am Main, Germany

Phone: +49 69 6302-0
Fax: +49 69 6302-317
Email: zvei@zvei.org
www.zvei.org