Brno University of Technology
Faculty of Electrical Engineering and Communication

DISSERTATION THESIS

To obtain a doctoral degree (Ph.D.)

Doctor Study Programme

Microelectronics and Technology

Mammadov Anar

PARTIAL DISCHARGE IN ELECTRONIC EQUIPMENTS

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Supervisor:

Doc.Ing. Jaroslav Boušek, Csc.

Thesis is available at the Research Department FEKT VUT Brno, Údolní 53, Brno.

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Keywords

Partial Discharge, Electrical Insulation, Planar Transformer, Amplitude Analysis, Optocoupler, Pulse transformer, Thermal stress, Voltage stress

Abstract

This dissertation thesis is devoted to study of partial discharge (PD) caused decrease of reliability and lifetime of electronic equipments and systems. PD diagnostic is nowadays well known method for high voltage high power equipments but in case of electronic devices PD testing it is not used routinely despite that there is also a potential for high electric load due to extremely short distances. The risk of PD caused failure is here extremely high because of high working frequency and consequently high repetition rate of PD events. Therefore, this work is focused on investigation of PD activity in electronic equipments. The workplace for PD diagnostic in electronic devices based on switched power supply was designed and made. Working frequency ranges from several hundreds of Hertz up to 100 kHz. The maximal amplitude of PD testing voltage is higher than 10 kV. Despite the simple design this equipment brings high repeatability and reliability of measurement. More than 300 PD tests were made on different electronic devices and electronic components, on planar transformers, and on components for voltage gate drivers for use in high voltage power converters. Possibilities of PD tools in investigation and engineering ofd insulation systems were demonstrated.

List of symbols

Symbol	**Unit**	**Quantity**
A	μm^2	Surface area
C	F	Capacitance
C_a	F	Capacitance of the test specimen
C_k	F	Coupling capacitance
C_e	F	Earth capacitance
C_x	-	Capacitance of the sample
G	-	Calibration pulse generator
f	Hz	Frequency
q_i	C	Apparent charge
R	Ω	Resistance
S	-	PD source
T	K	Temperature
t	s	Time
$tan\delta$	-	Power dissipation factor
U_{inc}	V	Inception voltage
U_{ext}	V	Extinction voltage
V_{AC}	V	AC voltage
U_t	V	Test voltage
Z	Ω	Impedance
Z_M	Ω	Measuring impedance

Contents

1. Introduction

Partial Discharges (PD) is defined as an electrical discharge that only partially bridges the insulation between conductors and that may or may not occur adjacent to a conductor. PDs occur when the local electrical field intensity exceeds the dielectric strength of the dielectric involved, resulting in localized ionization and breakdown. Depending on the intensity, PDs are often accompanied by emissions of light, heat, sound, and radio influence voltage (with a wide frequency range).

Partial Discharges (PD) are localized releases of internal energy stored in electrical insulation systems in regions of defects in the media and/or at interfaces of different materials. These discharges of energy take place within the insulation system, being restricted to only a part of the dielectric material, hence not necessarily forming electrically conducting paths amongst system conductors. The series resistance limits partial discharge current in the insulation system.

The term "Partial Discharge" includes a broad spectrum of life reducing (i.e., material damaging) phenomena such as:

1. Corona discharge in gases.
2. Treeing and surface contamination.
3. Surface discharges at interfaces, particularly during fault induced voltage reversals.
4. Internal discharges in voids or cavities within the dielectric.

Determining whether electrical equipments are suffering from internal arcing or dangerous levels of PD is important because failure without warning can result in damage to neighboring equipment, customer dissatisfaction, disruption to economic activity, and possibly the imposition of regulatory fines. Effective asset management is therefore important for generation, transmission and distribution companies – it can provide information about the nature and severity of PD location. [20].

In-service PD measuring is used to assess the progressive degradation of electrical apparatus under operational stress to minimize outage time. Modern PD instrumentation and sophisticated digital techniques allow a wide range of approaches for the analysis of PD signals in spite of the transient nature of the PD signals, which limits available processing options. The design of in-service PD testing apparatus is complicated by various types of noise in industrial environments, which sometimes limit PD detection sensitivity, to the level above that required for effective diagnosis [21].

Since PD are essentially electron avalanches, they give rise to impulses of electric charge, which produces a burst of current and voltage signals outside the insulation system. The identification, separation, and possibly location of a partial discharge (PD) source can become a feasible pattern-recognition problem that allows considerable improvement in diagnostics of solid insulation systems, to be achieved by means of PD detection and analysis. These complex problems can be addressed and solved only by means of new diagnostic procedures.

Among various degradation mechanisms that affect the reliability of electrical apparatus, those regarding insulation systems are often (PD) phenomena; that is, partial breakdown of gas or liquid inclusions in the solid insulation. PD phenomena accelerate the local degradation and can generate electrical trees that are both the final stage leading to breakdown. For example PD can occur within a transformer where the electric field exceeds the local dielectric strength of the insulation. Although PD may initially be quite small, it is by nature that damaging process causes chemical decomposition and erosion of materials. Left unchecked, the damaged area can grow, eventually risking electrical breakdown.

PDs can occur in gas-filled cavities within the solid insulation, in air gaps between several layers within an insulation construction or in gaps between insulating material and electrodes when the breakdown voltage of the enclosed gas (mostly air) is exceeded. This depends on the voltage distribution between single parts of the insulation system where significant differences between AC or DC voltage stress exist. Because of low permittivity of the gas in case of capacitive voltage distribution for AC voltages, the cavities are usually stressed much higher and also the PD-pulse rate is there by orders of magnitude higher.

The AC voltage must be considered to be the more critical stress, and measurements at DC voltage are only to be considered if the operational stress is really DC voltage. Further, the risk that PD will cause failure is extremely high if the working frequency of the equipment is high consequently suffering from high repetition rate of PD events.

2. Purposes

Partial discharge decrease reliability and lifetime of equipments and systems. The topic of PD measurement and diagnostic is therefore very important. PD diagnostic is nowadays well known method for high voltage high power equipments. In case of electronic devices PD measurement is not used routinely despite that there is also a potential for high electric load due to extremely short distances. The risk of PD caused failure is here extremely high because of high working frequency and consequently high repetition rate of PD.

By the time when I start to work on my thesis, there were only few groups in Czech Republic dealing with the problematic of measurement of Partial Discharges [1Záliš..]. To the problematic of PD activity in electronic equipments there were only limited attention and practically no technical literature. In my thesis I therefore tried to elaborate a system for PD diagnostic of insulation in electronic equipments. To achieve this goal following steps needed to be fulfilled:

1. Design and preparation of the workplace for PD diagnostic in electronic devices with working frequency from several hundreds of Hertz up to 100 kHz.

2. Elaboration of measurement and calibration methods convenient for the workplace at the department of microelectronics. The method of Amplitude Analysis of PD pulses was chosen as the most convenient.

3. Measurement of PD in different electronic devices and in electronic components to gain the experience with PD testing and also with PD properties of special electronic components as for example planar transformers, components for high voltage gate drivers, high voltage power converters etc.

4. Understand correlation of PD measurement with other device characteristics to make the assessment of the device properties and to help with improving of the insulation structure.

5. Show that PD may be used not only for high voltage equipments but also in case of low voltage applications and even in “non electric” applications, where PD can help to discover different material defects.

For measurement of PD activity in power generation devices there is a broad choice of measuring equipments. Contrarily, the measurement of PDs in electronic devices is not much elaborated. In comparison with power devices where the PD diagnostic is performed mainly on three devices - power generators, power transformers and high voltage power cables - in case of electronic devices there is a broad variation of different devices giving thus different conditions for the testing and results interpretation.

Further, the problematic of partial discharge in electronic devices is relatively new and lack of specialized instrumentation is evident. On the other hand the achievements in measuring electronics in last few years give possibility to use sophisticated measuring techniques as high speed digital oscilloscopes, amplitude analyzers, frequency analyzers, ultrasonic detectors, etc.

PD free components must be used for all circuits of the PD testing equipments. This is especially problem in case of high voltage transformers with working frequency of several tents of kHz, because they work with large voltage difference between the winding layers.

To make an assessment of the dependence of PD activity on temperature thermal chamber with temperature control up to 150 ^{o}C and possibility of work with voltage up to 10 kV is indispensable. For thermal cycling there may be used a standard climatic chamber.

Expected contribution of the work to the development of problematic of PD testing in electronic devices may be summarized as follows:

1. A simple design of the workplace for PD diagnostic in electronic devices based on switched power supply will bring high repeatability and reliability of measurement with working frequency in very broad frequency range. Part of this work is very convenient for publication.

2. Proper measurement and calibration methods will ease the use the PD diagnostic on workplaces dealing with design of electronic circuits which are not specialized in high voltage technique.

3. Acquisition of an experience in measurement of PD in electronic devices, electronic components, in planar transformers, in components for high voltage gate drivers, in high voltage power converters etc. Especially this part of work is expected to be published.

4. Acquisition of better understanding of correlation of PD measurement with other device characteristics needed to make good assessment of the device properties and to help to improve the insulation structure.

5. Prove that PDs may be used not only for high voltage equipments but also in case of low voltage applications and even in “non electric” applications, where PD can help to discover different material defects.

6. The results obtained in points 4. and 5. may also serve as a good start for collaboration in research and industry and in application of results of the work in manufacturing and instrumentation.

In following chapter basic ideas from PD physics and methods of PD measurement will be shown and discussed shortly to become acquainted with this topic.

3. Origin of PD

Before study the measurement of PD it is important to know the origin of PDs and the discharge mechanism which takes part in individual cases. That's why it will be better to analyze the mechanism and properties of origin discharge. Let's start with dielectric barrier discharges (DBDs), historically also called 'silent discharges' [1].

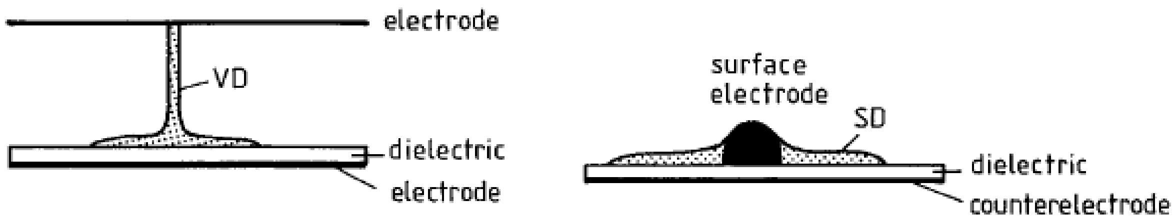
DBDs are used for many applications. In 1857, Siemens already used this type of discharge for the generation of ozone from air or oxygen [30]. Today, these silent discharge ozonizers are effective tools and a large number of ozone installations are being used worldwide for water treatment. Other applications are for example the generation of excimer radiation in the UV and VUV spectral regions, the production of ethanol from methaneyoxygen, various thin-film deposition processes, the remediation of exhaust gases and in CO_2 lasers or in plasma display panels [1].

DBDs operate at approximately atmospheric pressure (typically 0.1–1 atm). An AC voltage with an amplitude of 1–100 kV and a frequency of a few Hz to hundreds kHz is applied to the discharge, and a dielectric layer (made of glass, quartz, ceramic material or polymers) is placed between the electrodes. The inter-electrode distance varies from 0.1 mm (in plasma displays), to approximately 1 mm (in ozone generators) and to several cm (in CO_2 lasers) [31]. Typically, the DBD consists of a number of microdischarges (MDs) sometimes also referred to partial discharges or discharge filaments [1] of nanosecond duration, randomly but uniformly distributed over the dielectric surface.

Below we can see two configurations of dielectric barrier discharges. The *Volume Discharge* (VD) electrodes arrangement consists of two parallel plates (see Fig. 3.1a). The micro-discharge takes place in thin channels which cross the discharge gap and are generally randomly distributed over the electrode surface. The number of micro-discharges per period is proportional to the amplitude of the voltage. The *Surface Discharge* (SD) electrode arrangement consists of a surface electrode on a dielectric layer and a counter electrode on its reverse side (see Fig. 3.1b). There is no clearly defined discharge gap. The so-called micro-discharges are, in this case, rather individual discharge steps that take place in a thin layer on the dielectric surface and can be considered homogeneous over a certain distance. An increase in the voltage now leads to an enlargement of the discharge area on the dielectric.

The nanosecond duration of DBDs is caused by a charge build-up at the dielectric surface, within a few ns after breakdown. Indeed, this reduces the electric field at the location of the micro-discharge to such an extent that the charge current at this position is interrupted. Because of the short duration and the limited charge transport and energy dissipation, this normally results in little gas heating. Hence, in a micro discharge, a large fraction of the electron energy can be utilized for exciting atoms or molecules in the background gas which remains at low temperature. This can be used to initiate chemical reactions and/or produce light emission [1].

Under typical conditions of the DBD operation (discharge gap width of 1-2mm; dielectric: glass of 1-2 mm thickness and dielectric constant ε = 5-7; gas pressure: 1-3 bar), these micro-discharges (MD) can be treated as tiny plasma-chemical reactors that act independent one from each other [2]. That is why the study of the dynamics of a single MD is one of the most important research topics in the field of the DBD physics and chemistry. It is hard to carry out any experiment with a single MD, since high temporal resolution (in a sub-nanosecond range) and spatial resolution (down to 10^{-1}- 10^{-2} mm) is required. Moreover, in the case of a commonly used parallel-plane electrode arrangement, it is usually impossible to predict the location of a MD emergence.



a) **b)**

Fig.3.1 Schematic representation of a dielectric barrier discharge (DBD) in 2 different configurations.

a) The volume discharge (VD) arrangement consists of two parallel plates; the micro-discharge takes place in thin channels, which are generally randomly distributed over the electrode surface.
b) The surface discharge (SD) arrangement consists of a number of surface electrodes on a dielectric layer, and a counter-electrode on its reverse side [1].

3.1 Review of the MD models

Complete model of the MD in the partial discharge event includes the descriptions of electrical breakdown (time scale: 10^{-8} – 10^{-7} s), chemical kinetics (10^{-6}-10^{-4} s), and the consequent diffusion and heat transfer, occurring in a millisecond scale. Below, the attention is focused prevalently on the development of electrical breakdown phase of the MD [2].

All proposed physical models of MD mechanism appeared either as a result of interpreting of experimental observations and measurements, or by means of the technique of computer simulation.

3.1.1 Electrical breakdown via avalanche-to streamer transition

The first attempt to provide a full theoretical description for a single MD in a Partial Discharge device by means of 2-dimensional numerical modeling was made by the authors [2]. Basic conditions used in this model (initial electric field somewhat higher than the corresponding Paschen value; initial avalanche starting from about 10^6 electrons located near the cathode) account for the mechanism of „avalanche-to-streamer transition“ (Fig.3.2).

The origin of this model belongs to the field of the physics of electrical breakdown in the long gaps [2]. For large devices as ozonizer devices (gap width of a few millimeters), this mechanism has been never observed experimentally, excepting the use of devices with pulse feeding voltage with rise time near to 1kV/ns).

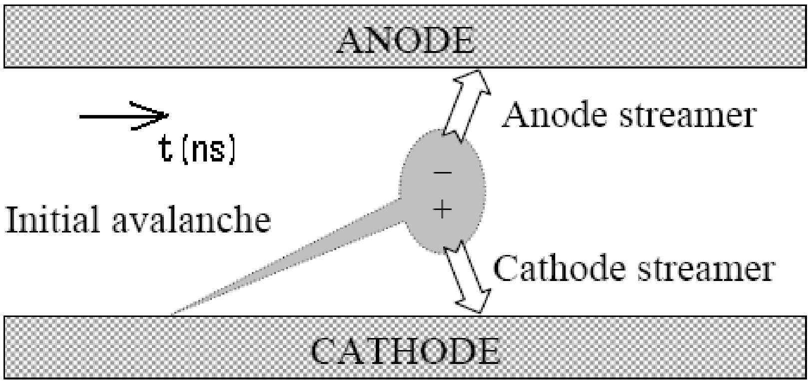


Fig.3.2 Schematic illustration for the breakdown mechanism within the frame of the model of "avalanche-to-streamer transition". Time axis is directed from the left to the right, and for the discharge gap width of 1 mm it has a scale range of a few nanoseconds. [2].

3.1.2 The model with a pusled electric field

This model may be considered as a semi-empirical one, based on the results of the first measurements of the microdischarge current pulse [2]. Model current density line based on the "pulsed electric field" used in the computer simulation of the MD in oxygen is depicted on the Fig.3.3.

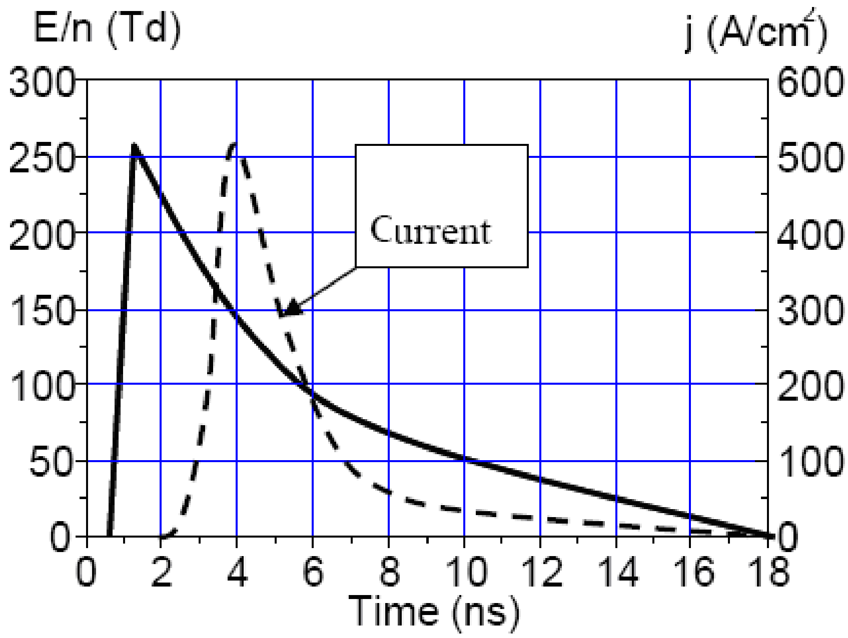


Fig. 3.3 Model of the "pulsed electric field" used in the computer simulation of the MD in oxygen. Assumed variation of the reduced field (solid line), and calculated current density (dashed line, right Y-axis), fitted to comply with the results of experimental measurements [2].

However, despite that this model complies with the current measurements it cannot provide a reasonable estimation of gas reaction kinetics and for example predict the ozone concentration in case of oxygen gas discharge.

3.1.3 Accumulation of positive space charge followed by the cathode-directed streamer

This model has been widely used in a number of computer simulations of the MD development since 1986. The first experimental evidence for the existence of a cathode-directed streamer in a DBD was obtained by means of the technique of streak-photography. On the Fig.3.4 there is demonstrated that if the development of the breakdown begins with a single electron emitted from the model cathode, than for a sinusoidal feeding voltage, the development of the MD proceeds according to the mechanism „avalanche-to-streamer transition“ can be realized.

According to the described model, the development of the cathode-directed streamer is caused by the distortion of electric field due to a positive space charge within the MD channel (Fig.3.4). Accumulation of this charge occurs during the pre-breakdown phase of a MD development, which can take up to 10 ns [2]. The final phase of decay is characterized by the deposition of the charge carriers (electrons and ions) onto a dielectric surface resulting in a monotonous decrease of electric field [2].

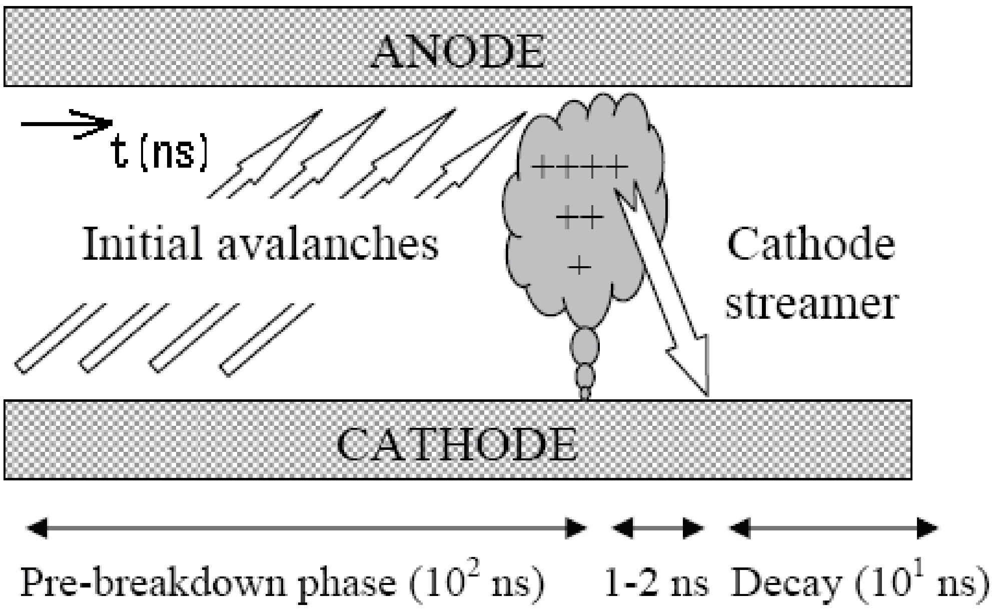


Fig. 3.4 Schematic illustration of the breakdown mechanism for the model of “cathode- directed streamer, caused by a positive space charge”. Time axis is directed from the left to the right. “Initial avalanches” denote here a continuos process including the electron drift, ionization, and the secondary emission from the cathode [2].

3.1.4 Accumulation of negative space charge followed by the cathode-directed streamer

This model appeared as a result of the attempts to give a reasonable interpretation to certain experimental findings. Some ideas of the MD mechanism including an accumulation of the negative space charge during the pre-breakdown phase have been stated in [2].

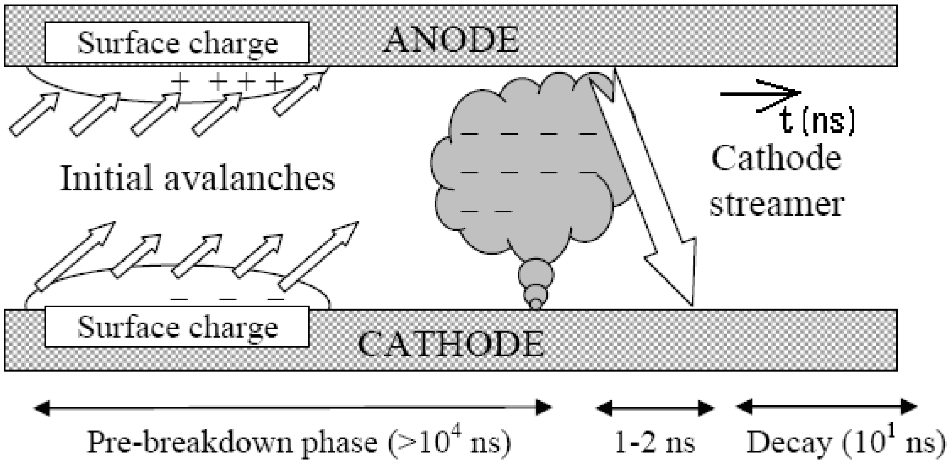


Fig. 3.5: A scheme for the microdischarge mechanism, based on the assumption of a pre-breakdown accumulation of the negative space charge within the microdischarge channel. Initial avalanches are caused by a local field enhancement due to the surface charges on the dielectric electrodes. It is also assumed to be a continuous process including electron drift, ionization, attachment and secondary emission from the cathode (see text for the details) [2]

Contrary to all above described MD mechanisms, the scheme in Fig.3.5 takes into account surface charge left on the dielectric electrodes after a previous MD. Initial electric field is therefore assumed to be non-homogeneous, the mean value of the field strength being considerably lower than that one corresponding to Paschen law (probably, proportional to the ratio of the burning and ignition voltages of the BD). Under such conditions, ionization may be expected to occur mostly near the charged dielectric surface, and attachment in the center of a gap [2].

An appearance of the negative space charge causes certain rearrangement of initial electric field, the maximum of the field strength being located exactly on the anode surface. Duration of this „pre-breakdown“ phase of the MD development is at least a few µs. Cathode-directed streamer starts from the anode surface and propagates through the medium enriched with negative ions, and its velocity depends on electro-negativity of the feeding gas.

It was confirmed that there are three distinct phases of the MD development. The pre-breakdown phase lasts for a period of more than 0.5 µs. It is characterized by a continuous glow on (dielectric) surfaces of both electrodes. During the last 100 ns of the pre-breakdown phase, the maximal light intensity is observed on the anode. The third phase of the MD is a phase of decay of the light and current pulses.

The experimental data were used to test the validity of the above physical models of electrical breakdown in a BD, in particular the model of accumulation of positive space charge followed by the cathode-directed streamer (chap. 3.1.3), and the model of accumulation of negative space charge (chap. 3.1.4). They came to the conclusion that their results provide unambiguous experimental evidence in favor of the model in chap. 3.1.4.

Taking into account the initial conditions, assumed for the model in chap. 3.1.3, we may expect this model to describe some special cases of BD operation. For example, it can account for the first electrical breakdown event in a PD device (i.e. at the moment when a PD devices is just switched on), since only at this moment there are no surface charges on the dielectrics. Also, in some laboratory experiments, the BD was operated in a special single-pulse mode, when the periodical slow voltage pulses were applied to the discharge cell. In order to get rid of a surface charge, a rest time interval of about 30 minutes between the successive single pulses was provided [2]. Obviously, for an ordinary (continuous) operation mode of a BD, the model from chap. 3.1.4 should be used.

That is why it is very important to understand differences between two modes of a BD operation: single pulse and continuous. To provide a correct theoretical description of the MDs for an ordinary continuous mode, a model should be used, that takes into account an existence of initially non-uniformly charged dielectric surfaces.

There are two distinct regions with essentially different plasma properties of plasma within the MD channel. Electric field near the cathode is higher than near the anode, and electron density near the cathode, on the contrary, is considerably lower. Moreover, different physical properties of these regions result in a noticeable difference in kinetics of chemical reactions.

3.2 Corona discharges

Beside the barrier discharge with two electrodes, there also exists another type of pulsed DC discharge, with the cathode in the form of a wire [32, 33]. A high negative voltage (in the case of a negative corona discharge) is applied to the wire cathode, and the discharge operates at atmospheric pressure. The name ‘corona discharge’ arises from the fact that the discharge appears as a lighting crown around the wire.

The mechanism of the negative corona discharge is similar to that of a DC glow discharge. The positive ions are accelerated towards the wire, and cause secondary electron emission. The electrons are accelerated into the plasma. This is called a streamer [34], i.e. a moving front of high-energy electrons (with average energy approx. 10 eV), followed by a tail of lower energy electrons (order of 1 eV).

The high-energy electrons give rise to inelastic collisions with heavy particles, e.g. ionization, excitation and dissociation. Hence, radicals can be formed, which can crack larger molecules in collisions. Therefore, there is a clear distinction between the electron kinetics (to create the plasma) and the heavy particle kinetics.

The corona discharge is also strongly in non-equilibrium, with respect to the temperatures and to the chemistry. The main reason is the short time-scale of the pulses. If the source was not pulsed, there would be a build-up of heat, giving rise to thermal emission and to a transition into an arc discharge close to equilibrium.

It should be mentioned that beside the negative corona discharge, there also exists a positive corona discharge, where the wire has a positive voltage, hence acting as anode [34].

However, despite of deterioration mechanism in case of electrical insulation systems there are also “useful” applications of the corona discharge which include flue gas cleaning, the destruction of volatile compounds that escape from paints, water purification, etc. Dust particles are removed from the gas or liquid by the attachment of electrons from the discharge to the dust particles. The latter becomes negatively charged and will be drawn toward the walls.

3.3 Influence of PD on insulation

For certain electrode geometry, the breakdown field strength of air can be defined very precisely. As shown in Fig.3.6 for homogeneous and or non-homogeneous fields (point-plane) [3], it is dependent to a great extent on the distance *d* (gap width). In addition, other parameters, such as air pressure and air temperature, also influence the breakdown field strength.

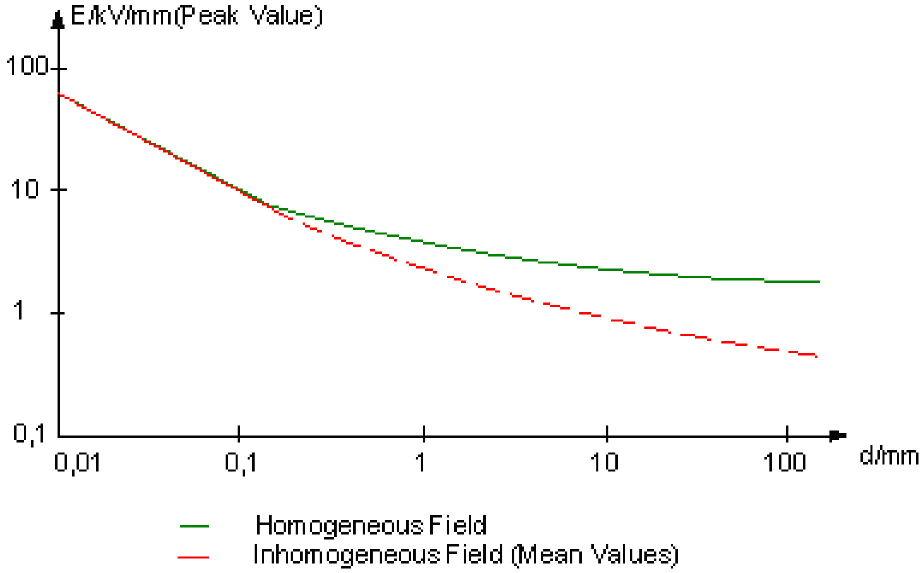


Fig. 3.6 Breakdown field strength of air at normal air pressure; AC voltage (50/60 Hz) [3].

Solid insulation, compared to air, can provide a breakdown field strength that is at least one magnitude higher. However, there is a large dependence of the breakdown field strength from parameters such as insulation thickness, temperature of the insulating material, and duration of electrical stress. Material-specific influences related to composition and processing also have to be considered. The result comparable to that shown in Fig.3.6 for a given insulating material can only be defined with great difficulty and its validity would be severely restricted.

In general, one can say that in low-voltage equipment with the relatively small insulation thickness (<1mm) being used for short-time stress, very high breakdown field strengths of more than 100kV/mm can be achieved. On this basis, one might assume that usual stresses of some kilovolts might not involve severe insulation problems [3].

However, in practical use the high breakdown field strength of solid insulation cannot be generally utilized because partial discharge will occur far below the breakdown voltage within the cavities in the material itself, or in the gas gaps within layered insulation systems or on the insulation surface. The gas within cavity becomes conductive and the insulation between electrodes, for a short time, is maintained by the remaining part of the solid material.

Since during the partial discharge within the cavity a breakdown of air (or similar gases) occurs, the relatively low breakdown field strengths as shown in Fig. 3.6 apply, at least approximately. A further impairment results from the fact that for AC voltage due to capacitive voltage distribution and relatively high dielectric constant of solid insulation the larger fraction of the voltage is applied across the gas. Consequently, its lower breakdown field strength is even more stressed.

PD can affect the insulation system reliability in different ways, depending on the insulation system characteristics. Indeed, some insulation systems (particularly mica based) are designed to withstand a moderate level of PD occurring in distributed micro-voids (internal discharges), while others (organic-polymer based) are degraded by PD activity very quickly.

Discharge phenomena produced by different kinds of defects may mix their characteristic features, so that recorded patterns cannot be easily deconvoluted, and thus may result in inaccurate risk assessment. The picture may be further complicated by the presence of significant external noise, which defaces measured patterns.

Measurement of PD has long been used to assess the condition of high voltage insulation in components such as bushings, capacitors, transformers, and switchgear. During preventive maintenance programs of electrical apparatus, diagnostic tests are performed to evaluate the likelihood that apparatus can remain in operation without experiencing outages until the next planned maintenance, or must be taken out of service immediately. Such an evaluation requires that degradation phenomena must be detected and the defects causing damage identified.

One ageing condition observed for electrical equipment with increasing occurrence is high-frequency stress, such as recurring voltage peaks with frequencies up to and exceeding 100 kHz. These stress influences the occurrence of partial discharges and their damaging effect, as well as dielectric heating combined with a drastic reduction of the breakdown strength. It has to be assumed that, as already utilized for time accelerated testing, the damaging effect, especially from partial discharge, increases with the frequency of the voltage. The simulation of this high-frequency stress by appropriate testing is currently not yet completely solved [3].

For the choice of the PD evaluation method, there is important if it gives a possibility of on-line operation, it means to measure without a shutdown or disconnection of electrical equipment. Depending on the type of sensor PD evaluation methods may be divided into electrical and non-electrical methods. Non-electrical methods usually evaluate the external behavior of partial discharges such as acoustic, optical and thermic or chemical effects. Therefore it can be possible to quantify the frequency of PD and their intensity or in the case of chemical methods to examine the composition of the outgas media.

In comparison with electrical methods non electrical methods are simple but usually their sensitivity is low. Because of higher sensitivity electrical methods are used prevalently. Electrical methods (measurement of power dissipation factor tan δ, methods of amplitude and frequency analysis, the measurement of spurious electric fields, impedance methods, etc.) also give the best results when referred to acquisition of basic parameters of partial discharges:

- apparent charge q,
- pulse repetition rate,
- average discharge current I,
- cumulative charge Q,
- discharge power P,
- quadratic rate D,
- partial discharge inception voltage U_{inc},
- partial discharge extinction voltage U_{ext},

Determining whether electrical equipments are suffering from internal arcing or dangerous levels of PD is important because failure without warning can result in damage to neighboring equipment, customer dissatisfaction, disruption to economic activity, and possibly the imposition of regulatory fines.

Effective asset management is therefore important for generation, transmission and distribution companies – it can provide information about the nature and severity of PD location. Knowledge of the PD location would be great help to the engineering specialist who must make decisions [3].

3.4 Model of the discharge gap

It is clear that PD may occur primarily in equipment working with the AC voltage. Partial discharges always take place in the gas - for example, in places with imperfect impregnation, but may also occur on the surface of printed circuit boards. Different types of partial discharges are schematically shown in Figure 3.7.

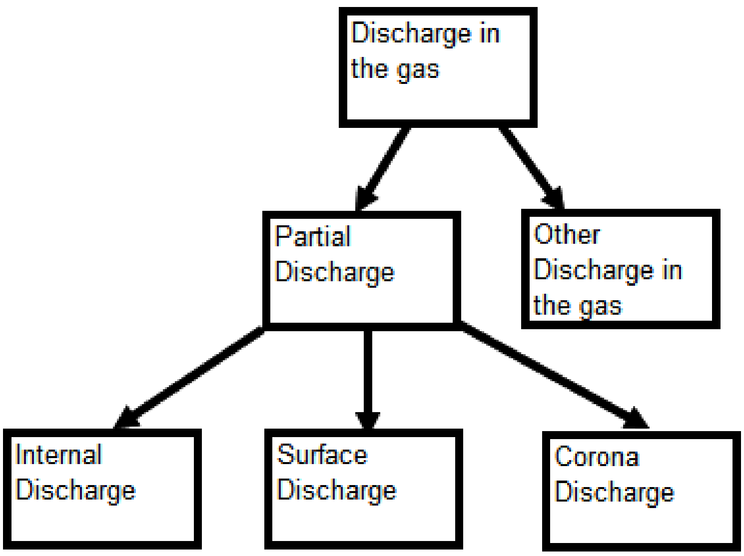


Fig. 3.7: Different types of Partial Discharge activity.

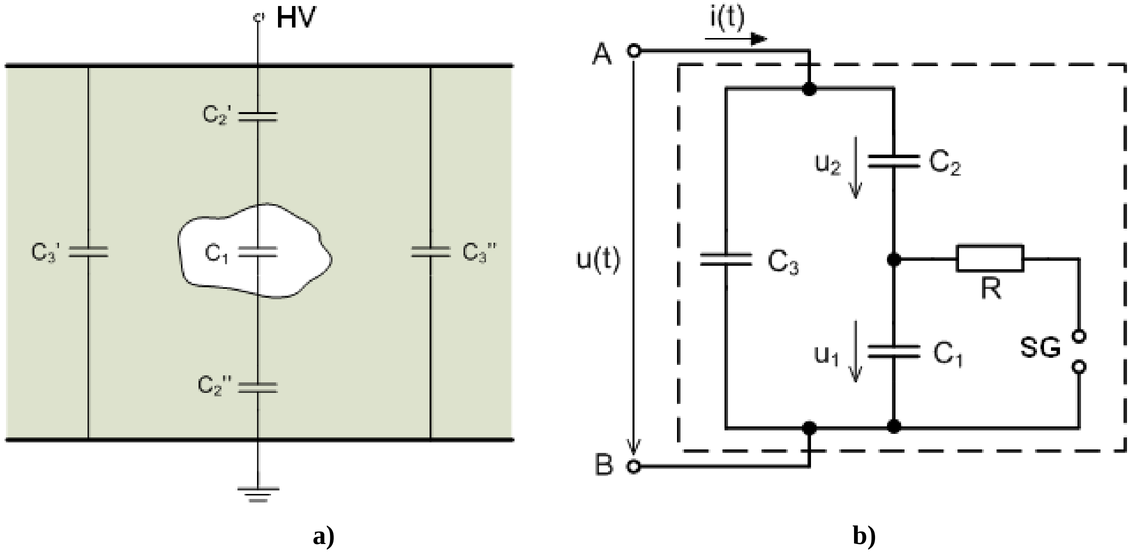


Fig. 3.8: Solid insulator with internal gas cavity. **a)** Substitution scheme using the capacitance of the discharge cavity. **b)** Gemant-Philippow model with the spark gap (SG). The resistor R represents the resistance in discharge channel through the gas cavity during the spark discharge.

Figure 3.8 a) shows the schematic picture of insulator with internal cavity filled with the gas [38]. Capacitance of insulator is a parallel combination C_3=C'_3|| C''_3. The capacitance , C_D, of the insulation area with the gas cavity is given as serial combination of capacitance of remaining part of insulator C'_2 and C''_2 and capacitance of the gas cavity C_1.

Resulting capacity of this model is given by the sum of the capacitance of insulator C_3 and the capacitance of area with the gas cavity C_D.

To implement partial discharge into this model the spherical spark-gap (SG) is added. Resulting substitution scheme which is called Gemant-Philippow model is depicted in the Figure 3.8 b) [38]. For the small cavity condition C_3>>C_1>> C_2 the spherical spark-gap SG in parallel to the capacitance of the gas cavity C_1 is used to model the breakdown of the gas in the cavity.

After applying AC voltage u(t) across the measured object the current i(t) flows through the insulation. If the spark in cavity (represented by the spherical spark-gap, SG) will not happen the change of voltage $u_1(t)$ on the capacitor C_1 is defined by following relationship [38]:

$$u_1(t) = \frac{C_2}{C_1 + C_2} u(t) \tag{3.1}$$

Resistor R in the diagram represents resistance of a simplified discharge routes (discharge channel through the gas cavity) during the spark discharge in the spherical spark gap, SG. Due to very small dimensions, which are in real cavities in insulating materials, this action takes place in the order of ns.

Electrical breakdown occurs when actual voltage from HV source corresponds to inception voltage of partial discharge U_I in the gas cavity. During the spark time (due to small resistance of conductive discharge channel) the voltage in the gas cavity decreases. When the voltage on the gas cavity reaches the value U_0 the discharge stops.

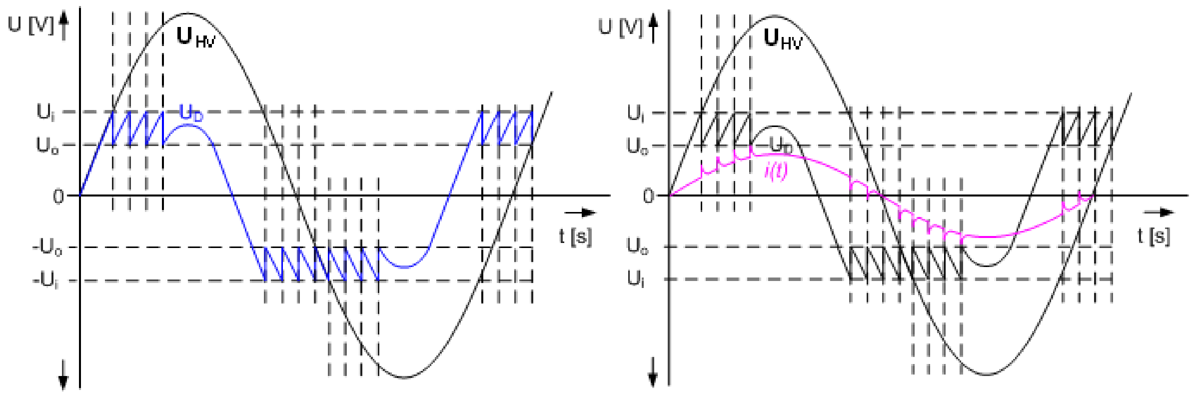


Fig. 3.9: Voltage and current in Gemant-Philippow model.
a) Voltage U_D on the spark gap. Voltage drops correspond to individual breakdown sparks.
b) Voltage U_D on the spark gap and the current through the insulation system. The spikes on the current corresponds to individual breakdown sparks.

Figure 3.9 is the graphical representation of voltage and current in Gemant-Philippow model. Here U_D is the voltage on the gas cavity and U_{HV} represents high voltage applied across the insulator. The spikes on the current, i(t), through the insulation system given on the Figure 3.9 b) corresponds to individual breakdown sparks.

Described simple model according Gemant-Philippow does not respect the fact, that during partial discharge in the gas cavity the discharge process includes not only the area of gas cavity, but also a neighboring dielectric.

During the discharge the voltage decrease on not only on the gas cavity but also on the gas cavity interface, causing thus the drift of charge carriers which consequently affects the resulting voltage on the gas cavity. Therefore, when spark breakdown in the gas cavity occurs the electric charge is drained also from the small volume of the dielectric near the gas cavity.

This phenomenon is reflected, for example, in extended model made by Böning. This model ads to previous Gemant-Philippow model two capacitors, C_4 and C_5 , and resistor R_4 which represents the substitution scheme for charge transport in the dielectric volume near the gas cavity - see Figure 3.10. [38]

The capacitor C_4 stands for the model of the small dielectric volume surrounding the gas cavity and has such a value that the voltage U_1 and U_4 before discharge are the same. Resistance of cell walls, including gas cavity surrounding area is described as R_4. Before the spark event in the spark gap (SG) there is no electrical current because this bridge circuit is in balance. Resistance R represents resistance of discharge channel in the gas cavity. Capacitor C_5 in series with the capacitor C_4 represents the capacitor of the rest of insulation system [38].

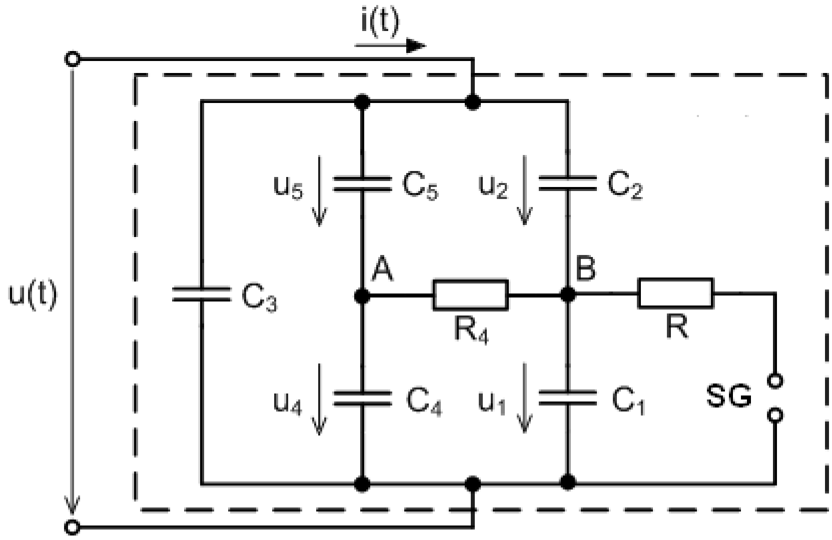


Fig. 3.10: Böning model for the internal partial discharge.

In the analysis of voltage conditions in the model during the discharge event in the gas cavity the system is in balance with the following initial conditions for time t=0:

$$U_1(0) = U_4(0) = U \frac{C_2}{C_1 + C_2} = U_Z \quad (3.2)$$

$$U_2(0) = U_5(0) = U \frac{C_1}{C_1 + C_2} \quad (3.3)$$

Where U_z is the ignition voltage of the gas in gas cavity.

To make the calculations easier, it is assumed that: $C_3 >> C_2$ and $C_3 >> C_5$.

Furthermore, it is assumed that $R << R_2$ threfore: $RC_1 << R_4C_4$

And, finally, $C_2 << C_1$, $C_2 << C_4$, $C_5 << C_1$ and $C_5 << C_4$.

Using Laplace transformation under such conditions it is possible to express both voltages $U_1(t)$ and $U_4(t)$:

$$U_1(t) = U_Z . e^{-\frac{t}{T_1}} \quad (3.4)$$

$$U_4(t) = U_Z . e^{-\frac{t}{T_4}} \quad (3.5)$$

where $T_1 = RC_1$ a $T_4 = R_4C_4$.

Repetition frequency of partial discharges in this model depends on the ratio p with following relationship:

$$p = \frac{U_R}{U_Z} \tag{3.6}$$

Where U_R is the value of recovery voltage after discharge and U_Z is ignition voltage.

Assuming that the ratio of the time t_s representing time of the discharge duration and time constant T_4 is much smaller than 1, it is possible to simplify this relationship by:

$$p = \frac{1}{1 + \frac{C_1}{C_4}} \tag{3.7}$$

Other models that describe the problem of internal partial discharges, for example Kranz model, differ from the Böning model by replacing the resistance R by specially defined function R = f(t,u) which better describes the dependence of resistance on the time and on the voltage after inception of discharge and, further, it also describes the resulting resistance after the discharge ends. [38]

4. PD dependence on operation conditions

The insulation of electronic equipments is subjected to a combination of different stress factors: **T**hermal, **E**lectrical, **A**mbient and **M**echanical (TEAM). The mentioned factors lead to deterioration of the insulation material and finally to failure and breakdown. Partial discharges (PD) are mostly indication of material deterioration caused by the factors which are mentioned above. That's why PD can be used as an indicator for possible material degradation.

As degradation of the material cannot be observed visually, a correlation between the internal material degradation and the external measurable PD-values must be made available. In order to estimate residual life of the insulation, this correlation should continuously be drawn up to final breakdown [4].

4.1 Thermal stress

Thermal aging is a chemical process, such as molecular decomposition and oxidation of organic material. As a result, internal gas pressure increases, and the adhesive strength of the layered insulation system decreases. Both lead to the delamination at this interface [8].

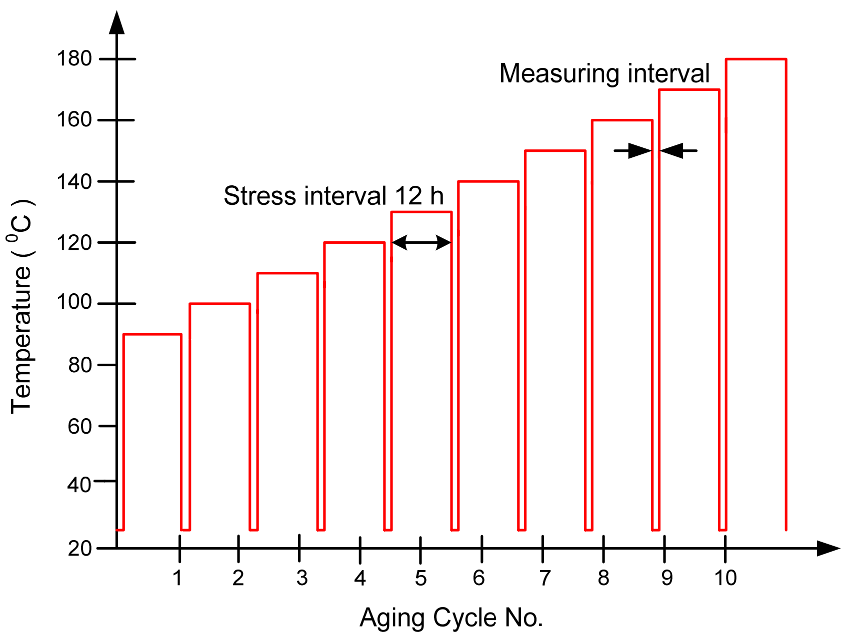


Figure 4.7.: Example of temperature profile versus aging cycle during thermal aging [4].

To assign the influence of thermal stress in the insulating system at different temperatures, an accelerated thermal aging procedure with cycling increase of temperature was tested in [4] using the model stator bars. The thermal aging test had 10 cycles. During each aging cycle, the test object was heated by current from ambient temperature to a specific temperature and remained at this temperature for 12 h. After it, the heating current was switched off, and the tested object was cooled to room temperature (approximately $\theta = 25\ ^{o}C$), at which time the characterization of the specimens by a series of PD and *tanδ* measurements was carried out. The thermal stress was then repeated with a 10°C higher temperature up to 180°C. The starting temperature was 90°C [4]. The respective temperature profile is shown in Fig.4.7.

On the Fig.4.8 we can see the change in the PD pattern and the number of PD pulses per second change as a consequence of the thermal stress. All PD patterns were collected by integrating the PD activity over a fixed period of time, and the number of PD pulses is shown for charges > 100 pC. As a result we can see a sensitivity of the PD measurement to changes within the insulation caused by the aging process.

The symmetrical patterns in the positive and negative half cycles of the PD patterns have indicated that the discharges were mainly within the groundwall insulation. During the 8^{th} aging cycle, the PD behavior of the insulation was significantly influenced by the thermal stress, after the aging temperature was above the thermal class of the insulation (155°C). The intensity and number of PD pulses increase greatly in this case. The change in the number of PD pulses can be thus characterized as the change in the number of voids and delaminations in the insulation.

These faults may be the result of the different thermal expansion behaviors, e.g., of copper and the mica-epoxy insulation, that lead to delaminations, within the main insulation or at interfaces between the copper conductor and the main insulation. In these delaminations, interlaminar PD take place, leading to defect growth parallel and perpendicular to the field direction [4].

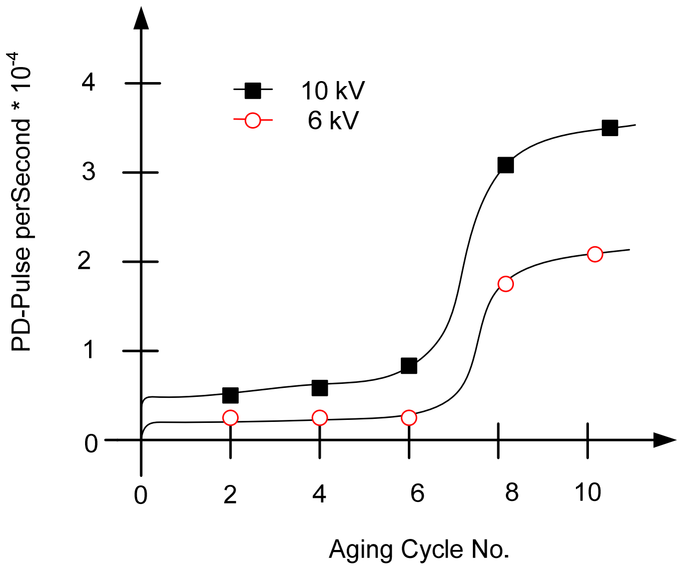


Figure 4.8 Change in the number of PD pulses per second (q>100pC) during thermal aging measured at 10kV and 6 kV at room temperature. [4]

One of the important factors for evaluation the PD is the change in PD intensity as a function of the test voltage. On the Fig.4.9 we can see the mean value of the maximum apparent charge as a function of test voltage at different thermal aging stages, which has been calculated for each test voltage as the average of charges with maximal amplitude. The charge values initially increase with increasing test voltage, as we can see on the Fig.4.9. Then, with a further increase of the test voltage, the measured values remain approximately constant. Moreover, Fig.4.9 shows that the maximum rise of the charge/voltage curves increases with increasing aging cycle.

In good insulating systems of high voltage rotating machines, the change in *tanδ* is very small with increasing applied test voltage. However, an increase in the number and size of the voids or the formation of delaminations in the insulating system during the device service life caused by different stresses can lead to a large increase in the value of *tanδ* with applied voltage.

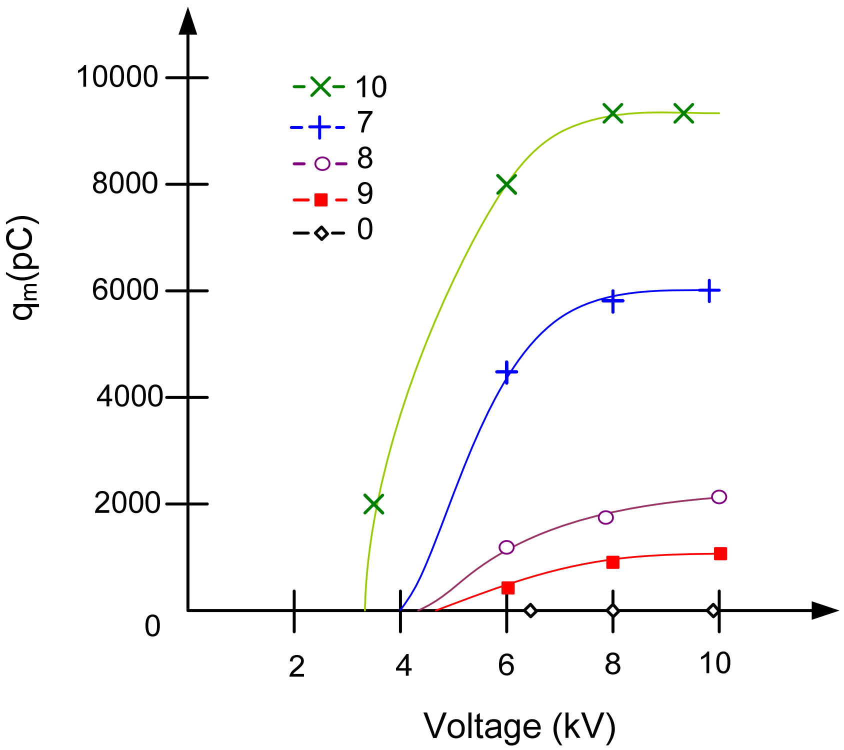


Figure 4.9 Mean value of maximum apparent charges as a function of the test voltage for different thermal aging stages measured at room temperature [4] .

The Fig.4.10 shows the change in the dissipation factor *tanδ* caused by the thermal stress at different test voltage levels. As a result, the difference between the *tanδ* before and after the first aging cycle is mostly because of drying and post-curing of the insulation in this period of the aging procedure. Thus, a shift of the *tanδ* curve is to be observed at all voltages toward lower losses. In addition, the *tanδ* of the device insulation before and after the first aging cycle is independent of the test voltage [4].

One of the factors of the electrical stress in insulation systems is voltage dependence of *tanδ*. As we can see on the Fig.4.8 - after the aging cycle number 8 (where the temperature is above the thermal class of the insulation 155°C), the frequency of PDs increases with increasing test voltage significantly bringing thus also the increase of *tanδ*. This change is due to an increased PD activity at this aging state.

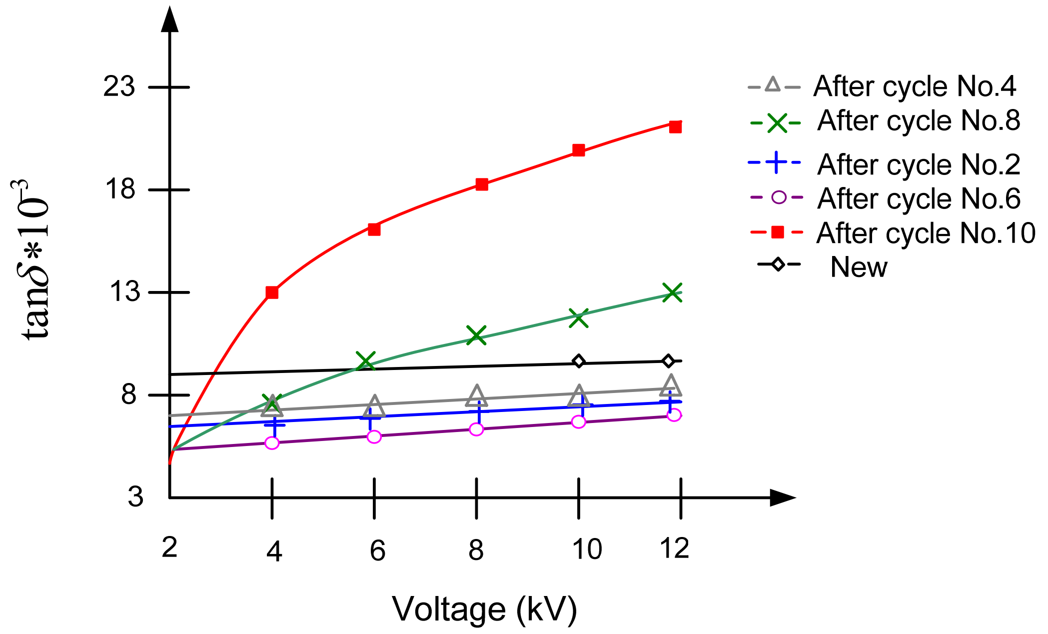


Fig.4.10 Change of dissipaition factor *tanδ* with aging cycles at different voltages. [4]

4.2 Electrical stress

An insulating system is subjected to electrical stress caused by the time dependence and spatial distribution of the electrical field [1]. Electrical stress can lead to insulation degradation because of PD activity within the insulation adjacent to the conductor or in the bulk of the groundwall. One of the reasons of lead electrical treeing is electrical stress, which is often referred to as the most important degradation mechanism in solid insulation.

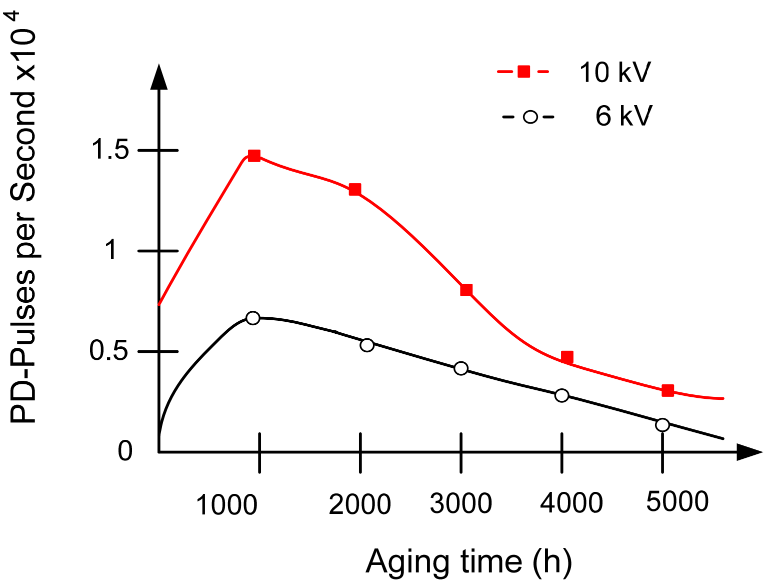


Fig.4.11 Change in the number of PD pulses per second (q>100pC) during electrical aging measured at 6 and 10 kV at room temperature [4].

To understand the influence of electrical aging on the insulation, an electrical stress of 8.3 kV/mm (1,5kV, 50Hz) has been applied to model stator bars at room temperature, and the change in the PD pattern and dissipation factor has been studied [4]. The service stress is about 2.5 times less than the electrical stress applied in this test.

On the Fig.4.11 we can see the change in the PD pattern and the number of PD pulses per second during the electrical aging. Due to the accelerated aging, an electrical breakdown occurred in the insulating system after 5825 h. The last measurement was made 25 h before the breakdown.

The PD patterns confirm the existence of voids in the insulation. The PD magnitude and the number of PD pulses show high variability, particularly concerning the large pulses during the first few hundred hours of electrical stress.

Fig.4.11 shows how consequently, the magnitude and the number of the discharge pulses decrease abruptly, resulting in a near disappearance of the discharge pulses. The measured PD activity shows an increase in magnitude and starts to drop approximately after 1000 h. After 5800 h the PD activity drops below the ”zero time “ value.

The origin of PD has been shown by many researches in the case of occluded voids [2], [17], [18], [19], [20], [21]. There are some different mechanisms which have been introduced to explain this transition in PD regimes - the transition from a streamer-like mechanism (highly localized with large magnitude) to a Townsend-like mechanism (diffuse with small magnitude) or pseudoglow discharge.

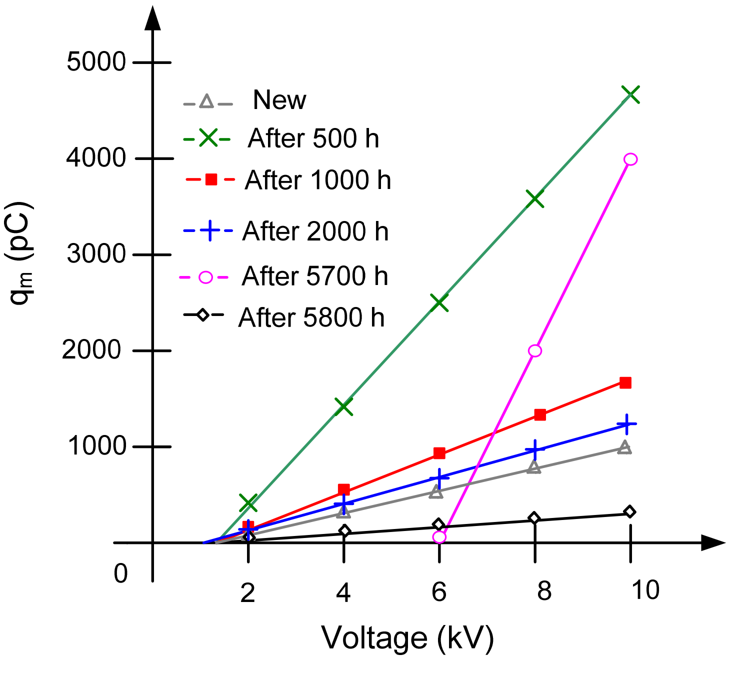


Fig.4.12 Mean value of maximum apparent charges as a function of the test voltage during electrical stress measured at room temperature [4].

The behavior of PD can be alternated due to some changes in gas composition caused by gas formation from decomposed surface material. The changes in the gas pressure can be caused by plasma reaction and the low diffusion constant of gases in epoxy resin [2]. The void pressure typically fluctuates at the beginning of the aging and subsequently decreases at a constant rate. The PD activity creates highly reactive species such as ozone and oxygen ions.

The pressure decrease is probably caused by the consumption of oxygen by its reactions with the epoxy resin [21].

The electrical surface conductivity of the void surfaces increases, because of the formation of acid layers. The decomposition of the layers is dependent on the intensity of the discharge process [18], and the surface conductivity can increase by at least six orders of magnitude [22]. PD activity can be suppressed due to high surface conductivity [23], because the change in the void surface can change the voltage distribution and space charge distribution across the rest of the specimen. Mechanisms found in closed cavities were attributed to glow-like pulse-less or "swarming" micro PD [24].

On the Fig.4.12 we can see the change of the maximum charge amplitude during the electrical aging as a function of the test voltage for the same case as depicted on the Fig. 4.11. At the beginning of the aging process, the PD amplitude grows up with increasing test voltage. After continuation of the aging process, the PD amplitudes decrease slowly and are more or less independent on the test voltage. When we pass 5700 hours of aging time there is a strong increase in the PD activity at about 6,0 kV, which assign a various weak points relating to PDs creation. After 5800 hours the PD activity drops below its"zero time " value.

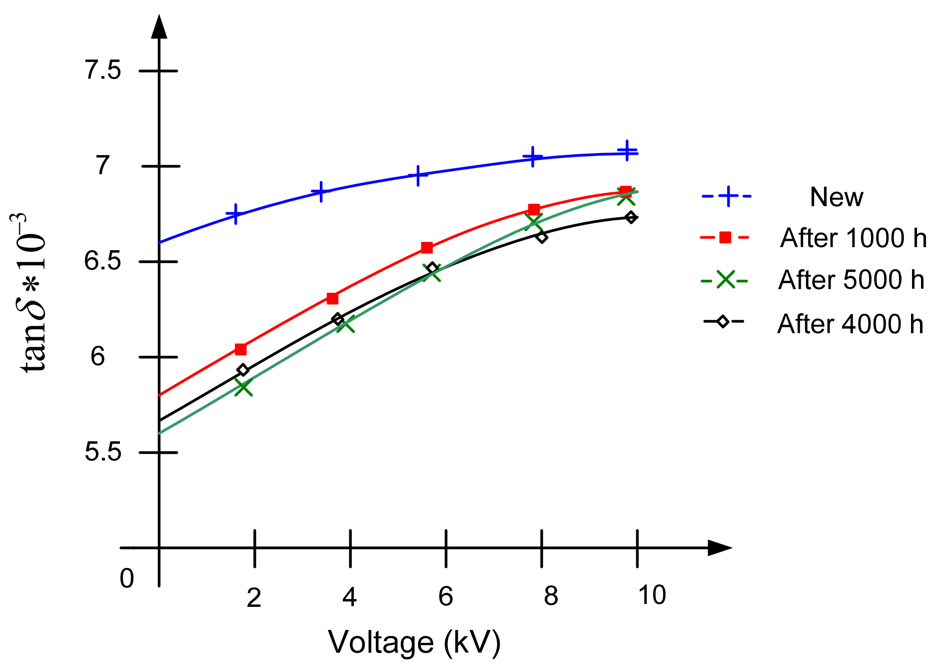


Fig. 4.13 Change in dissipation factor (*tanδ*) as a fiunction of test voltage during the electrical stress of 8.3 kv/mm. [4].

Fig.4.13 shows changes of *tanδ* when we apply different test voltage levels during the electrical aging. As we can see, the *tanδ* decreases after few hours of electrical aging. The origin of *tanδ* decrease is not clear in this case. Probably, the reason is related with a type of post-curing and additional cross-linking in the resin matrix during the time when electrical field was applied [26].

The research of thermal and electrical stresses has been provided on the model stator bars with thermal stress at a temperature of 130 ^{o}C during 500 hours. Fig.4.14 presents that due to drying and post-curing of the insulation during the first hours, a shift in the *tanδ* is observed at all voltages toward lower losses.

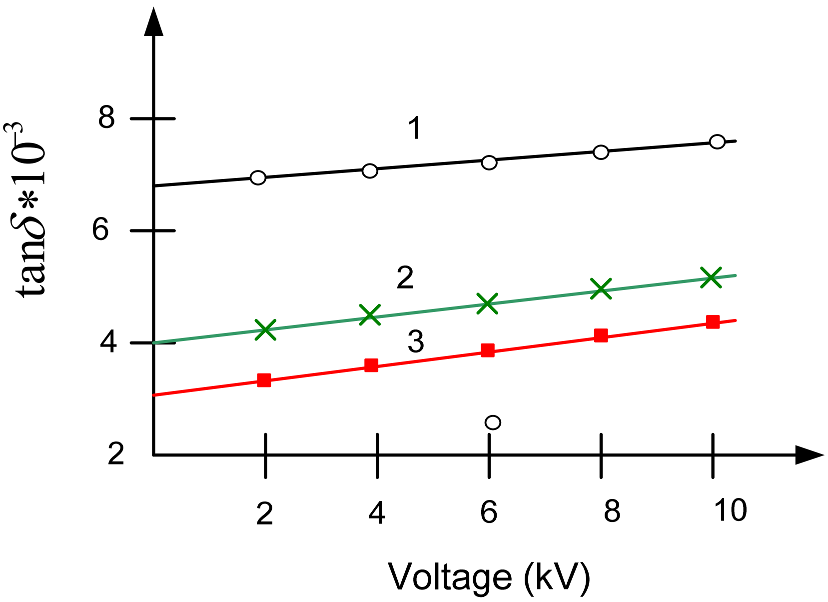


Fig.4.14 Change in dissipation factor (*tanδ*) as a function of test voltage during thermal and electrical stresses: **1** new ; **2** after 500 h of thermal stress at 130 ^{0}C; **3**) after an additional 100 h of electrical stress (8.3 kv /mm) [4].

In a few hours, this change will become insignificant, and the *tanδ* remains relatively constant. After that the test was continued and the electrical stress (8.3 kV/mm) was applied for 100 h to the bar again. This investigation of the dissipation factor, came to conclusion that the electrical stress has a particular influence on the decrease in the *tanδ* [4].

There exists some reasons for delamination within the insulation systems of electronic equipments. For example we can define some of them as thermal and thermo-mechanical stresses. If strong thermal aging was applied, then relatively small parts of the insulation that are not clamped within the slot lose their thermo-mechanical stability and can partly delaminate.

The results clearly indicate the sensitivity of PD measurements to changes within the insulation which are caused by the thermal and thermo-mechanical stresses. The stresses which were mentioned also cause an increase in the *tanδ* in dependence on the test voltage. The dissipation factor *tanδ* can be therefore considered as an important parameter which describes the influence of aging in the insulating systems.

Electrical stress can lead to insulation degradation caused by PD activity and electrical treeing. It was stated that electrical stress can also cause an unexpected decrease in the detected PD activity. Under specific conditions, the discharge process caused by electrical stress within the cavities or voids may assume a pseudoglow or even a pulseless glow character.

It should be noted that conventional PD pulses detectors may not always provide measurement of all PD activities in electronic systems. Many investigations have shown that such degradation mechanism may also not be detected by a *tanδ* measurement [4].

It was confirmed that different defects generate different PD patterns and that the defect type can be thus recognized by pattern evaluation. Consequently, a number of evaluation methods can be used [4].

If the test of PD is performed at different temperatures, it can be detected that relevant change in temperature causes changes in the PD pattern. In the case of slot and end-winding discharges, an increase in temperature leads to an intensification of PD activities; on the other hand, the amplitude and number of PD pulses in the case of internal discharges decrease with increasing temperature. [4]

4.3 Thermo mechanical stress

There are several stresses, which cause deterioration in insulation systems. One of them is thermo-mechanical stresses when during the service time of electronic equipment the heating-cooling cycle is caused by on-off operations. With these load changes, the insulation is thermo-mechanically stressed and ages because of the different thermal expansion coefficients of the materials involved and because of local and temporal gradients.

If the insulating system cannot resist this stress, the bonds between the copper and insulation may tear or fatigue. In addition, PD will occur in the delaminated areas [1],[15],[16]. The coefficients of thermal expansion in core stacks (steel), copper, and insulating material may differ by a factor >10 [1].

The accelerated procedure for thermo-mechanical aging stress includes numerous current heating and active cooling cycles. During each aging cycle, the test object is heated by current (50 Hz) for 30 min. from ambient temperature to 155^{o}C and then cooled by a fan in 30 minutes to ambient temperature (Fig.4.15).

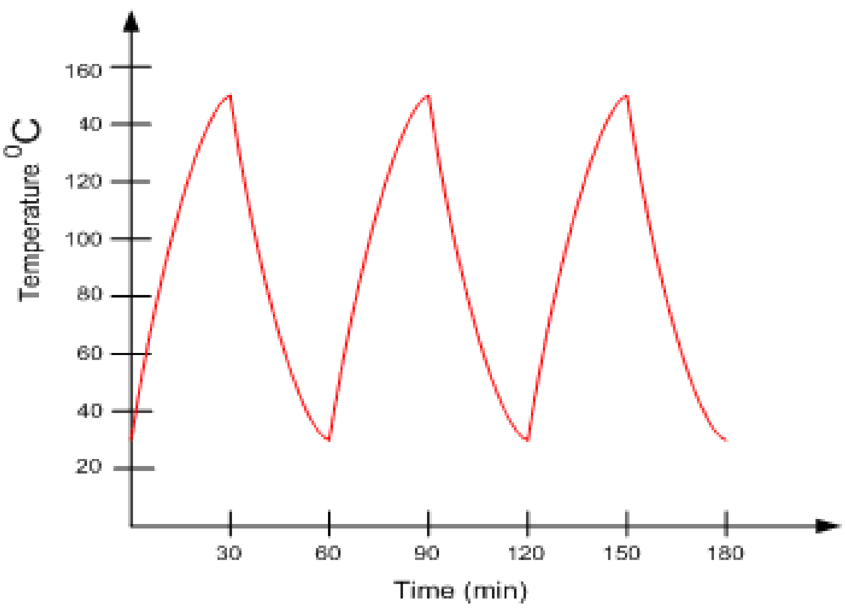


Fig.4.15 Copper temperature profile versus time during the cycling thermal test [4]

Fig.4.16 shows changes of PD activity during thermomechanical stress after several numbers of thermal cycles. If we compare it with the virgin state, it is obvious that PD activity will increase with increasing numbers of aging cycles.

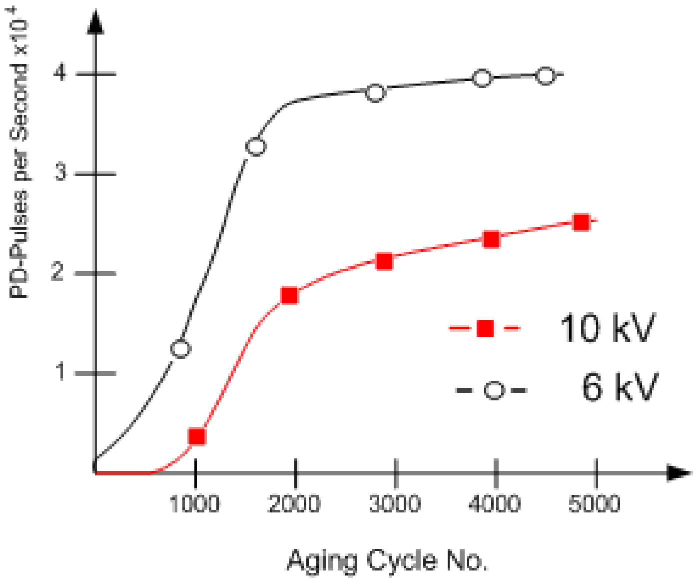


Fig.4.16 Change in the number of PD pulses per second (q>100pC) during thermo-mechanical aging measured at 6 and 10 kV at room temperature [4].

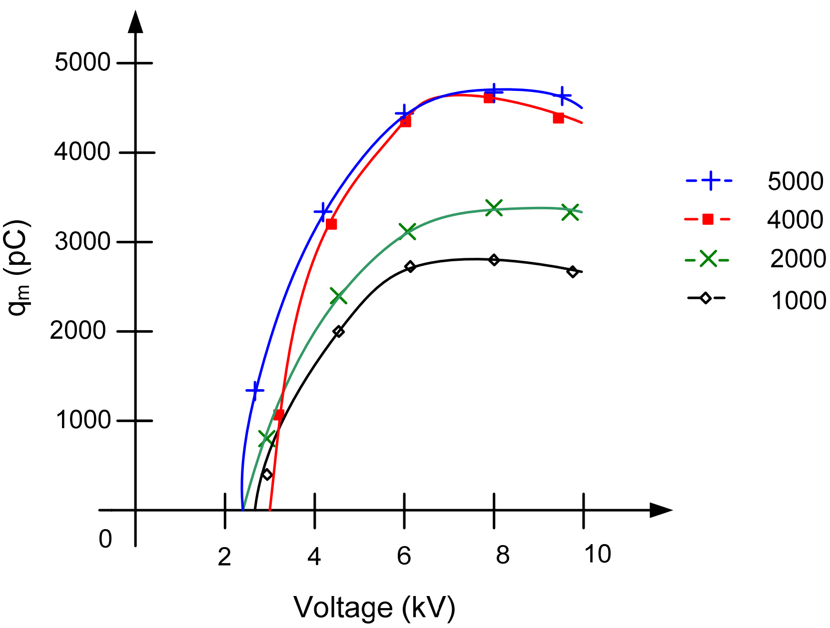


Fig.4.17 Mean value of maximal apparent charges measured at room temperature as a function of the test voltage for different aging cycles with thermo-mechanical stress[4].

After a certain number of aging cycles (about 2500 cycles), this change is very small, and the PD magnitudes are relatively stable because the size of the worst delamination is also approximately stable. The number of voids and delaminations in the insulation generally increase during this period of the aging.

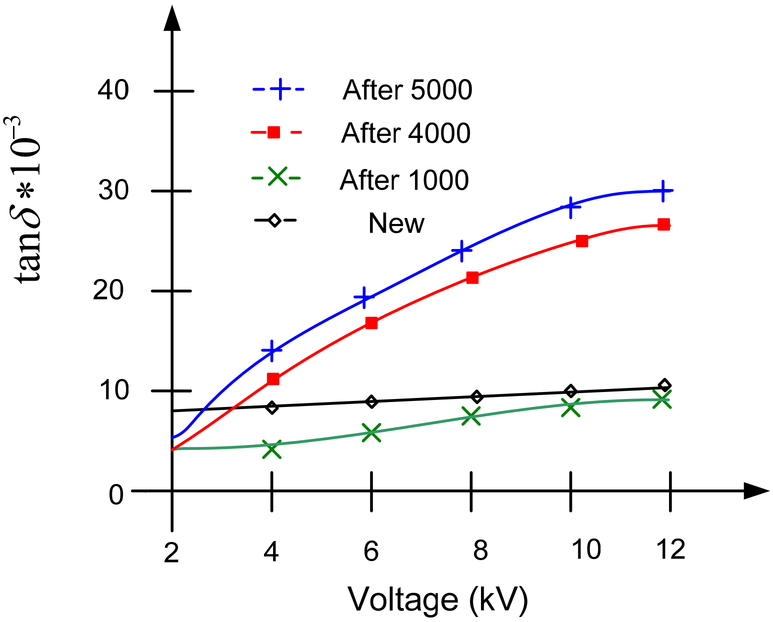


Fig.4.18 Change in dissipation factor (tanδ) as a function of test voltage during the thermo-mechanical aging procedure. [4]

On the Fig.4.17 we can see the PD activity as a function of the test voltage at different aging cycles. The maximum of the charge/voltage curves increases with increasing number of aging cycles, but after approximately 4000 hours this change is very small. The charge increases with increasing test voltage up to a maximum and then remains more or less stable.

Fig.4.18 shows the change of the *tanδ* at different test voltage levels when thermo-mechanical stress was applied. Consequently, testing of the the change in the *tanδ* and the trend of the change can be used as a sensitive parameter for evaluation of this type of aging in the insulating system.

The reason why the dissipation factor *tanδ* generally increases is probably that the number of voids within the insulation (and consequently the number of PD pulses), increases with increasing number of aging cycles. Therefore, *tanδ* is considered proportional to the total volume of discharging voids and two factors which can influence it there are PD magnitude and the number of PD pulses.

As it was shown on the Fig.4.16 the number of PD pulses increase with increasing aging cycles, but it is also possible that because of the higher probability of the occurrence of sequential impulses within a short time and the possibility of overlapping errors. Consaquently, the PD measuring systems may not be able to count all PD pulses. Hence, the *tanδ* measurement can better reflect the changes in the number of voids within the insulation.

5. Influence of PD on the electrical equipments

Partial discharge testing the has been introduced to estimate the lifetime of the insulation without the need of high voltages stress as usually happen in the dielectric tests [1]. An example for a PD source is a small void in ceramics. If the voltage exceeds the breakdown voltage of the gas included, a sudden flash-over discharges the void. This transfer of charge can be consequently measured. PD occurs when increasing the voltage beyond the inception voltage and it disappears when decreasing the voltage below the extinction voltage.

As it was mentioned before - PD are localized releases of internal energy stored in electrical insulation systems in regions of defects in the media and/or at interfaces of different materials. For example PD can occur within a transformer where the electric field exceeds the local dielectric strength of the insulation.

Possible deterioration mechanisms include for example insulation damage caused by over-voltages and lightning strikes or incipient weakness caused by natural aging processes. Although PD may initially be quite small, it is by nature that damaging process causes chemical decomposition and erosion of materials. Left unchecked, the damaged area can grow, eventually risking electrical breakdown.

Insulation failure process exhibits PD events as a consequence of a local concentration of the Electric Field. Different defect typologies can generate different shape of PDs. Among them distributed micro voids, localized macro voids, insulation delaminating, insulation/conductor detachment, slot detachment and in case of power generators and transformers the defects close to bars of different phases on the end of windings are of great importance. Thus, PDs are a symptom of the presence of defects and an indication of degradation process that may cause the failure of the electrical insulation.

Since electrons displace in high electrical field with high velocity and the distance to travel is very short PD pulses have a short duration, typically few nanoseconds. Each PD pulse-current, originated in a localized site of the device passes through the device circuitry till to the detection point. Thus, the detectable PD signals present different shapes depending on the type of defect typology and its location in the device. In general, the magnitude of PD pulses is related to the concentration of the electric field produced by the insulation defect.

Consequently, very small defects tend to produce small PD pulses. In contrast, not always big defects generate large discharges (it depends on the spatial distribution of the non-uniform electrical field). Moreover, insulation failures can be often related to small amplitude PDs originated by small defects, e.g. embedded voids, or by defects located far from the detection point. In the latter case, PD pulses are attenuated and distorted by the electrical noise interposed between the PD source and the detection point.

As the first aspect which always has to be considered is the frequency of working voltage. The heating problems caused by dielectric losses are seldom present in electrical equipment under normal conditions. Only stress frequencies above approximately 1 kHz can cause problems. In relation to the first mentioned stress, a partial discharge test is required if the peak voltages involved are above approximately 500 V (peak value). The test voltage is usually a 50 Hz AC voltage. High-frequency stress could, however, require tests with increased frequency of the test voltage.

In conclusion, there should be noted that the amplitudes of the test voltage which are used in standard dielectric tests seem rather high. Generally, AC voltage tests with such high amplitudes should be combined with a partial discharge measurement, since then the possible deterioration of the solid insulation can be avoided or at least detected, and additionally much more accurate information on the properties of the insulation design can be collected.

5.1 Influence of electrical treeing

During the testing experiments with PD some correlation between PD activity and electric insulation life were defined. As it was mentioned before, one of the factors that can influence electrical degradation process is electrical treeing.

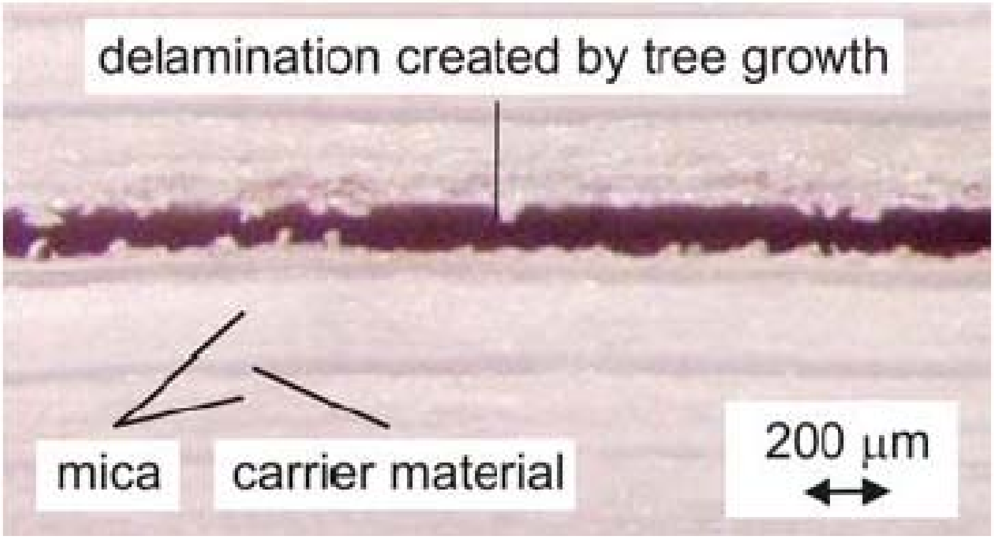


Fig.5.19 Delamination caused by tree growth in material [5].

This mechanism is important mainly for devices where layered insulation is used. As the result of the influence of high electrical stress in case of generator bars for example, where the insulation is made by mica tape, the tree spreads between the layers of mica tape until it can propagate to the adjacent level.

The discharges in a delamination can spread radically between the layers of mica tape [11]. Distinctive delaminations are thereby created as seen on the Fig. 5.19.

In this case no distinguished rise in PD could be measured before breakdown. From the calculations taken, it can be assumed that the tree growth did not cause large delaminations and that the discharges therefore did not significantly rise in magnitude.

It was reported that during the measurement the PD´s intensity for this material can heavily rise shortly before breakdown occurs. Continuous recording of the PD data is therefore recommended. As a result, this example demonstrates that one of the main factors of delamination within the layered material is treeing.

6. Measurement of PD in electronic devices

In-service PD measurement is used to make an assessment of the progressive degradation of electrical apparatus under operational stress and to minimize the possible outage time. Modern PD instrumentation and sophisticated digital techniques allow a wide range of approaches for the analysis of PD signals despite of the transient nature of the PD signals which limits available processing options.

Measuring methods are usually based on detecting one or more of the electrical, chemical and acoustic (i.e., mechanical) phenomena that are associated with PD. The design of in-service PD testing apparatus is complicated by various types of noise in industrial environments, which may limit PD detection sensitivity, to the level above that required for effective diagnosis [21].

In high-voltage engineering, the requirement of PD-testing is recognized as obvious in general because of the existence of high electrical field stress. However, due to the very small insulating distances in modern electronic equipments similar or even higher electrical fields can occur.

In the past, this aspect was only taken into account when very high stresses occurred or very high reliability was required. However, recent technologies with decreasing insulating distances require a reconsideration of this situation. As a lower physical limit for the occurrence of PD, a peak voltage of 300 V may be considered. According to practical experience, PD can occur when peak voltages in excess of 500 V are applied.

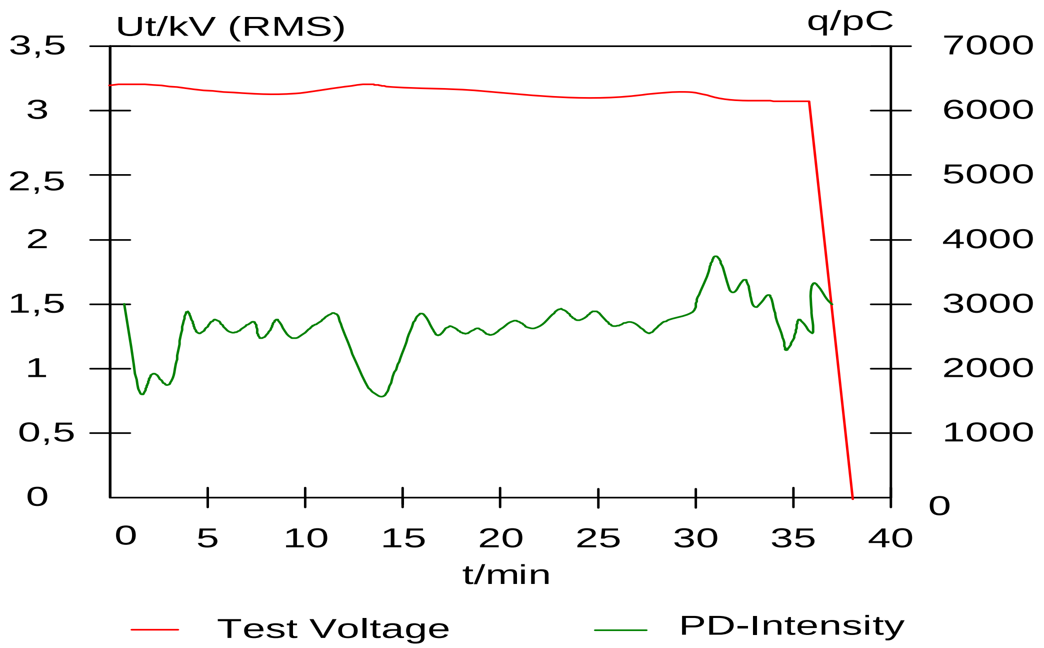


Fig.6.20 PD-withstand capability of insulating films; constant voltage stress (50 Hz)[3].

For example in insulation systems with solid insulation PD occur far below the breakdown voltage. During a long period, these can cause the destruction of nearly all solid insulating materials. This is especially important when the working frequency is higher than a few kHz.

During investigations of PDs measurement the question occurs: “How much time will pass until the PDs destroy the solid insulation”. The result of such lifetime investigations depends on many parameters; therefore, statements with general validity cannot be made.

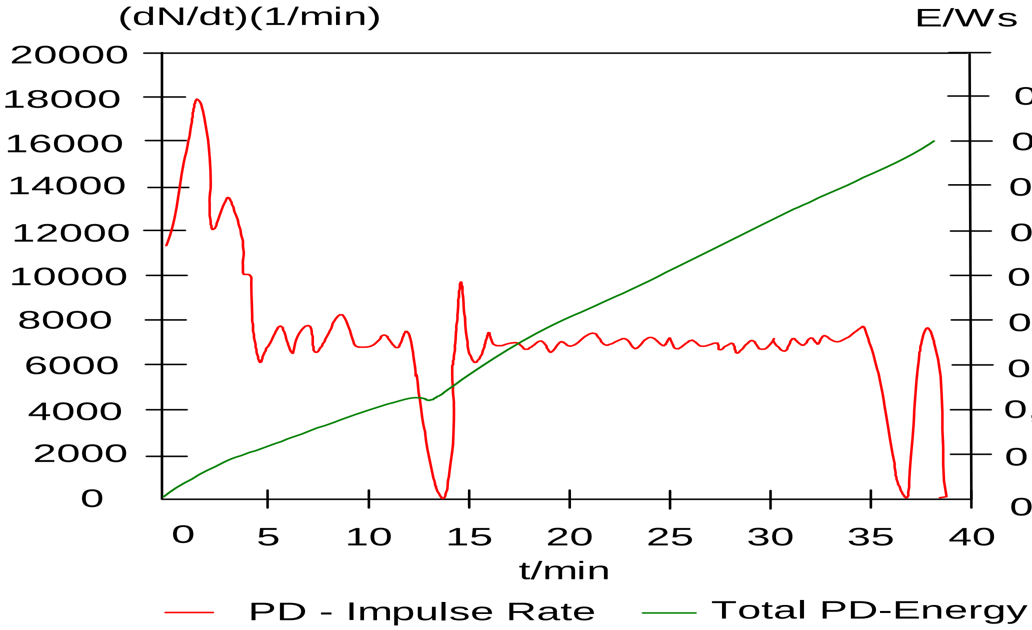


Fig.6.21 PD - withstand capability of insulating films; increasing voltage stress (50 Hz)[3].

In the next example the time duration until insulation failure under unfavorable conditions is so short that during the usual voltage test permanent damage of solid insulation is possible [3]. The device is a printed circuit board covered by an insulating film where the stress is applied between a conductor and a neighboring soldering pad at a nominal distance 0.4 mm.

After high voltage is applied to test the insulation strong PD exists underneath the insulating film (coating), this finally results in the deterioration or destruction of the test sample.

Fig.6.20 shows this result for a constant test voltage U_t of 3.15 kV (RMS). In such case the test voltage is already 45% above the PD-inception voltage U_{inc} = 2.2 kV (RMS). Because of the high quality insulating material, the test sample was able to withstand this stress for approximately 37 minutes displaying the charge Q transferred in the PDs in the range of nanocoulombs.

As shown in Fig.6.21 such a stress is already so severe that for each period of the AC voltage, in most cases, several PD-pulses occur. The total energy of the PD-pulses until insulation failure amounts to 0.8 Ws [3].

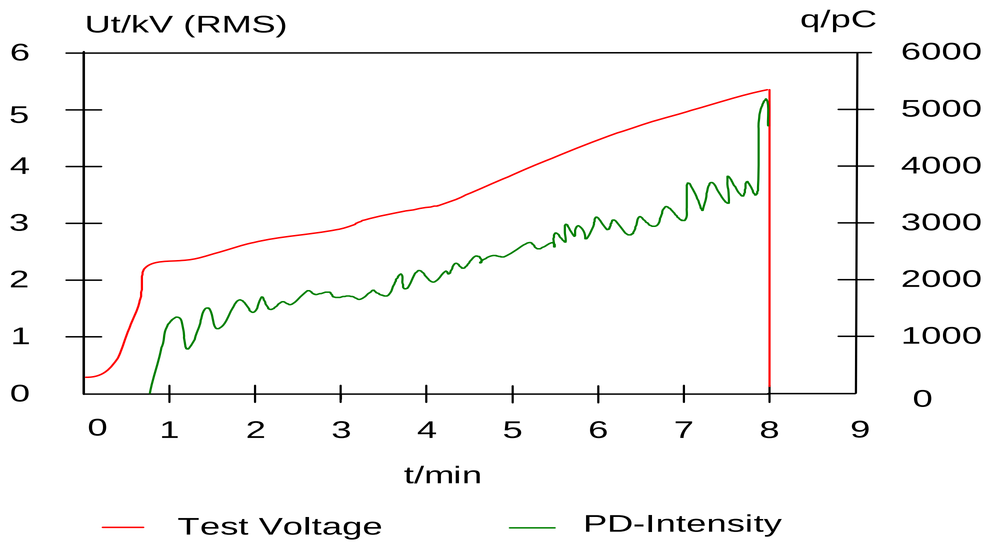


Fig.6.22 PD-withstand capability of insulating films; constant voltage stress (50 Hz);

Fig.6.22 shows the case when the test sample is stressed by an approximately linearly-increasing test voltage U_t, where a voltage rate of rise of about 0,4 kV per minute. The PD-inception at 2.2 kV is clearly visible. Typical for these test samples is the immediate occurrence of very high PD-intensity.

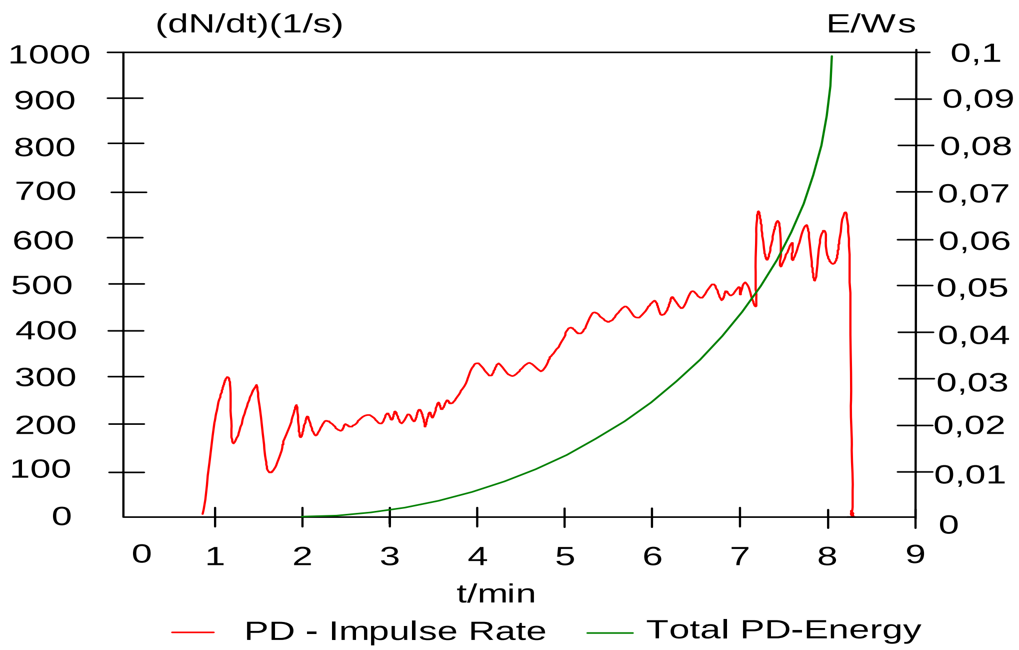


Fig.6.23 PD-withstand capability of insulating films: increasing voltage stress (50 Hz).
Total energy of the PD pulses $E = \Sigma\, N.U.q$ [3].

In Fig.6.23, near the PD-inception, the PD-pulse rate is about two per period of the test voltage; that means, on average one impulse per half-wave is occurring. PD intensity, as well as PD-pulse rate, is approximately proportional to the value of the test voltage.

The test sample can withstand the apparently much higher stress only for about seven minutes. The total energy of the PD-pulses, which lead to insulation failure with 0.1 Ws, is also much lower. This example shows very clearly that, at least for certain test samples strong partial discharges have a destructive potential during a relatively short period of time [3].

6.1 Philosophy of PD-testing

PD can affect the insulation system reliability in different ways, depending on the insulation system characteristics. Indeed, some insulation systems (particularly mica based) are designed to withstand a moderate level of PD occurring in distributed micro-voids (internal discharges), while others (organic-polymer based) are degraded very fast by PD activity.

Discharge phenomena produced by different kinds of defects may mix their characteristic features, so that recorded patterns cannot be easily deconvoluted, and thus may result in inaccurate risk assessment. The picture may be further complicated by the presence of significant external noise.

Determining whether electrical equipments are suffering from internal arcing or dangerous levels of PD is important because failure without warning can result in damage to large equipments, customer dissatisfaction, and in some cases also possibility of imposition of regulatory fines. Effective management of PD diagnostic is therefore important for power generation, power transmission and power distribution companies. In case of electronic equipments, this is not common praxis, but there are many attempts in the PD testing on component level.

The most accurate time-acceleration ageing can be made for pure thermal stress. However, this can be utilized only if there is a simple mechanism, such as chemical ageing, for example. If, the deterioration mechanism changes during the accelerated stress, the time acceleration is no longer permitted. Especially when applying increased electrical stress to achieve time-acceleration, a change of the deterioration mechanism is likely to occur [19].

6.1.1 Breakdown Voltage in conventional test

The ASTM (American Society for Testing and Materials) definition of dielectric breakdown voltage is: the potential difference at which dielectric failure occurs under prescribed conditions in an electrical insulating material located between two electrodes. This is permanent breakdown and is not recoverable.

It is obvious that the results obtained by this test can seldom be used directly to determine the dielectric behavior of a material in an actual application. Here should be noted that this procedure is a “Proof Test” which is used for detection of fabrication and material defects to the dielectric insulation. Obviously this test is not a “fit for use” test in the application because due to the variety of devices, dielectric types, thicknesses and layouts of dielectric layers the electronic devices differ each to other.

In first view all insulated metal substrates closely resemble to a parallel plate capacitor where the capacity is:

$$C = \varepsilon . \frac{A}{d} \qquad (6.1.1)$$

where: ε = Permittivity , A = Surface Area, d = Distance of electrodes.

The capacitance value changes with different configurations of device and dielectric materials. Therefore, it is very important to properly design the testing and test parameters with the material characteristics in mind. Test set-up arrangements and choice of parameters that over-stress or do not consider reactance of the material and its capacitive and resistive components, can lead to false failures and/or test induced damage.

Another test characteristic that is generally misunderstood with insulated metal substrates is the leakage and charge current that take place during the test. In most cases, the leakage current value on insulated metal substrates is much smaller than the current measured as consequence of partial discharge. Leakage current measurements can only be realized once the insulation system has been brought to the full test voltage (DC voltage) and is held at that voltage during the test. This current value and rate dI/dT is directly related to the capacitance of the system investigated. Therefore, a device that has an effective capacitance higher than another device will have a higher charge current rate than the one with a lower effective capacitance.

6.1.2 Inception and extinction voltage by PD test

There are two necessary conditions for an electric discharge to start in air: the electric field strength must be high enough and there must be a free electron available to start an electron avalanche. The voltage at which the first condition is fulfilled is called the inception voltage U_{inc}. Sometimes there is a lack of free electrons to start the electron avalanche. This results in a delay in time between that the inception voltage is exceeded and the discharge starts. The average of this time delay is called the statistical time lag τ_{stat} . Once a discharge has started it continues until the electric field strength is too low to run the discharge. The voltage at which the discharge stops is called the extinction voltage U_{ext}. Consequently, two parameters are important for the judgement of the PD behavior.

PD Inception Voltage U_i : The PD inception voltage is determined by a stepwise or continuous increase of the voltage applied to the test object. U_i is the voltage, where measurable PD starts. Note that the sensitivity of the measuring system and the existing ground noise during the measurement influence the recording of the inception voltage.

PD Extinction Voltage U_e : The PD extinction voltage is the voltage at which PDs are still observed when voltage decreases. PD sources often show a hysteresis response regarding the inception and extinction voltage. The PD in ignited locations are often only extinguished below the PD inception voltage. The value of the extinction voltage is important for the judgment of the risk factor.

As the voltage over the channel reaches the inception voltage level a discharge starts. The discharge continues until the voltage over the channel has dropped below the extinction voltage level. After that the voltage build-up over the channel starts over again.

6.2 PD testing of electronic devices and components

Measurement of PD has for long been used to assess the condition of high voltage insulation in components such as bushings, capacitors, transformers, and switchgears. During preventive maintenance programs of electrical apparatus, diagnostic tests are performed to evaluate the likelihood that apparatus can remain in operation without experiencing outages until the next planned maintenance, or must be taken out of service immediately.

In-service PD measuring is used to assess the progressive degradation of electrical apparatus under operational stress to minimize the outage time. Modern PD instrumentation and sophisticated digital techniques allow a wide range of approaches for the analysis of PD signals despite of the transient nature of the PD signals, which limits available processing options.

There are some electronic components in which we can test PD such as: optocuoplers, transformers or printed circuit boards (PCB) substrates. For example the purpose testing of PD on substrates is to verify that no defects reside in the dielectric material. In the case if we want decrease frequency of origin PD we can use anti-solder mask on the printed circuit board. Using of anti-solder mask can substantially raise both inception and extinction voltages when partial discharge is detected. Potting the completed assembly can eliminate partial discharge.

6.2.1 Optocouplers

In the past a lot of tests were applied for optocouplers and many results has been used for a long period with success. The insulating distance between the light transmitter and receiver is here in the range between 0.15 and 1 mm. Consequently in this insulation system exist very high fields, especially during high-voltage testing. On the other hand, if the insulation is of high quality then the structure is essentially without gaps and PD may not necessarily occur. Such characteristics can be verified during testing of different types of optocouplers.

For the smallest optocouplers currently used insulation distances are from 0.15 mm up to 0.4 mm. For voltages in excess of approximately 2 kV (RMS) PD has been observed for optocoupler with insulation distance 0,4 mm (Fig.6.24). With transferred charge in the order of 10 pC the PD-intensity is rather small - the test equipment used must therefore provide high sensitivity. On the Fig.6.25 PD results in case of smaller insulating distances d = 0.15 mm are shown. It is obvious that in this case PD already can exist for voltages of approximately 1 kV (RMS). The average PD-intensity in that case is higher [3].

It is obvious that the thickness of solid insulation, has some influence on the PD-characteristics. Nevertheless, this is only one of the many parameters. Other parameters such as the structure of the insulating system and the proper processing of the insulating material have the same importance. Consequently, the thickness of the solid insulation cannot be the only dimensioning criterion as is the current practice.

In addition a determination of behavior of the insulation system with thickness less than 1 mm is difficult during the usual “type testing” and is nearly impossible during routine testing. In case of the high-voltage type testing with elevated test voltages (for instance 4 kV RMS), PD is likely to occur during the test. Therefore, at least during type testing with usually “one-minute test duration” a degradation of the insulation material has to be expected.

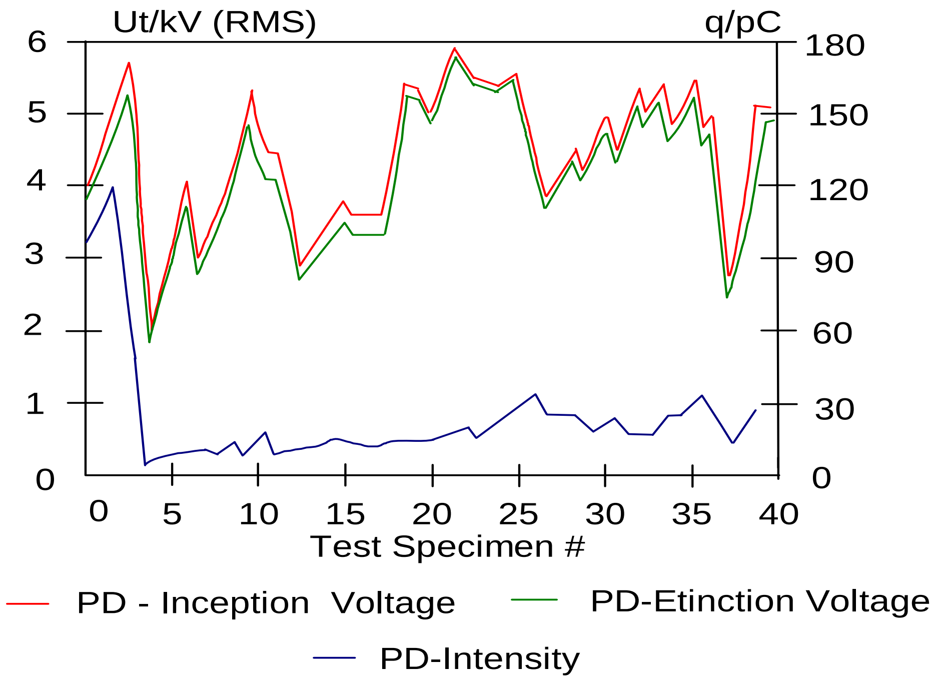


Fig.6.24: PD-testing of optocouplers; virgin state; nominal insulation distance 0.4 mm [3].

After high voltage testing without PD-measurement, which would allow the detection of the progressive degradation, a further use of the test specimens implies a significant risk. It has also to be noted that, very likely, all optocouplers with greatly different results in PD testing would have passed the traditional high-voltage test. Therefore this high voltage test can only be considered as a rough criterion, and only allows the detection of major defects.

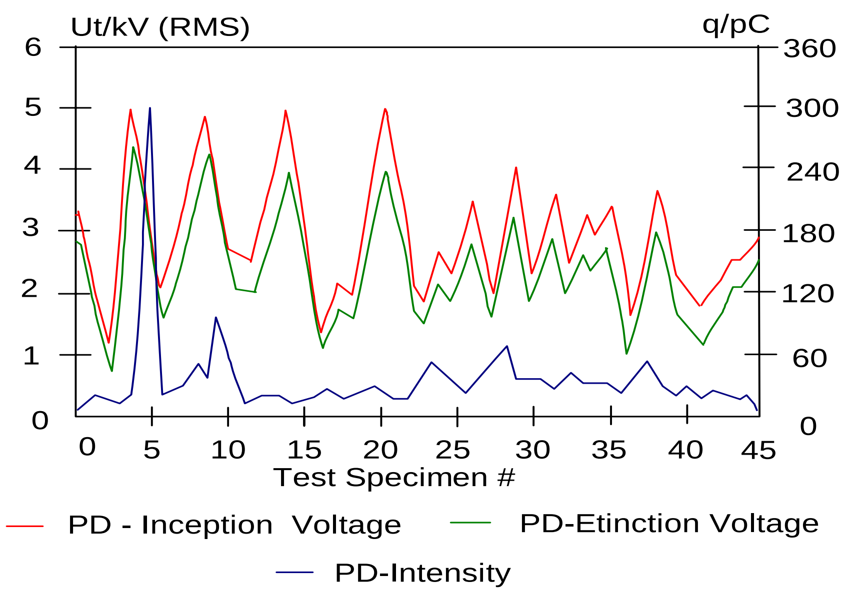


Fig.6.25 PD-testing of optocouplers; virgin state; nominal insulation distance 0.15 mm [3].

6.2.2 Transformers

Transformers are widely used for electrical separation, and usually two or three thin foils are used for primary to secondary insulation. About the PD-characteristics, not much information seems to be available.

Insulation systems that are not molded can have strong PDs in order of some 100 pC even at 700 V (RMS). Since these discharges usually are external (corona), the degrading effect may not necessarily be very high. For the detection of these external discharges very simple test methods can be used.

Molded transformers in general provide much higher PD-inception and PD-extinction voltages. As shown in Fig.6.26, these can be between 1.5 and 3 kV (RMS). Ignition transformers can exhibit PD-voltages in excess of 4 kV (RMS), as shown in Fig. 6.27.

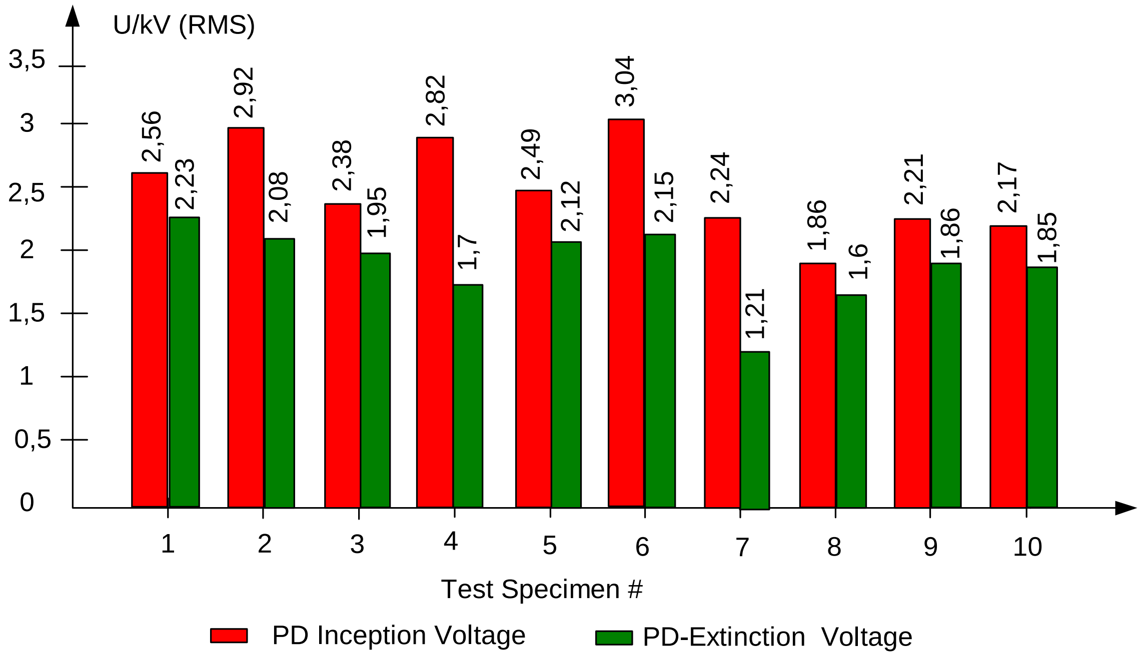


Fig. 6.26 PD – testing of transformers for switched mode power supplies; virgin state [3].

Fig.6.27 shows that the PD intensities usually increase with increasing test voltage, test voltages exceeding the PD-inception voltage should not be applied during any routine testing. On Fig.6.28 we can see higher PDs activity when the test voltage exceeds 4 kV. In such a case strong PDs are likely to reduce the expected lifetime even during rather short duration tests.

At present time, for using typical test voltage up to 4 kV (RMS), PD is likely to occur during the test. During longer test duration or by repeating the test, a degradation of the insulation is to be expected. This situation can only be detected if PD-measurement is being performed during the high voltage testing.

During operation of the device, a significant temperature increase at the insulation system will occur, which will influence the insulation characteristics as seen on the Fig.6.29. The influence of the manufacturing tolerance has been reduced by evaluation of the mean values from eight test specimens. A serious problem seems to be that the PD-extinction voltages are greatly reduced at the highest temperatures [3].

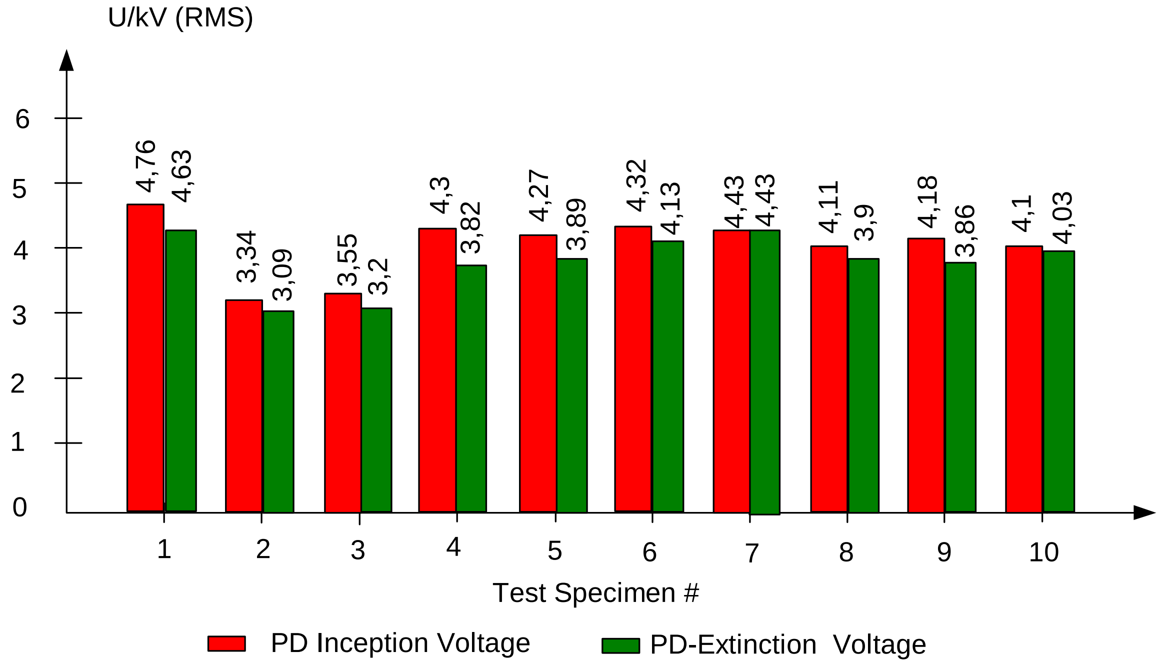


Fig. 6.27 PD – testing of ignition transformers; virgin state [3].

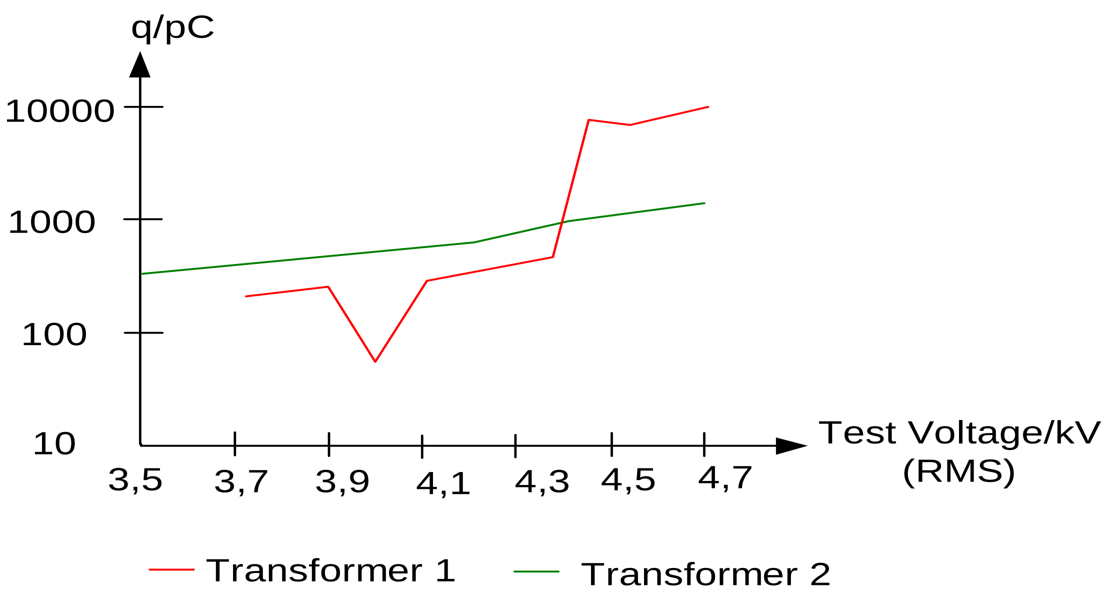


Fig.6.28: PD-testing of ignition transformers ; virgin state; the test voltage is increased beyond the PD-inception voltage [3].

For transformers, the frequency of the voltage is an important influencing factor. By increasing the frequency above power frequency, the PD-characteristics are changed significantly. Fig.6.30 shows, that the PD-extinction voltages are markedly reduced. The PD-intensity is not specifically high, but with the increasing of the frequency of the voltage, the repetition rate of the PD-pulses will increase proportionally, which exhibits an increasing potential of degradation [3].

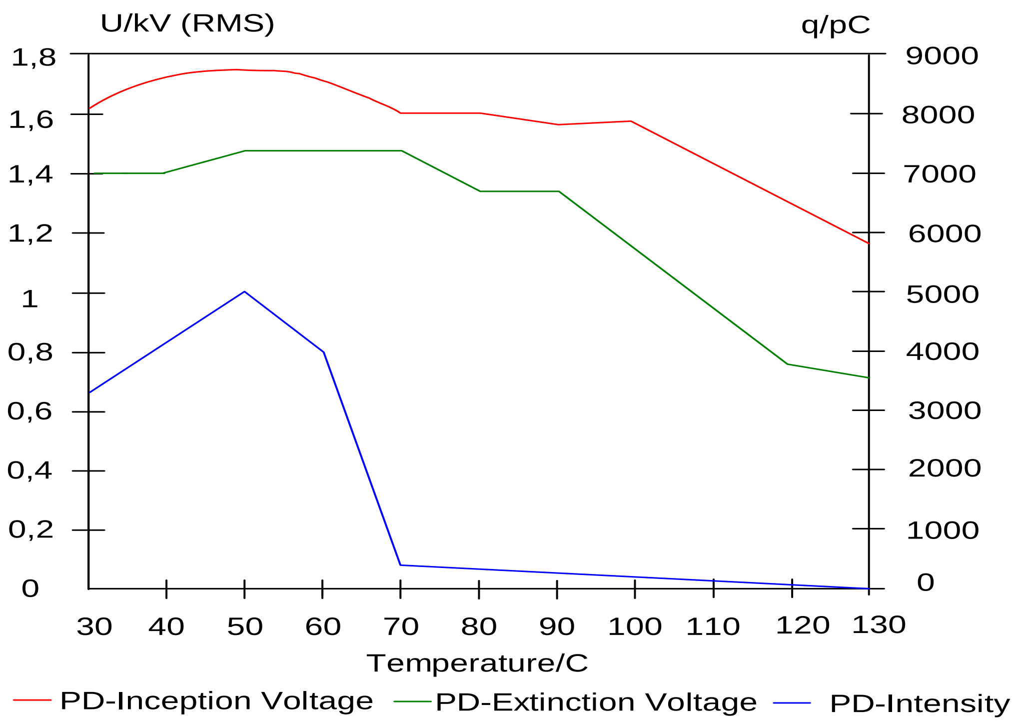


Fig.6.29: PD-testing of transformers for switched-mode power supplies; Values given are mean values for 8 specimens. [3]

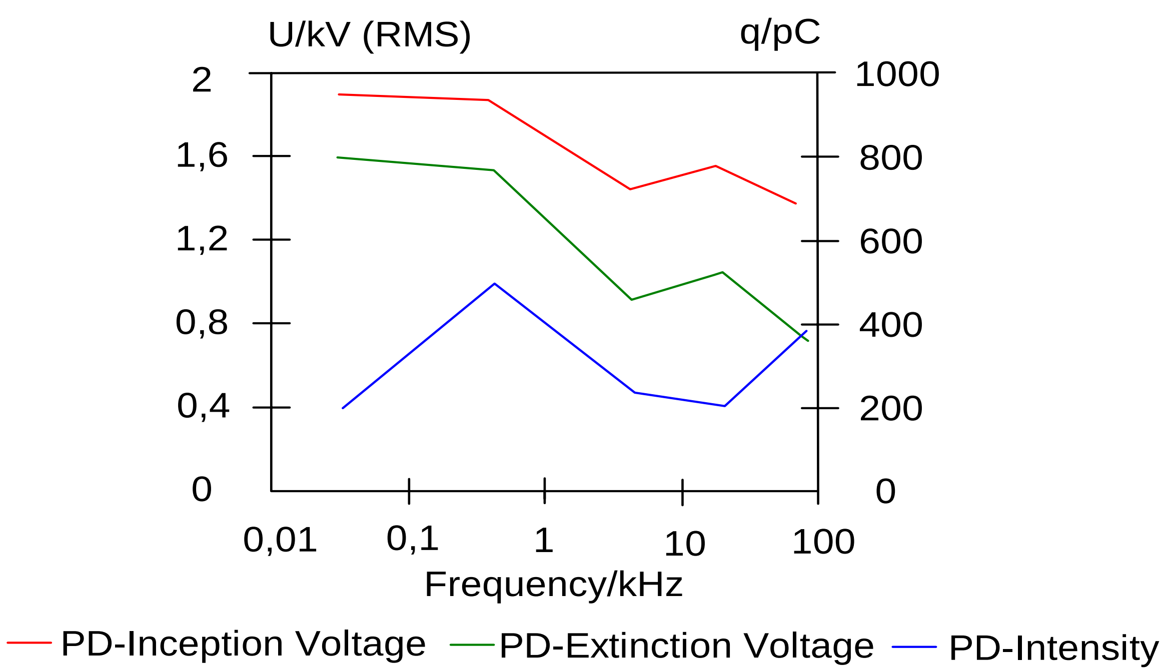


Fig.6.30: PD-testing of impulse transformers ; influence of the test frequency of the voltage. [3]

6.2.3 Coated printed circuit boards

Dielectric testing of varnishings or coatings is of special interest. In this case the real thickness of the insulation cannot be evaluated in practice; the PD-test is the only reliable method to verify the insulation capability. At the same time, the homogeneity of the insulation is verified.

A thin enamel coating is used, for instance, in combination with a membrane switch keyboard for insulating of crossing conductors. In this case the insulation is not a safety-related application, but the coating has to be regarded as a functional insulation. PD testing has here a high application potential with respect to quality insurance. The PD-test will provide detailed information about the quality of the enamel coating and its precise positioning.

Measurements of coated printed circuit boards have shown that some varnishings and, especially, solid films can improve the insulation characteristics. However, this can only be evaluated in detail if PD-testing is performed. An example is shown in Fig.6.31 for distances between parallel conductors from 0.25 to 0.9 mm. For comparison - the breakdown voltages without varnishing for homogeneous and for non-homogeneous clearances are also plotted [1]. It is obvious that for small distances between the conductors such coatings can significantly improve the insulation characteristics.

Coatings can also be used in order to reduce and to control the pollution at the surface of the printed circuit board [4]. This requires a homogeneous type of coating that lasts for the expected life of the equipment under the predicted environmental stresses. Such characteristics can be verified by using the PD-test after appropriate conditioning of the test specimen. Very high-quality coatings may even allow reduction of the clearances and creepage distances to something less than the usually required minimum values. However, the performance of such coatings can only be verified by appropriate conditioning and successive PD-testing [4].

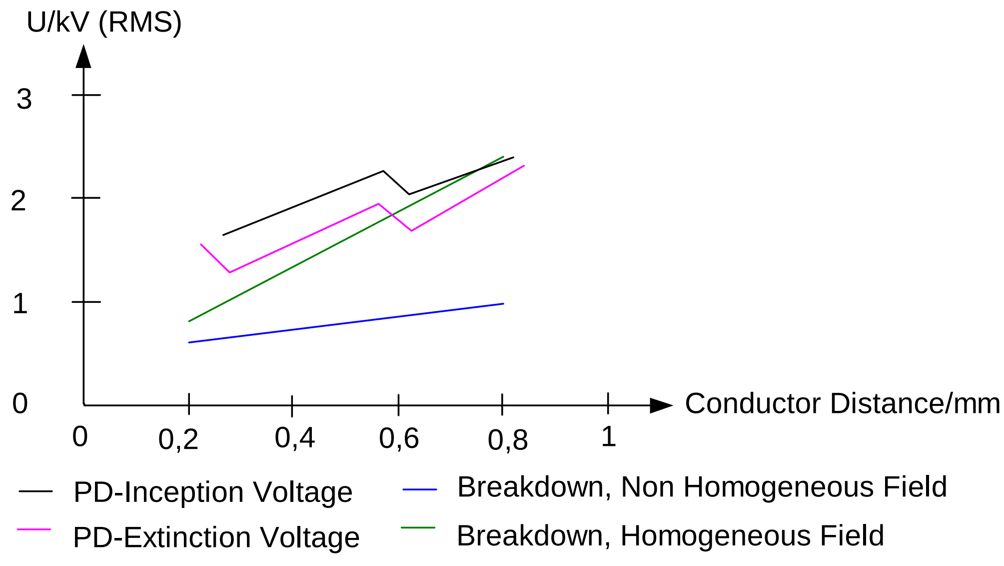


Fig.6.31 PD-testing of coated printed circuit boards; virgin state [3].

Many investigations have been performed on how the various influencing factors affect the insulation characteristics of coated printed circuit boards [5]. As shown in Fig. 6.32, a temperature increase usually has a degrading effect on the insulation characteristics.

To take this and other ageing factors into account during short time testing, an increase of the PD-test voltage above the highest working voltage stress by certain factors [1] is needed. In no case may PD occur due to operational stresses as the PD-intensity is usually very high and insulation failure has to be expected after a short time.

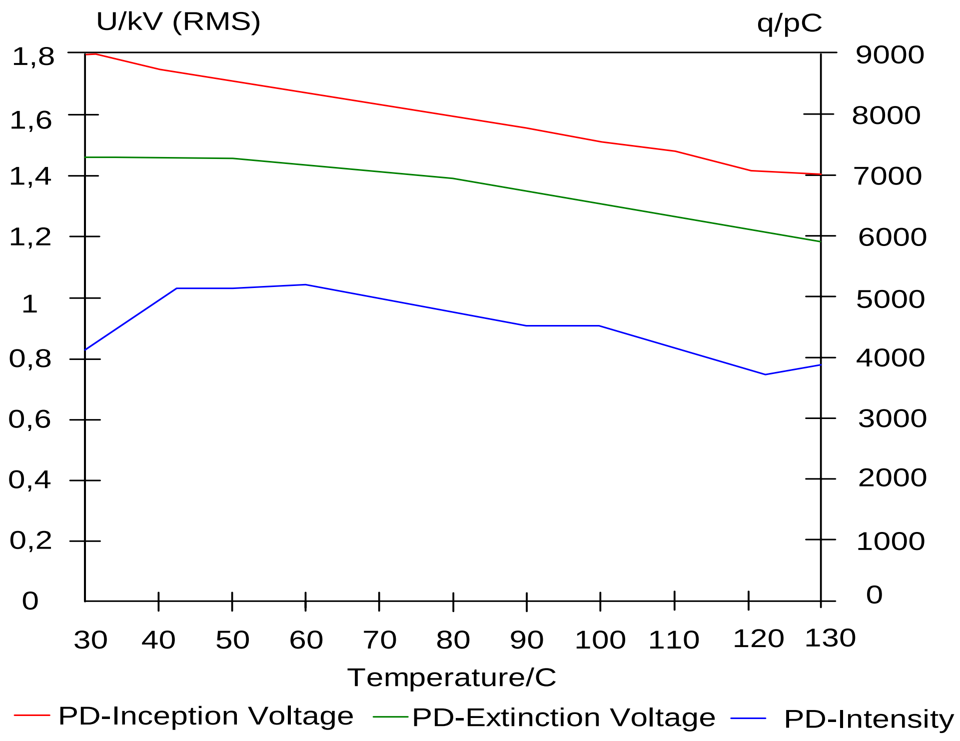


Fig. 6.32 PD-testing of coated printed circuit boards; d=0,4 mm, mean values.[3]

On Fig.6.33 is shown a comparison of PD-inception voltages of coated printed circuit boards with different types of varnishings and solid films. The tests were obtained after different types of conditioning.

According to the intended use of printed circuit boards, any conditioning must include a soldering procedure. This seems to represent a very high stress for the coating, much higher than that of any other conditioning procedure that was used in addition to soldering. As a result, solid films exhibit superior insulation characteristics as compared with varnishings [3].

For coated printed circuit boards, the insulation characteristics are not affected very much by the frequency of the voltage. As shown in Fig. 6.34 for different conductor patterns, the PD-inception voltage is only slightly reduced with the frequency of the voltage. Nevertheless, 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.

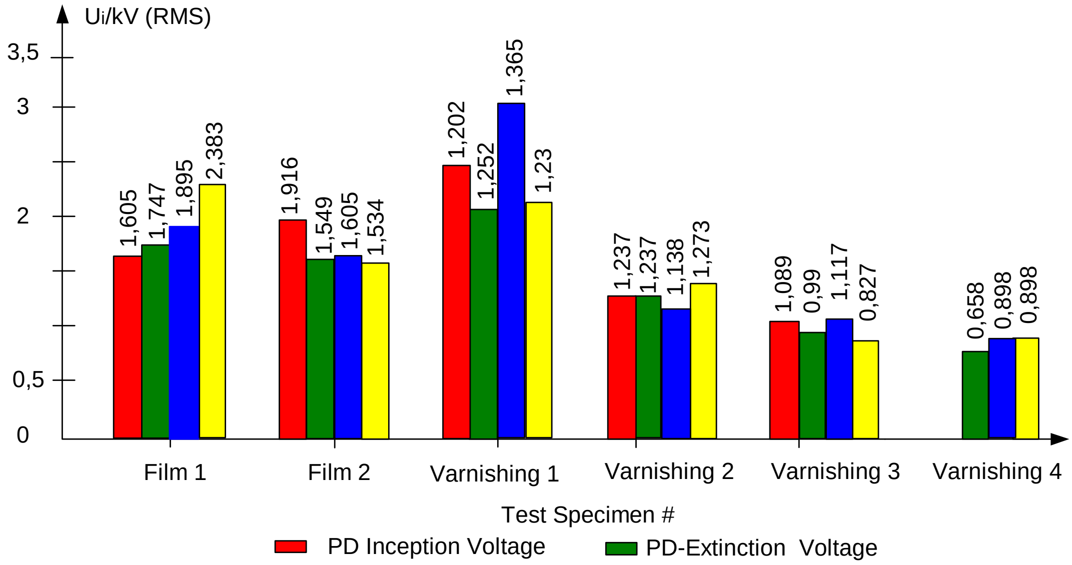


Fig. 6.33 Testing of coated printed circuit boards; d=0,3 mm; component side. PD activity is demonstrated by U_{inc} : Conditioning #1: soldering, Conditioning #2: soldering + 21days climate 40/93, Conditioning #3: soldering +50 cycles -10°C/+125°C +21d climate 40/93, Conditioning #4: soldering +4d – 25°C+ 56d +125°C + 50 cycles -10°C/+125°C +21d climate 40/93.[3]

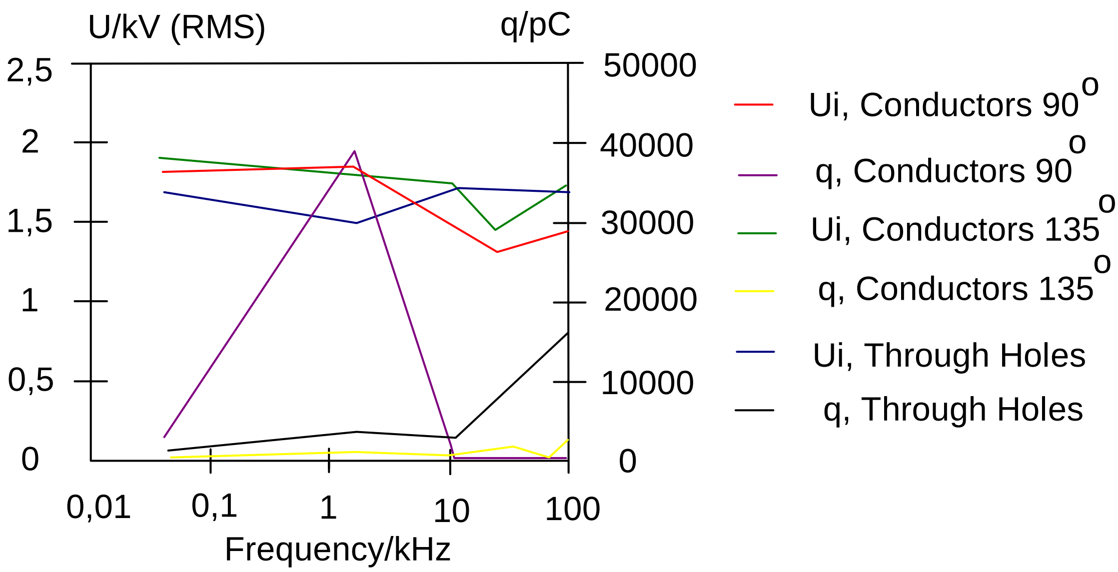


Fig. 6.34 Testing of coated printed circuit boards; d=0,2 mm. PD activity is demonstrated by U_{inc} [3].

6.2.4 IGBT modules

IGBT transistor is a modern device which is potentially able to have very high working voltage. Obviously, electrical insulation is of great importance in such a case and all manufacturers make PD investigations and testing to ensure reliable work of the device.

In reference [6] is described how PD testing helped to elevate the safe working voltage and to reduce PD level of the 3.3 kV IGBT. As shown in Fig.6.35 it had low inception and extinction voltages and partial discharge values were in the range of 200 to 300 pC. From that reason the voltage has to be limited during the first test runs on complete modules to 5 kVrms, 1 min.

On Fig. 6.36 there is an example of PD activity in new insulation structure with very low inception and extinction voltages typical for this material. Testing with voltage up to 6kV RMS is possible with very low PD activity, which is typically below 10 pC.

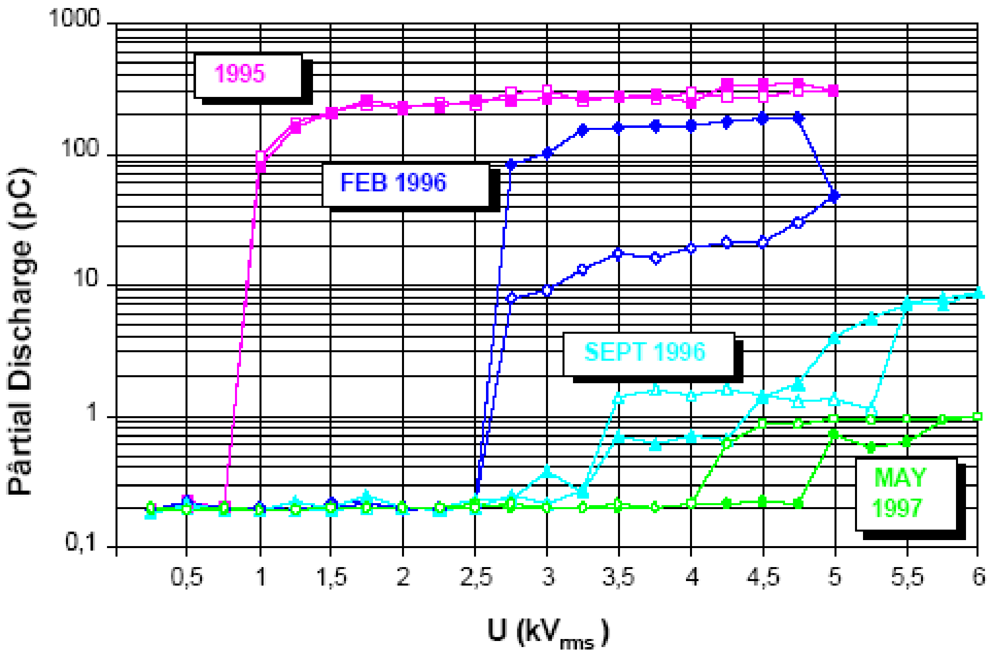


Fig. 6.35. PD-Improvements on 3.3kV IGBT Modules [6].

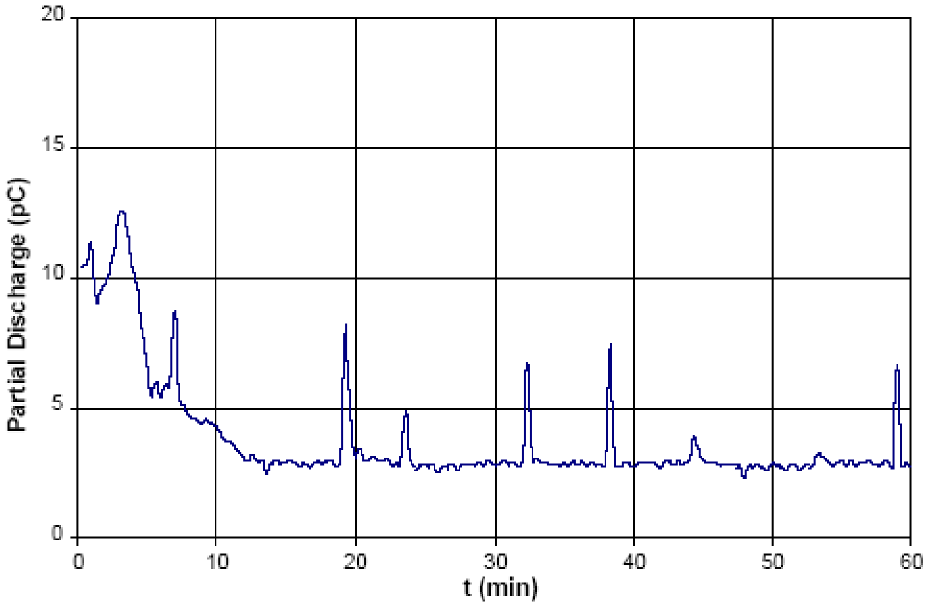


Fig. 6.36: PD-test of a 3.3kV IGBT module with enhanced insulation capability.
Test conditions: Up = 6 kV RMS, t = 60 min [6].

6.2.5 Other electrical components

In addition, standard components within electrical equipment should be tested with respect to their PD-characteristics. Fig.6.37 shows the PD characteristics of heating elements used in electrical appliances. As shown before the PD usually occurs at test voltage value of approximately 1,5 kV (amplitude more than 2 kV). The mentioned voltage is actually considered for routine testing, but it is a significant risk of degradation since some test specimens (samples 10 and 11 in Fig.6.37) already have shown strong PD activity at such testing voltage levels. It has to be assumed that the types of ceramics being used in heating elements cannot withstand PD for a long period of time [3].

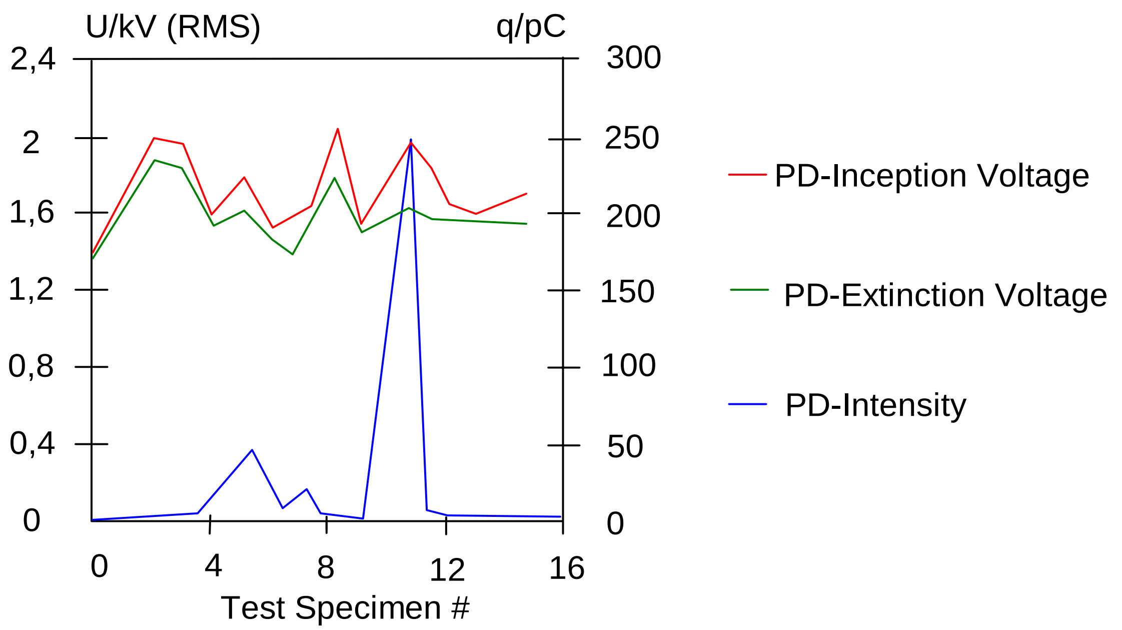


Fig. 6.37 Heating elements (220 V/2850 W); PD characteristics demonstrated by U_{inc} ; virgin state [3].

6.2.6 Solder mask on PCB

The way how to verify that there has been no degradation of the dielectric material as consequence of fabrication process or any material defects is to manage measurement of PD on substrate. Continuous testing at usually used voltage levels will only take away from the life of the dielectric on the circuit board. In the past it was repeatedly verified that the testing of PD above the inception voltage of partial discharge will detect any defects in the dielectric insulation.

Any micro-fractures, delaminations or micro-voids in the dielectric will cause breakdown or respond as a short circuit during the test. The area of test voltage levels typically used ranges from 1500 to 2250 V_{DC}. Because of capacitive nature of the circuit board construction, it is necessary to control the ramp up of the voltage to maintain effective control of the test. This is to avoid premature surface arcing or voltage overshoot. After the test, from safety-related reasons, the operator must verify that the board tested is fully discharged, prior to removing from the test fixture.

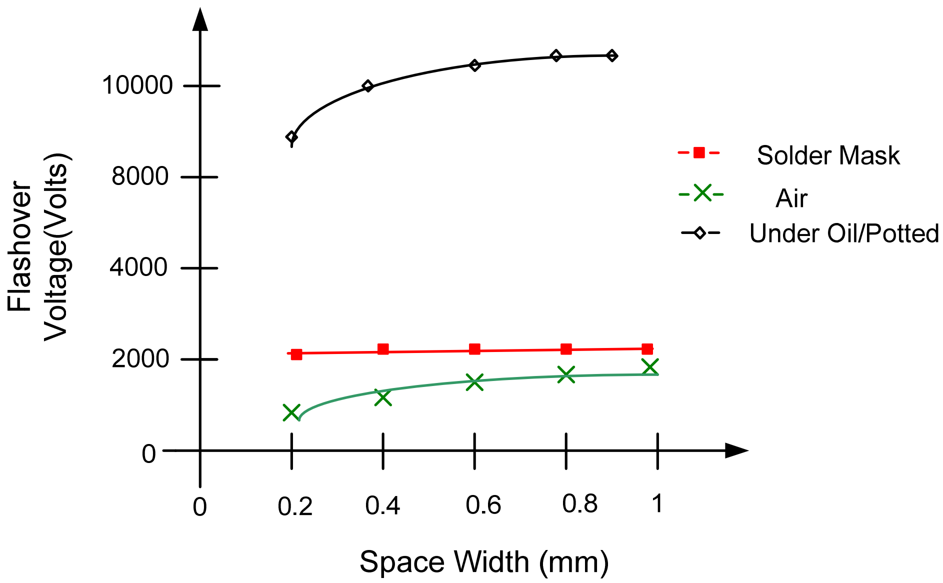


Fig.6.38: Typical Flashover Voltage with 150 µm dielectric cover (solder mask) with 25 mm circular electrodes. [7]

Graphs on Fig.6.38 and on Fig.6.38 depict flashover without soldermask, with soldermask and under oil for thickness of solder mask 150 µm and 70 µm respectively [7].

Finally, creepage distance has also to be taken into account because Thermal Clad dielectrics often incorporate a metal base layer. Circuit board designers should consider testing of PD characteristics for: a) conductor-to-conductor and b) conductor-to-circuit board edge or c) through the holes.

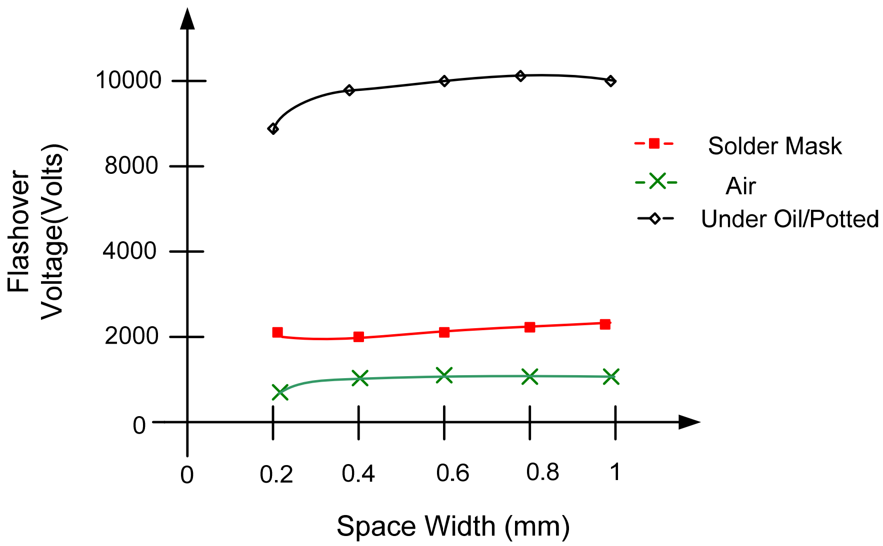


Fig.6.39: Typical Flashover Voltage with 75 µm dielectric cover (solder mask) with 25 mm circular electrodes. [7]

7. Separation and identification of PD

The separation and identification of PD features is a fundamental requirement to obtain effective insulation diagnosis and avoid misleading evaluations of the defects which display PD activity. The identification and separation procedure is problematic in case when features relevant to each PD phenomenon are partially or totally overlapped**.** The different sources may generate PD-pulse signals with a large variety of shapes, and rise times of the order of nanoseconds (up to GHz of frequency content) [8], [9]. As it was mentioned before the PD is a spark discharge with very low power which is formed inside insulation, or on the surface in the equipment of an average and high pressure. PDs appear in a weak place of the insulation and lead to gradual development of defects and destruction of insulation. There are four analysis tools which can help us to detect PD: frequency response, acoustic analysis, tanδ measurement and amplitude analysis.

7.1 Frequency response analysis

Frequency response analysis, generally known within the industry as FRA, is a powerful diagnostic test technique. This method can be also useful for PD testing in electrical equipments. Generally it consists of measuring the response of the tested sample over a wide range of frequencies and comparing the results with a reference set. For optimum measurement, the lead lengths need to be as short as possible, and the test configuration must remain constant for repeated test [27].

7.2 Acoustic analysis

Acoustic PD measurement methods have the benefit that electrical disturbances like broadcasting stations or corona have little or no influence and PD detection can be managed by one sensor. The acoustic PD measuring method features a high sensitivity in on site and online use, beyond that of an online electrical PD measurement. This is a result of the insensitivity of the acoustic measuring system to the electric disturbances which is an outstanding benefit. Furthermore the acoustic noise ambience of laboratories remains mostly unchanged.

Another additional advantage is that a simple high-pass filtering of the acoustic signals suppresses disturbances sufficiently to produce afterwards easy interpretable patterns. This simplifies PD detecting and helps to distinguish it from disturbances in the frequency-time domain.

7.3 Amplitude detection

At the present time the method of amplitude analysis is very useful for PD detection. The equipment consists of filters, calibration equipments and smoothing circuits. In low level equipment the PD activity and also the calibration signals can be measured by means of the oscilloscope. In presented work amplitude analysis was used for PD testing of electronic devices as planar transformers, pulse transformers, optocouplers and IGBT modules.

8. PD testing by means of Amplitude Analysis.

Basic arrangement of the PD test circuit is shown on the Fig 8.40. In order to suppress interference, a filter Z is inserted between the test voltage source and test specimen. In some cases the test specimen is described by an equivalent capacitance C_a. The PD-source can be assumed in parallel and charge transfer caused by the PD-source activity is going to be measured. This requires that the PD-current is flowing across the coupling capacitor C_C and the measuring impedance Z_m.

From previous analysis of the charge distribution, it is clear that a part of the internal charge q_i is passed through the test specimen itself (q_{v1}). This can be a severe problem especially for capacitors with high capacitance. Only the remaining apparent charge *q* is measurable at all. In order to achieve the maximum sensitivity, additional charge losses must be avoided. The charge loss across the test voltage source (q_{v2}) can be reduced by the filter Z. The charge losses across the earth capacitances (q_{v3}), however, cannot be influenced very much [3]. Both q_{v2} and q_{v3} influence the charge loss across the measuring impedance q_m .

Currently, it is important to know that C_C must provide low impedance at the frequency corresponding to PD pulses. However, measuring impedance Z_m must represent approximately a short circuit for the frequency of the test voltage [1].

Obviously, there must be ensured that the test voltage source being used does not produce any PD. The exact peak value of the test voltage which is relevant for the electric stress has to be measured. For PD-measuring instruments, it is important to distinguish between the measuring frequency (center frequency of the measuring band) and the bandwidth of the instruments.

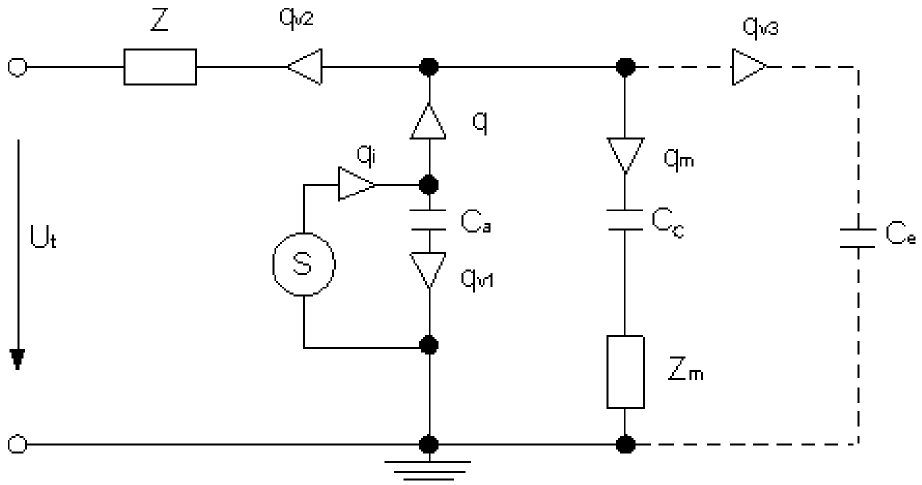


Fig. 8.40 Basic arrangement of PD - test circuits: U_t - Test voltage source; Z - impedance (Filter); S - PD source; C_a - Capacitance of the test specimen; C_C - Coupling capacitor; Z_m - Measuring impedance ; Ce - earth capacitance; q_i - Internal charge (not measurable); q - Apparent charge; q_{v1} - Charge loss across the test specimen; q_{v2} - Charge loss across the test voltage source; q_{v3} - Charge loss across the earth stray kapacitance; q_m- Charge loss across the measuring impedance [3].

Comment: With regard to the bandwidth, PD-measuring instruments can be classified into narrow band type, limited broadband type, and real broadband type instruments. Narrow band type PD-measuring instruments usually have a band-width of less than 15 kHz, which is similar to some type of interference measuring instruments. Limited broadband type PD-measuring instruments have a bandwidth up to several MHz. Real broadband type PD-measuring instruments should cover whole spectrum of PD-pulses, which may require a bandwidth of more than 1GHz.

PD-measuring instrument with high bandwidth allows a more precise analysis of the discharge phenomena during the occurrence of PD. On the other hand, measurements with large bandwidth are more likely to suffer from interference problems than narrow band measurements. During PD-testing, it is important to achieve high sensitivity and ensure a precise measurement of the apparent charge *q* which displays PD-intensity. Obviously these requirements can be met easily by using narrow band PD measuring instruments, but because of pulse spreading and overlapping in such narrow band instruments, complication can occur at high repetition rates of the PD-pulses.

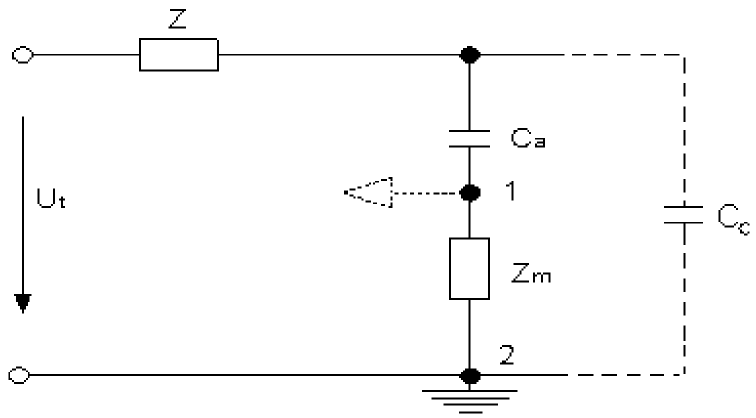


Fig.8.41 PD - test circuits: U_t - Test voltage source; Z - impedance (Filter); C_a - Capacitance of the test specimen; C_C - Coupling capacitance; Z_m - Measuring impedance [3].

The measuring frequency (center frequency of the measuring band) of narrow band PD-measuring instruments should be selected in order to obtain minimum narrow band interference. Hence, it is important that the measuring frequency remains in that range where the spectrum of the PD-impulses still has approximately constant amplitudes. Generally this condition can be assumed for frequencies up to approximately 2 MHz. Since sufficient separation between the test frequency and the PD-measuring frequency is required, a lower limit of the PD-measuring frequency is also obvious. In this case it is not much complicated during PD-testing with 50/60 Hz test voltage, but it can be a severe problem during PD-testing with high frequency test voltages [3].

Two different arrangements of test circuits are used - one for earthed (point 1) and the other for unearthed (point 2) test specimen, as depicted on Fig.8.41. Since the components for electrical equipments usually are not earthed, earthing at point 2 can be applied which will provide higher sensitivity [3].

Before measuring a calibration of the PD-measuring equipment within the complete test circuit is required. Basic scheme for the calibration circuit is given on Fig.8.42. For calibration test specimen is replaced by the capacitance C_x which does not show any PD activity and which provides similar impedance as the test specimen.

After calibration, it has to be verified that up to the highest relevant test voltage, the basic interference level is less than half of the value of that PD-intensity which is specified as the limiting (low) value of the PD-intensity. Otherwise, measures for interference reduction have to be introduced.

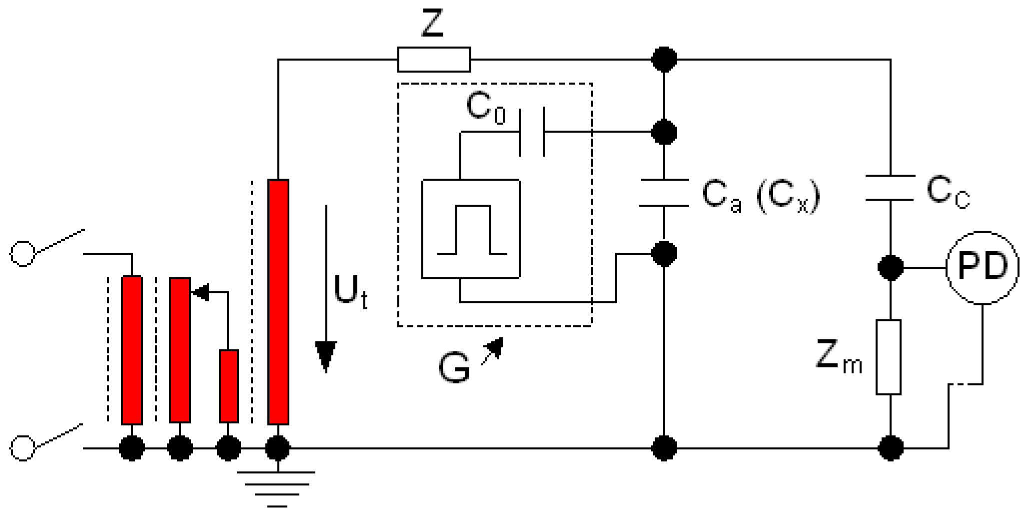


Fig.8.42 Calibration of the PD –measuring equipment within the complete test circuit [3]:
U_t - Test voltage source; Z - impedance (Filter); S - PD source; C_a - Capacitance of the tested device;
C_C - Coupling capacitance; Z_m - Measuring impedance ; C_x - PD-free replacement capacitance;
PD - PD measuring equipment; G – Calibration pulse generator with the capacitance C_0 [3].

Finally, a calibration with the test specimen connected to the test circuit has to be performed. In the case of using the same test specimens, or in the case of test circuits with rather large capacitance of the coupling capacitor when compared with capacitance of the specimen ($C_C >> C_x$), this calibration need to be repeated in larger time intervals.

8.1 PD detection

As it was mentioned before partial discharge is a spark discharge with very low power release which is formed inside insulation, or on the surface in the equipment in a gas with an average and high pressure. PDs appear in a weak place of the insulation and lead to gradual development of defects and destruction of insulation.

By suitable conditions in systems with surface discharge it is possible to detect PD with voltage amplitude larger than 500V. It means that by influence of oversights and defects in production process PD can be detected in some cases by working voltage value. Here as an example the drivers of IGBT transistors with operating voltage higher than 1 kV, small switched power sources for high voltage, high voltage planar transformers or high voltage pulse transformers can be given.

Because the working frequency of electronic devices range usually from some kHz up to tens of kHz the influence of PDs on the equipment operation is here much more significant than in the case of 50 Hz power line devices.

On the other hand when using low frequency testing voltage, there is easier to detach PD impulses from testing voltage and also electrical load on insulation is weak.

Simply way for low frequency test voltage generation is to use the line voltage transformer, but regulation should be controlled by the help of autotransformer. More advantageous is to generate the test voltage electronically. For this case I used switched converter shown on the Fig.8.48. The amplitude of high voltage for PD test was controlled by DC power supply.

Circuit diagram for measurement PD using the method of amplitude analysis is shown in Fig. 8.43. In the circuit the coupling capacitance is in series with measuring impedance. This test circuit is mentioned in the IEC 60270 standard for PD measurement. Indirect type should be preferred for safety reasons.

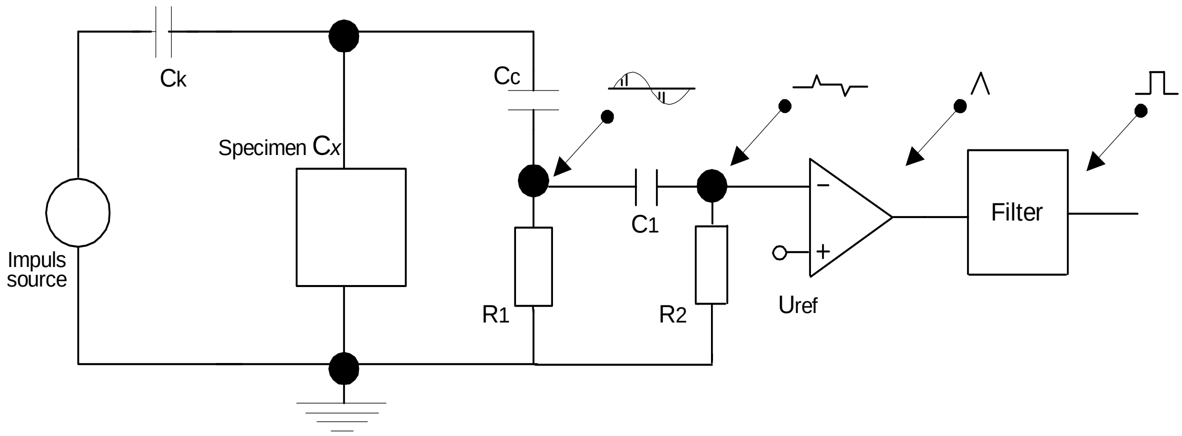


Fig.8.43 Circuit diagram for PD measurement.

The international Standard IEC 60270 is applicable to the measurement of partial discharges which occur in electrical apparatus, components or systems when tested with alternating voltages up to 400 Hz or with direct voltage.

This standard

- defines the terms used;
- defines the quantities to be measured;
- describes test and measuring circuits which may be used;
- defines analogue and digital measuring methods required for common applications;
- specifies methods for calibration and requirements of instruments used for calibration;
- gives guidance on test procedures;
- gives some assistance concerning the discrimination of partial discharges from external interference.

As seen from the Fig. 8.44 the polarity of detected PD pulses is opposite to polarity of working voltage.

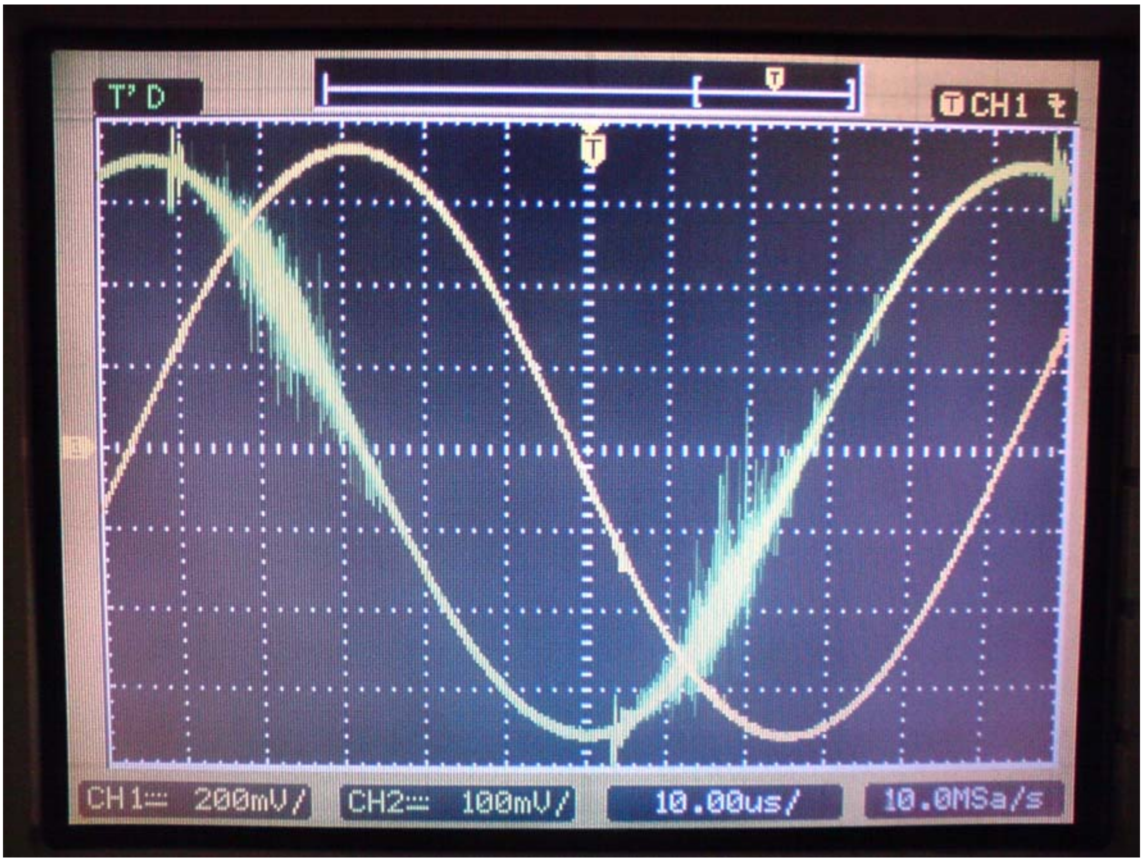


Fig.8.44 Partial discharge on enamel insulated wire. The voltage amplitude is 750 V. On the current signal there is a superposition of current spikes which corresponds to individual PD events. Note that in positive half-wave of the voltage the current spikes are negative and vice versa.

It is obvious that PD pulses separated from the working (or testing) voltage have negative polarity in case of positive half wave of the working voltage and positive polarity in case of the negative half wave. This may often help to distinguish and localize different sources of PD – see Fig. 8.45

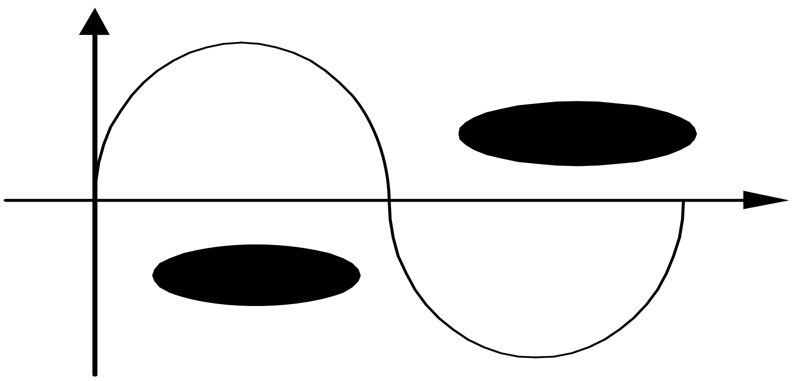


Fig. 8.45 Influence of the measuring circuit on the polarity of the discharges (Indirect type).

8.2 Calibration procedure

To understand better the calibration procedure of PD is necessary to refer to IEC 60270 standard. Partial discharge phenomena as defined by IEC 60270, are localized dielectric breakdowns of a small portion of a solid or liquid electrical insulation system under high voltage stress. This standard is primarily concerned with electrical measurements of partial discharges made during tests with alternating voltage [29].

The detection and monitoring of partial discharge is of vital importance because PDs often precede an insulation breakdown, leading to cost-intensive outages and repairs. The provisions of this standard should be used in the drafting of specifications relating to partial discharge measurements for electronic equipments. It deals mainly with electrical measurements of short-duration partial discharges, but reference is also made to non-electrical methods primarily used for partial discharge location.

The calibration of the acquisition system consists in correlating the PD pulse voltage amplitude estimated by the instrument to the apparent charge associated to the PD. In turn, the apparent charge value is a measure of the real process caused by charge transfer inside the defect in the system insulation.

Injecting pulses which have known apparent charge and measuring the pulse amplitude response as acquired by the acquisition unit we can calibrate the measured PD pulses voltage value to exact value of the apparent charge.

The scheme for calibration procedure is shown on the Fig.8.46. The calibration is carried out by injecting a standard calibration pulse into the measurement circuit in parallel to the test object.

A square wave pulses with amplitude 10 V and with different frequency were used. Calibration procedure was performed with coupling capacitors 15,6 pF, 23 pF and 47pF for pulse frequency from 5 kHz up to 100 kHz. The results are summarized in table Tab.9.1.

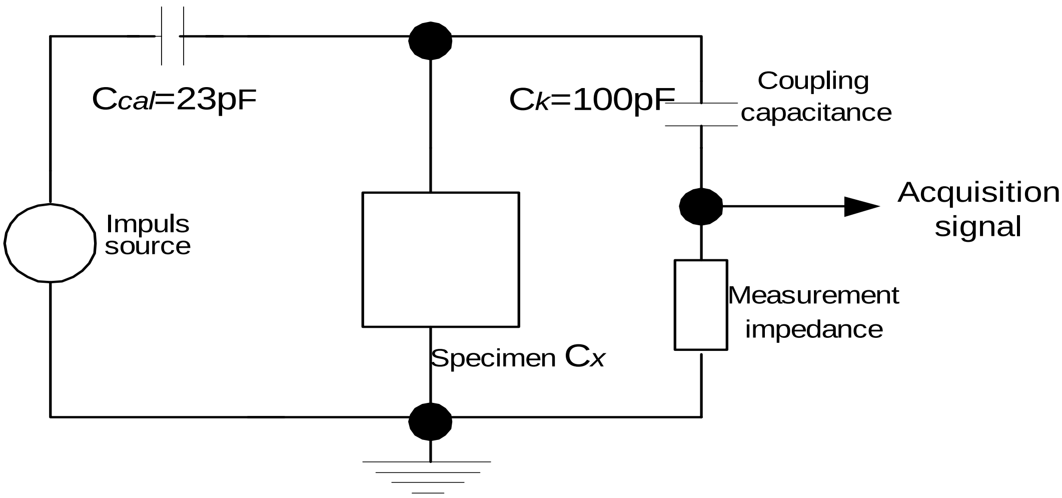


Fig.8.46 Calibration circuit for indirect- type.

Tab. 9.1: Calibration procedure for different coupling capacitors C_x. Survey of most important parameters. Charge transferred in one pulse corresponds to Q_i . Calibration coefficient in dependence on frequency.

	f	C_c	U_2	Q_{in}	Coefficient
V	kHz	pF	mV	pC	pC/1mV
10	5	47	325	470	1.446
10	5	23.5	280	235	0.839
10	5	15.6	235	156	0.664
10	9.2	47	310	470	1.516
10	9.2	23.5	270	235	0.870
10	9.2	15.6	240	156	0.650
10	10	47	330	470	1.424
10	10	23.5	280	235	0.839
10	10	15.6	235	156	0.664
10	20	47	325	470	1.446
10	20	23.5	280	235	0.839
10	20	15.6	250	156	0.624
10	100	47	320	470	1.469
10	100	23.5	270	235	0.870
10	100	15.6	240	156	0.650

On the basis of measurement results we can define that in a case of increasing value of C_{cal} the value of output voltage U_2 grows up. The influence of frequency on calibration characteristics is not much pronounced.

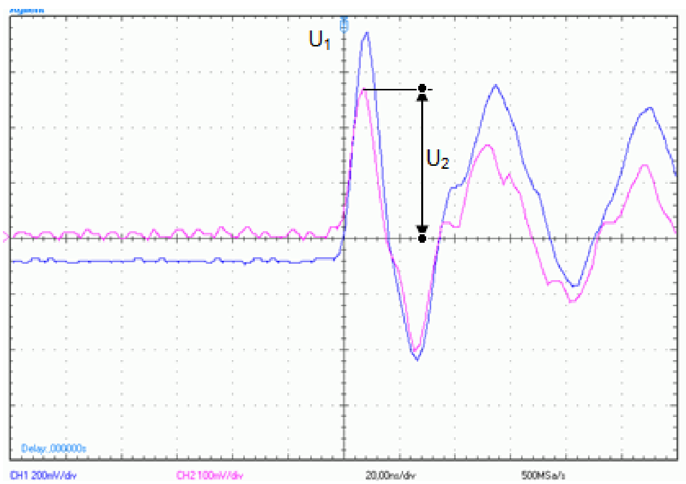


Fig.8.47 Calibration procedure. Voltage response to the calibration pulse.

The charge transfer detected by the acquisition system is:

$$Q = C * U = 23{,}5 * 10^{-12} * 10 = 235\,pC$$

By this charge value the amplitude of PD-like pulses was 280 mV. The voltage to charge transfer sensitivity of the PD pulse detection is therefore:

U_{QAP} = 235 pC / 280 mV = 0,839 pC /mV

Here we need an example to compare this value to real testing procedure:

When testing planar transformers (see chap. 9) than by the amplitude of the test voltage in range from 2700 V up to 3000 V the maximal measured PD pulses amplitude was in range from 450mV up to 1000 mV respectively. According the calibration this gives for the charge transferred in PD process the value in range approximately from 377 pC to 839 pC. By frequency of 33 kHz such PD intensity leads to insulation destruction in few minutes time.

In such a case the PD pulses occurred in each half-wave of the testing voltage. The acquisition of PD pulses is obviously very simple and can be made by means of digital oscilloscope.

However, by voltage amplitude less than 2700 V is in this case the detection of PD pulses by digital oscilloscope troublesome, because of random occurrence of PD events. For such purpose the acquisition system must be made other way – with single pulse detection capa,bility.

It is obvious that by starting the PD activity the charge transferred in this insulation system will be in the range of hundreds of pC. This also means that PD free condition can be stated for the transferred charge which is about ten times lower. For example, the charge level of 20 pC is represented by PD pulse amplitude of 16,8 mV.

8.3 Switched Power Source for PD testing

High voltage power generator was made using the switched mode converter. To control output of power MOSFETs of the generator the IC driver IR2155 was used. The electrical design using IR2155 is simple as it accepts ground-referenced logic level input signals and drives high and low side MOSFET or IGBT power transistors with an offset voltage of up to 600V.

The Switched Power Source IR2155 driver is one of a family of International Rectifier devices which provides a convenient and cost effective gate drive solution. The IR2155 circuit is a high voltage, high speed, self-oscillating power MOSFET and IGBT driver with both high and low side referenced output channels. The frequency is controlled by a programmable oscillator (pins 2 and 3) which is similar to the 555 timer.

The output drivers feature a high pulse current buffer stage and an internal dead-time designed for minimum driver cross-conduction. Propagation delays for the two channels are matched to simplify use in 50% duty cycle applications.

The scheme of the AC test voltage switched converter is on the Fig.8.48. The floating channel can be used to drive N-channel power MOSFET in the high side configuration that operates with voltage rail up to 600V. In bootstrap mode, the IR2155 driver can operate in most applications from frequencies in the tens of Hz up to hundreds of kHz.

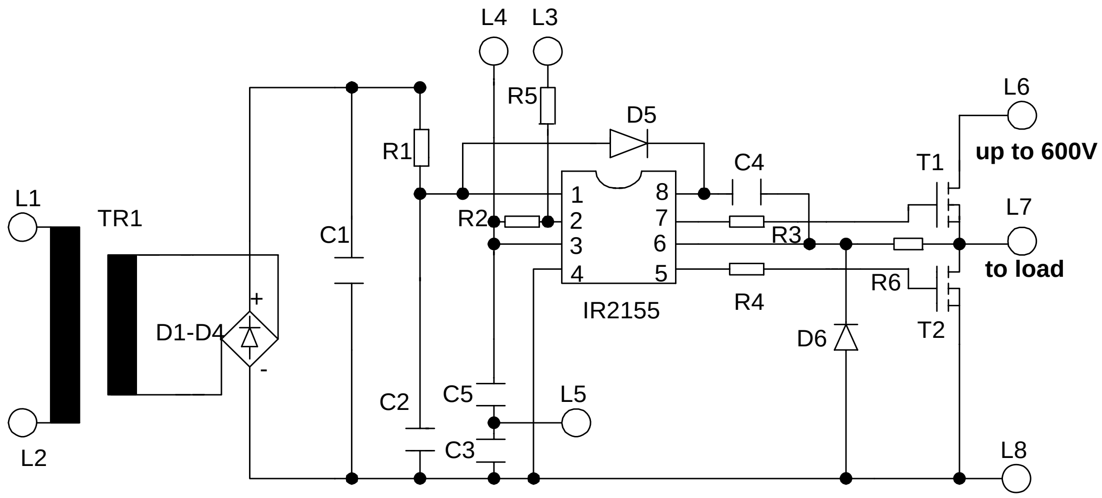


Fig.8.48 Wiring diagram of switched power source with driver IR2155.

8.4 PD measuring system

For the partial discharge detection an electronic circuit was designed working on the principle of amplitude analysis of impulses corresponding to individual partial discharge [37,38]. The block diagram of data acquisition is presented on Fig.8.49.

Partial discharge occurs in different places over the specimen surface and volume. The peaks modulated on the supply wave are separated on high pass filter. Impulses corresponding to individual partial discharges are compared with the reference voltage. For each channel, there are two high speed comparators, each for one polarity. The level of voltage reference is adjustable. Output signals from both comparators trigger high speed mono-stable multivibrator, and then they are processed by microcontroller.

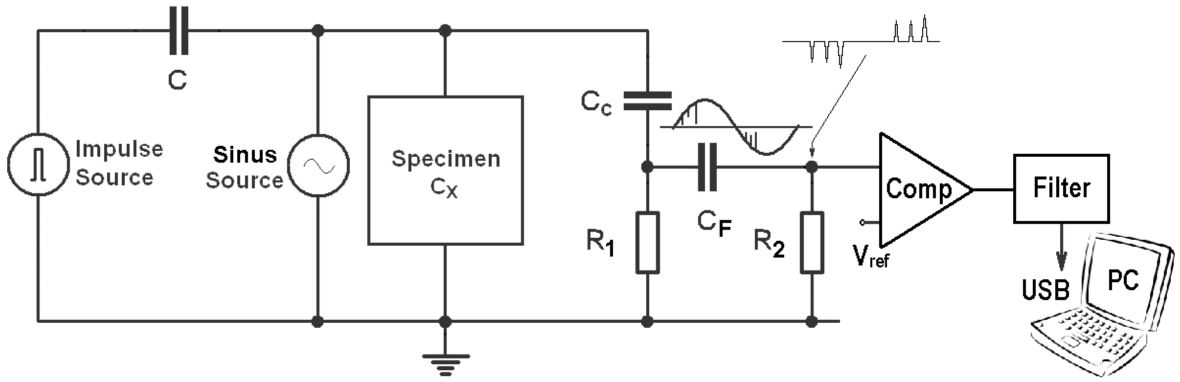


Fig.8.49 Block diagram of PD origin measurement

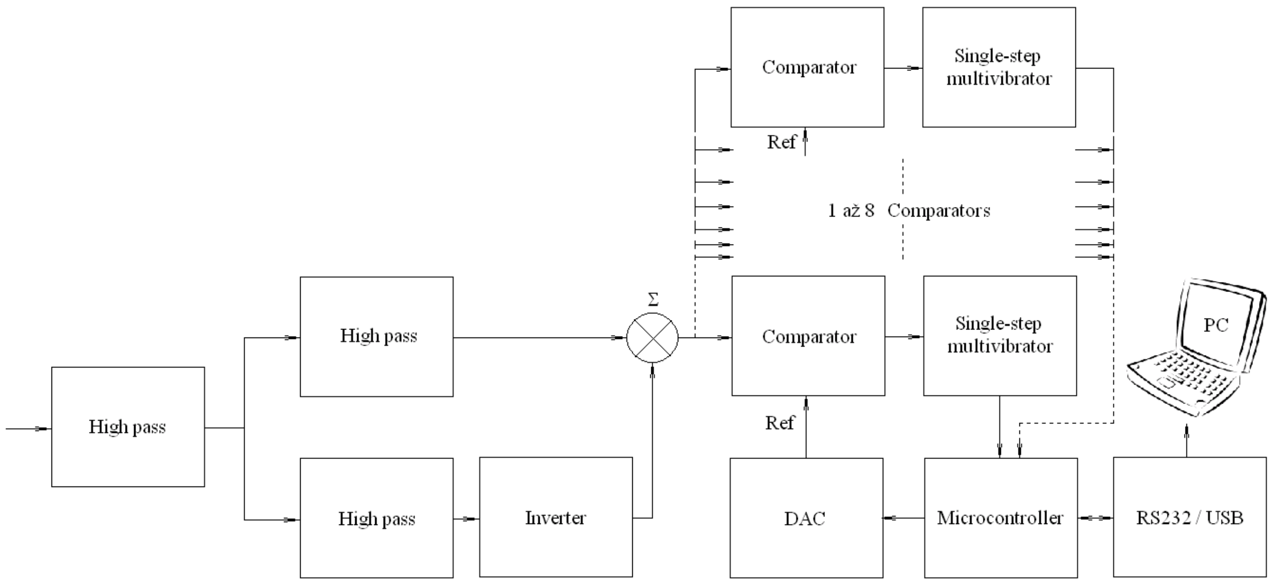


Fig.8.50 Block diagram of multi channel measuring system.

Because the occurrence of partial discharge is absolutely random it is suitable to analyze the signal in more levels. We get thereby a better idea of the number and size of monitored discharges. To ensure multichannel measurement the system can be expanded by adding up to eight comparators each with a mon-stable multivibrator.

Impulses corresponding to individual partial discharge are managed to a couple of high speed comparators each for one impulses polarity. The level of reference voltage is adjustable and for the comparator with negative polarity there is a reference inverter. Detected signal is managed to a single-step multivibrator which ensures sufficient time for processing, and can eliminate subsequent parasitic overshooting.

Due to this expansion we receive a multichannel system with one to eight detection levels at the same time. The block scheme of this device is on Fig.8.50. It is clear that a half of those eight channels are used for positive peaks and the other are used for negative peaks which are processed by microcontroller and then displayed in specialized partial discharge evaluating software [45,46]. For each couple of negative and positive peaks there are separate graphs.

8.4.1 Filtering

The shape of a PD pulse depends on the frequency and attenuation of the pulse propagation path, and the response of the detection circuit. If the waveform is known (for example pulse waveform), we can use matched filters for better noise separation. A matched filter maximizes the signal-to-noise ratio (SNR) for the partial discharge pulse detection (can be proven mathematically) and it is optimal for detection of a signal in the presence of noise, provided that the signal waveform is known.

The matched filter output signal has the highest SNR, and beats any other filter when it comes to noise reduction [4]. The output signal of any other filter which works with the same energy in particular PD event has a lower peak value. The filter that matches the best signal gives the highest output peak.

8.4.2 Description of Hardware

The core of hardware realization is the microcontroller ATmega88 [45,46]. This microcontroller communicates with PC via USB. Communication through USB is realized by USB I/O FTDI232. Setting detection levels for measured impulses is realized by 8 channels DAC, see Fig. 8.51.

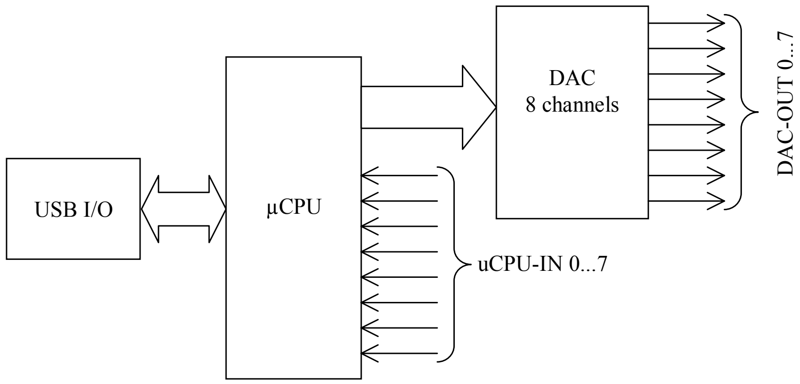


Fig.8.51 Block diagram of digital part.

The most common case of monitored signal is the sinus like shape which has voltage spike modulated on it. The width of this spikes is in the order of nanoseconds. To monitor the occurrence or a number of PD we need to suppress the "carrier" wave. The analyzed signal comes into an analogue pre-filter block and then into a comparator with single-step multivibrator.

The equipment supports a communication with PC by means of RS232/USB converter. The threshold level for the comparator is controlled by means of DAC.

8.4.3 Description of measuring interface

The measuring interface is segmented into three sections. In the first section, the user can select measuring device. In the second section, the user has to set the time measuring method. In the third section the measured signals and data are shown.

Measuring method:

There are two methods: the first is suitable for short time measurements and the second one is suitable for long time PD investigation (waiting for any occurrences of PD):

Measurement with real time**:** in this case the system measures and sends to the PC data in real time according to respective PD impulses.

***Measurement with discrete time*:** In this case the system measures impulses with discrete time. The PD measuring system registers only the received impulses without a true time record. The PC only receives impulses and their incoming sequence. It is suitable for a long time measurement - for investigation if there are any PD occurrences.

Measured data are shown in four graphs in both polarities. The user can enable or disable the measurement for any graph and can set the detection level for both polarities of measured impulses. Example of multichannel indication of PD events is presented on Fig.8.52

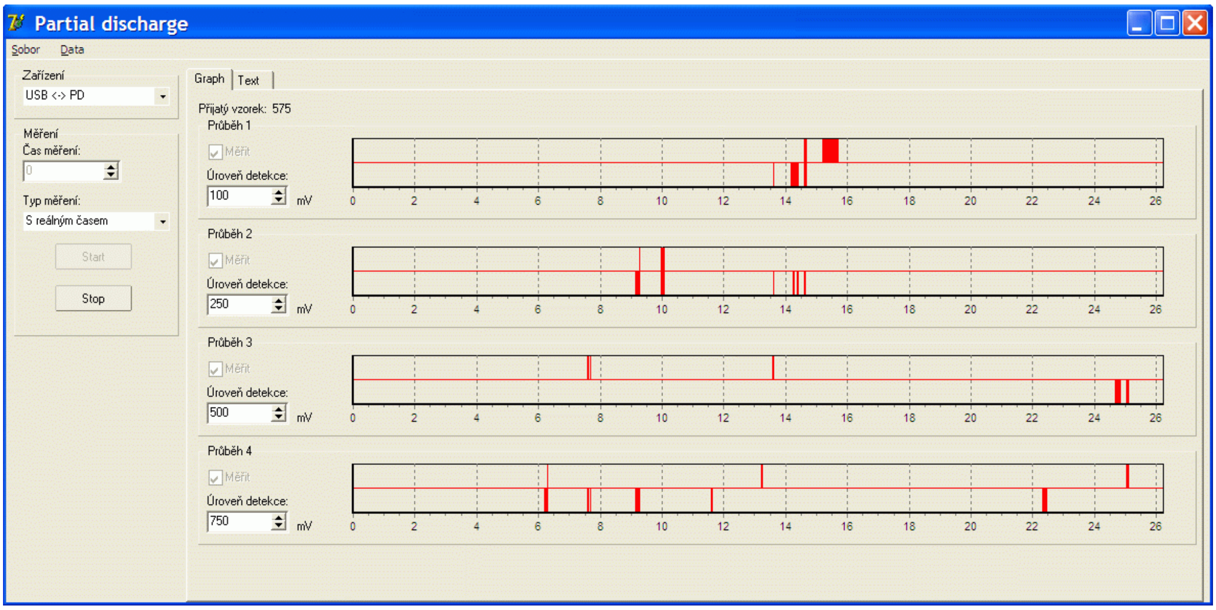


Fig.8.52 Measurement by means of amplitude analysis; Software for MS Windows: Example of multichannel indication of PD events [45,46].

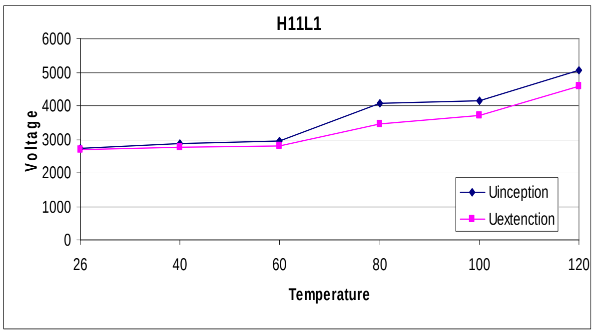
9. PD Testing

Based on the tools described in previous chapters PD activity in different electronic devices and components such as optocouplers, planar inductors, planar transformers and pulse transformers were investigated in respect of different load and different working conditions. After gaining some experience the possibilities of use of PD measurements in design of high voltage insulation systems were demonstrated. The results are summarized in this chapter.

9.2 Testing of optocouplers

Main operational function of optocouplers is galvanic detachments of two circuits. The potential difference may range from few mV in data processing systems up to several kV in power generation systems or in special equipments. There is also important to know whether the optron serve only as galvanic detachment or if it has to ensure the safety-related insulation of persons working with the respective equipment. The insulating distance between the light transmitter and receiver is therefore in the range between 0.15 and 1 mm.

Between many parameters which influence PD activity in insulation system of optoucuplers one of most important is temperature. Fig.9.53 shows the temperature influence on PD activity as measured by different types of optocouplers.



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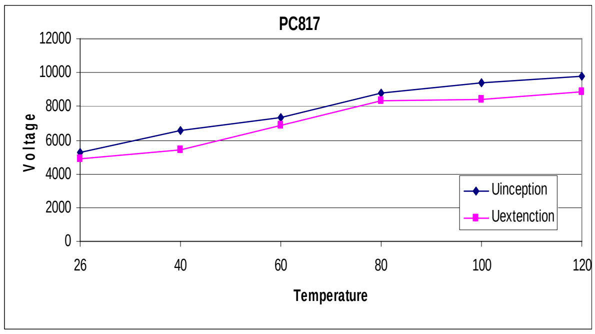

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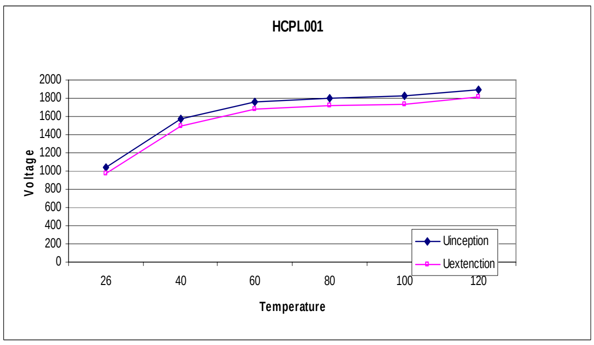

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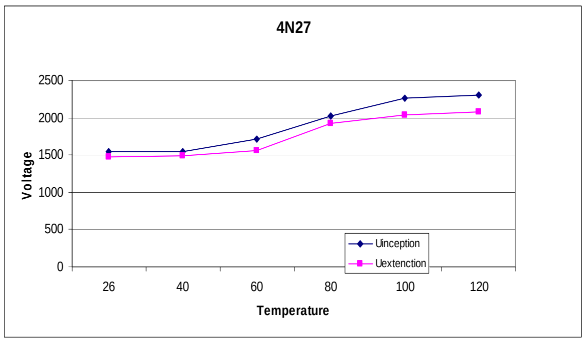


d)

Fig.9.53*:* PD activity in insulation system of optocouplers. Temperature dependence of U_{inc} and U_{ext}. **a)** H11L1 **b)** PC817**,** **c)** HCPL001 and **d)** 4N27.

Tab.9.2 Optoucuplers. Temperature dependence of U_{inc} and U_{ext}.

Optoucupler	Inception U[V]	Extinction U[V]	Time [s]	Temperature [°C]	Frequency [kHz]
H11L1	2720	2700	36	26	9.2
	2880	2760	1.06	40	9.2
	2950	2800	45	60	9.2
	4080	3460	52	80	9.2
	4160	3720	27	100	9.2
	5040	4600	45	120	9.2
PC 817	5300	4880	2.53	26	9.3
	6600	5440	33	40	9.3
	7300	6900	39	60	9.3
	8800	8350	1.05	80	9.3
	9400	8900	1.15	100	9.3
	9800	8400	1.12	120	9.3
HCPL001	1040	980	9.51	26	10.2
	1580	1500	5.3	40	10.2
	1760	1680	6.4	60	10.2
	1800	1720	2.28	80	10.2
	1830	1730	1.53	100	10.2
	1900	1810	1.43	120	10.2
4N27	1540	1473	3.12	26	10.3
	1550	1482	1.06	40	10.3
	1710	1560	4.28	60	10.3
	2020	1930	8.5	80	10.3
	2261	2040	1.42	100	10.3
	2300	2080	7.12	120	10.3

Tab.9.2 shows PD-inception and PD-extinction voltages of different types of optoucuplers after increasing temperature in thermal chamber. During the measurement in thermal chamber the temperature was changed slowly and changes in U_{inc} and U_{ext} voltage followed. The range of temperature was defined from 26 ºC to 120 ºC. At the beginning of the measurement, the PD amplitude was growing with increasing temperature, but in a case of optoucuplers 4N27 and HCPL001 the amplitude of PD slowly established at the moment when the temperature reached 100 ºC.

On the Fig.9.54 and Fig.9.55 we can see similar dependences measured only for one type of optocouplers, but different specimens were tested several times. During the measurement the behavior of each optocoupler was compared with their characteristics from previous measurement. As we can see each specimen has different characteristic and slightly different behavior. Such differences in PD characteristics are probably caused from non uniform material characteristics as consequence of technological processes.

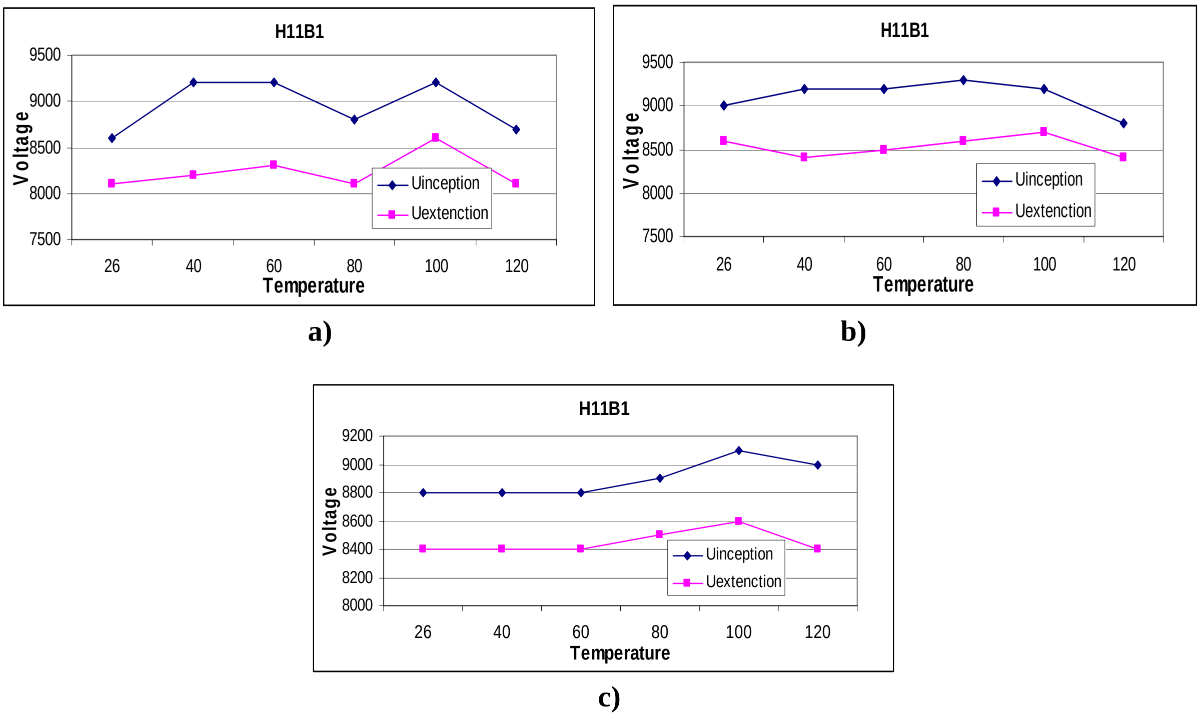
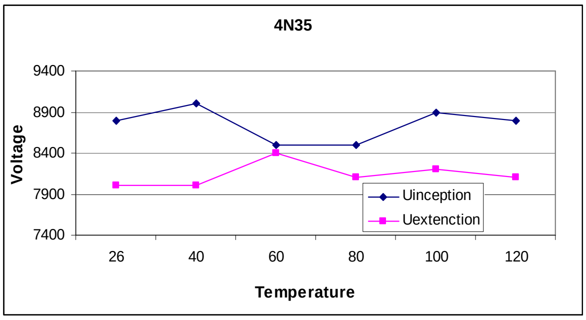


Fig.9.54 PD activity in insulation system of optocuplers. **a) b) c)** Different samples of the same type of optoucupler H11B1.

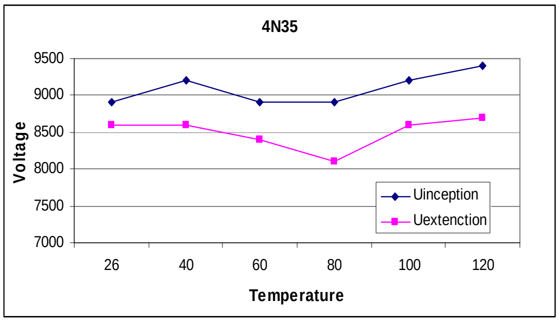
Another important influencing factor is the frequency of the voltage. An increase of the frequency above power frequency usually results in a deterioration of the PD-characteristics. It has to be taken into account that an additional increase of the degradation with the frequency has to be expected because, in principle, the repetition rate of the PD-pulses will increase approximately proportional with the frequency of the voltage.

It can be concluded from the results of the PD-tests that optocouplers with appropriate design will provide high PD-inception and PD-extinction voltages. The test of PD shows that between specimens of the same type exist differences with respect to the insulation characteristics.

Finally, it can be noted that despite slightly non uniform material characteristics as consequence of PD investigations the minimal values of the PD inception and extinction voltages for used insulation distances are indications of good insulation system design.



a)



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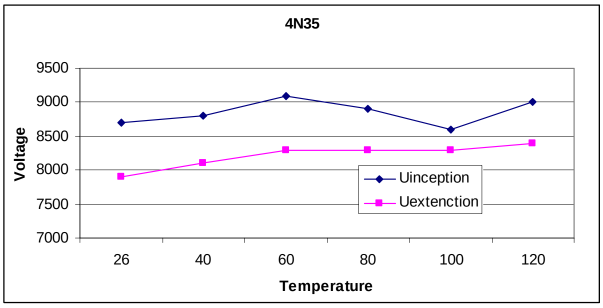
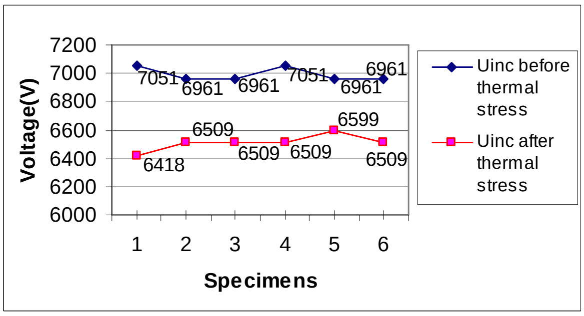


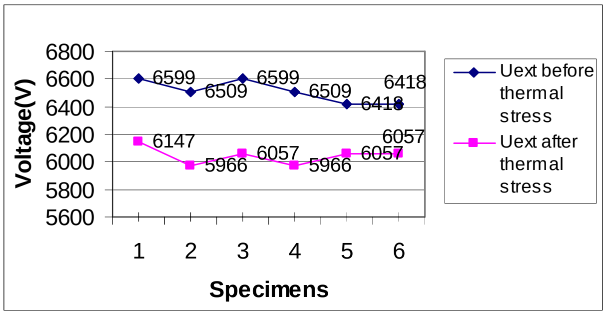
c)

Fig.9.55 PD activity in insulation system of optocouplers. **a) b) c)** Different samples of the same type of optoucupler 4N35.

Below we can see the influence of thermal stress to different types of optocuplers. Several specimens were placed in thermal chamber for 6 month. Fig. 9.56, Fig.9.57, Fig.9.58 and 9.59 shows the PD activity in insulation system of optocuplers before and after thermal stress.

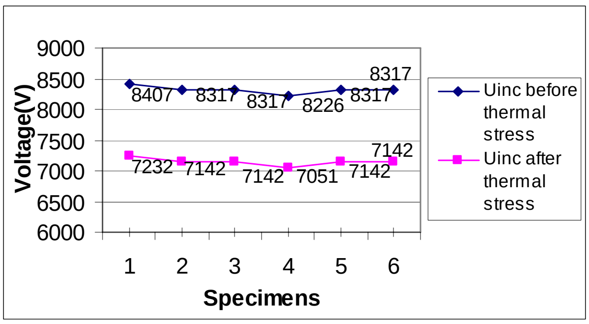


a)

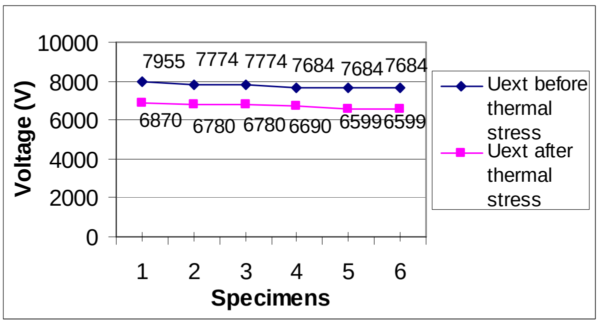


b)

Fig.9.56 PD activity in insulation system of optocupler PC 817 before and after thermal stress: a) U_{inc} and b) U_{ext}

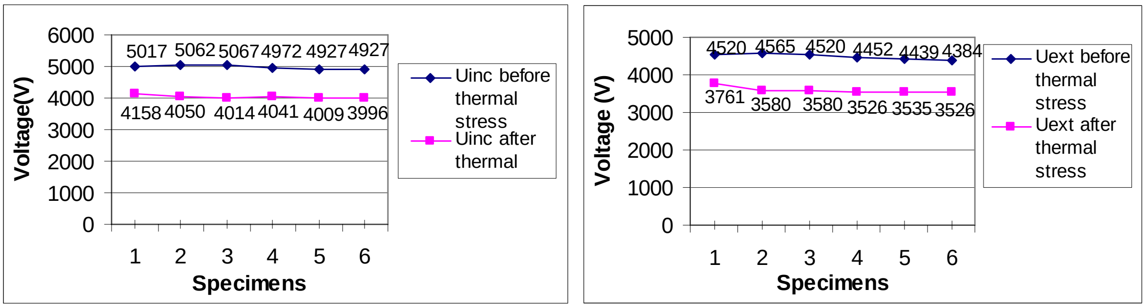


a)



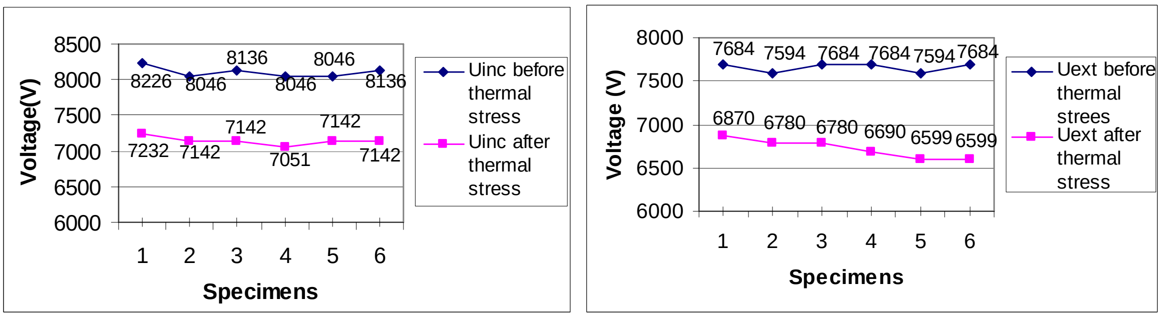
b)

Fig.9.57 PD activity in insulation system of optocupler 4N27 before and after thermal stress: a) U_{inc} and b) U_{ext}



a) **b)**

Fig.9.58. PD activity in insulation system of optocupler HCPL601 before and after thermal stress: a) U_{inc} and b) U_{ext}



a) **b)**

Fig.9.59 PD activity in insulation system of optocupler H11L1 before and after thermal stress: a) U_{inc} and b) U_{ext}

9.2 Testing of planar transformers

Recently many designs adopted planar transformer which utilize solid insulation throughout the printed circuit board. Planar design is advantageous mainly in cases where is a need for high current and high frequency, high repeatability or special features as low leakage inductance and high number of terminals. In planar design there is also much better possibility to have large number of windings and arbitrary arrangement of output taps.

Planar transformer have coils encapsulated within multilayer printed circuits board (PCB), sandwiched between low-profile ferrite cores. The windings can be interleaved reducing thus leakage inductance and enabling an operation in high frequency range. It is also possible to have a high level of insulation between transformer windings if required.

Comparison of planar and classic transformer structure is made in Fig. 9.60. The benefits of planar technology and their contribution to more efficient magnetic components can be summarized as follows [35]:

- There is no bobbin and transformer winding process. The cost of the windings included to main board is negligible and connections are eliminated. The assembly process has few stages and is highly repeatable.
- Planar design gives the lowest height. Pin positions can be more easily optimized and high current connections can be made more easily.
- The mechanical nature makes planar components easy to screen against EMI and RFI, so common EMC compliance is more easily achieved. High frequency performance of planar transformer is very good.

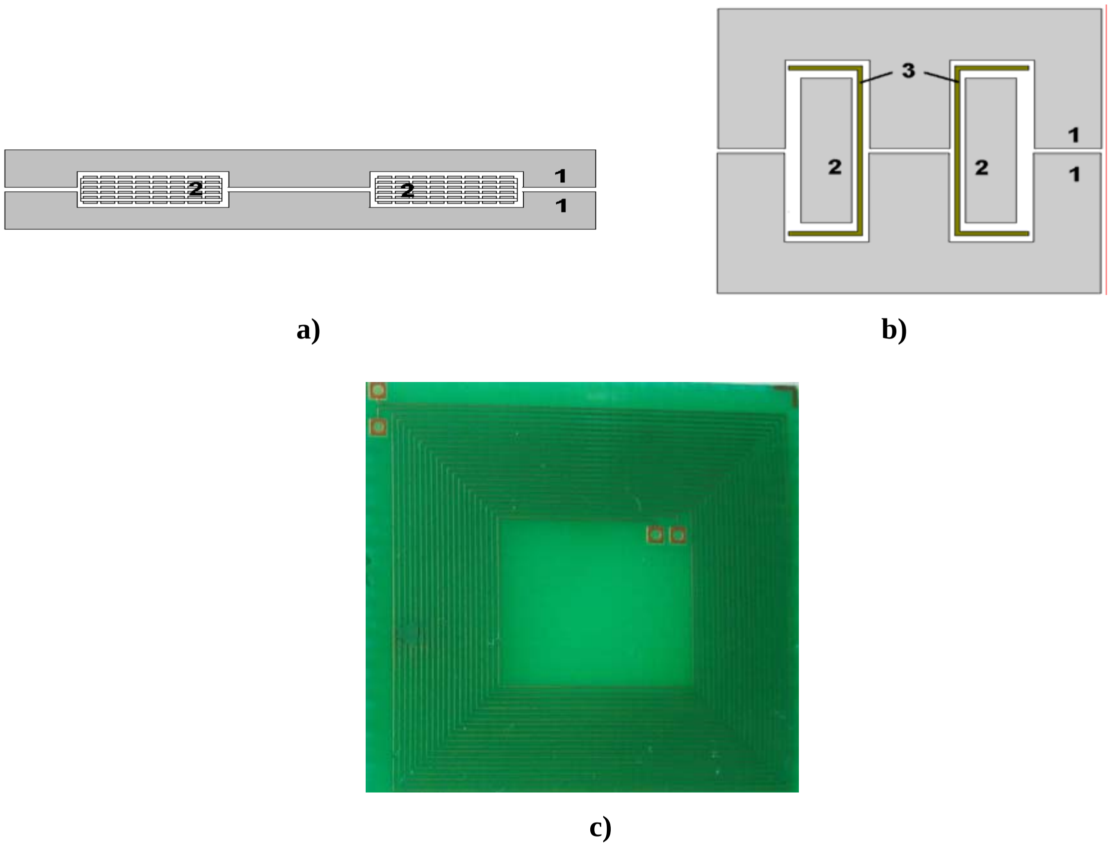


Fig.9.60: Comparison of planar a) and classic b) arrangement (1- Core; 2- Winding; 3 – Bobbin) [35] , c) Tested planar transformer with interlaced primary and secondary coils.

When leakage inductance is low the magnetic coupling between windings is very good and it makes planar transformers well suited to high frequency operation. In a planar transformer, turns ratio is guaranteed as the circuits are etched within PCB layers. Thus also winding polarity is guaranteed. Using the bobbin as a winding support there is large unused space in the classic core window.

Very important property of planar transformer design is that the insulation excludes air from the construction. PD activity is therefore greatly minimized and higher reliability is thus enhanced [36].

During the testing the experiments was performed to understand better the PD characteristics of planar transformers with respect to the temperature, thermal and voltage stress and with respect to the long time thermal cycling. Several different types of planar windings were designed and prepared for the testing. Based on PD testing results a comparison between different types of planar transformers as one layer and multilayer structure was this way possible.

9.2.1 One layer planar transformer.

Several specimens of planar transformers with different structure were designed and measured. The differences between one layer structure planar transformers were specified on the basis of following definition:

- width of planar conductors defined from 0.1mm to 0.2mm
- distance of planar conductors defined from 0.1mm to 0.5mm

The material of printed circuit board was FR4. Board thickness was 1,5 mm and thickness of laminated Cu layer was 18 µm. Other parameters were as follows:

- Volume resistivity : 10^{12} Ωcm, Surface resistivity : 10^{10} Ωcm;
- Relative permittivity $\varepsilon_r = 5{,}4$
- Power dissipation factor δ = 0,030 at 1 MHz and 25°C,
- Break-down voltage : 40 kV/mm.

First experiments were performed on one layer structure of planar transformer. In this design type the windings are placed on the same side of the PCB. The PD activity measurement was used to investigate the dependence of insulation strength on distance of windings.

Anti-soldering mask was used as surface treatment. On the Fig.9.61 we can see the samples of planar transformers with one layer structure. The distance between conductors is in range from 0,2 mm up to 0,5 mm. Most important parameters of planar transformers with one layer structure are summarized in the Tab.9.2.

Tab.9.2 One layer planar transformers. Basic parameters.

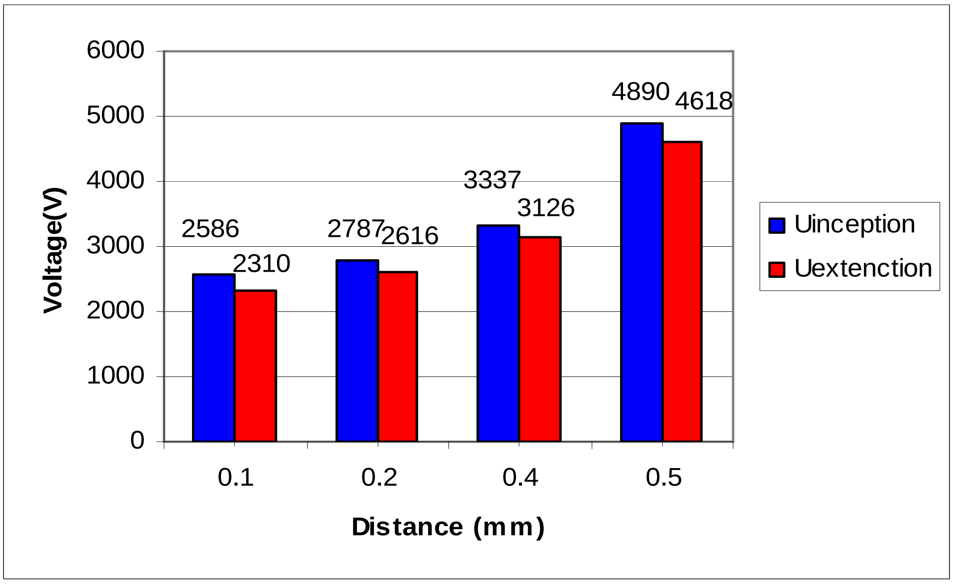
Specimens	Number of windings	Width of conductivity layer [mm]	Width of isolation space [mm]
PS 1-1	20,5	0,1	0,1
PS 5-3	8,5	0,2	0,3
PR 1-1	20,5	0,1	0,1
PR 5-3	8,5	0,2	0,3
CS 1-1	40,5	0,1	0,1
CS 5-3	16,5	0,2	0,3
1	15,5	0,1	0,1
2	10,5	0,15	0,15
3	8,5	0,2	0,2
4	6,5	0,2	0,3

A photograph of one layer transformers for respective distances between interlaced conductors is on the Fig. 9.61a). The insulation system which prevents the PD activity is here the anti-soldering mask

The structure has two planar coils in one plane which gives a possibility to use this device either as planar inductor or as a planar transformer. Resonance frequency of the coils is in range from 4 MHz up to 20 MHz depending on the number of turns and connection of coils.

On Fig. 9.61b) there is mean value of U_{inc} and U_{ext} for different distances between interlaced conductors in planar coils of this transformer. We can see that both U_{inc} and U_{ext} grow with distance d ranging from 0,1 mm up to 0,5 mm but not proportionally.

a)



b)

Fig.9.61 a) Planar transformers with the windings in one layer. The distance between conductors is in range from 0,2 mm up to 0,5 mm. **b)** Histogram of PD in planar transformers with different distance between coils for one layer structure.

In each experiment at means 6 samples were tested. The results for each specimen with respective windings distance are visualized on the Fig.9.62. Despite certain dispersion of U_{inc} and U_{ext} values, there is obvious that used technology gives almost uniform results which states to evidence the quality of the anti-soldering mask material.

Fig.9.63 shows the influence of temperature on the PD test voltage of one layer structure. In response to increasing temperature (from 40 ºC to 100 ºC) the value of origin PDs rapidly decreased.

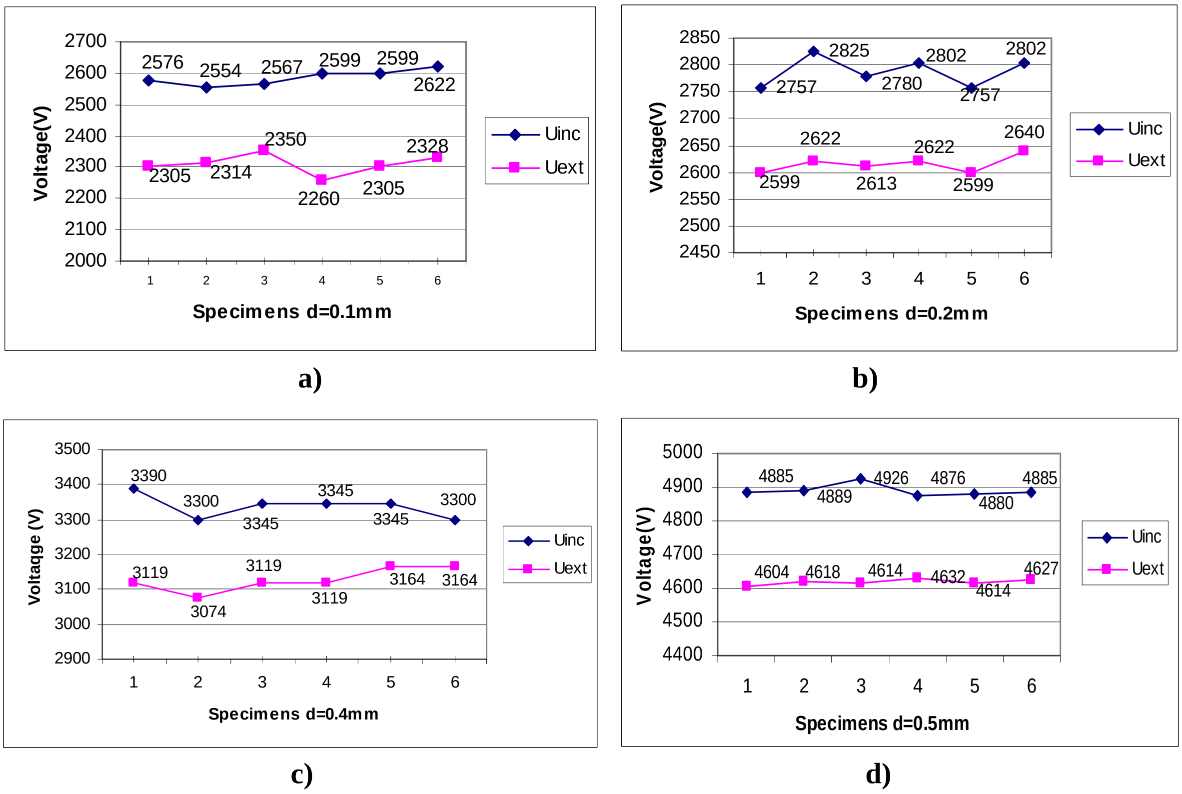


Fig. 9.62: Measuremnt of PD in planar transformer with one layer structure
a) d = 0,1 mm b) d = 0,2 mm c) d = 0,4 mm d) d = 0,5 mm.

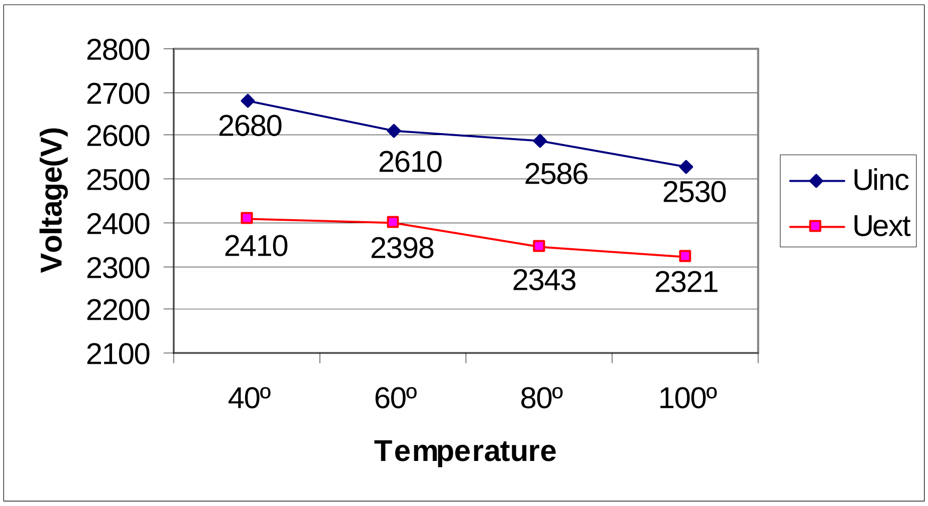
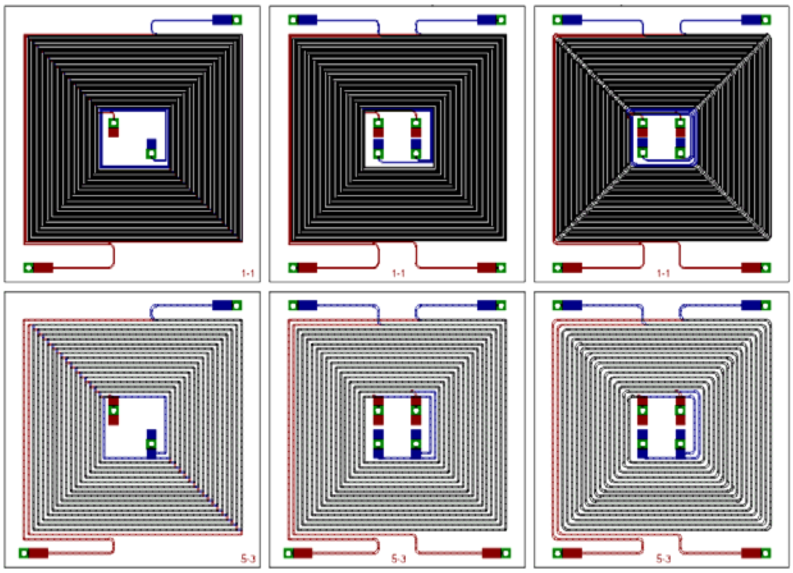


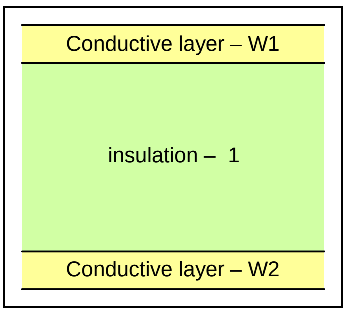
Fig.9.63 PD activity in insulation system of planar transformer: d=0.2mm (one layer structure). Temperature dependence of U_{inc} and U_{ext}.

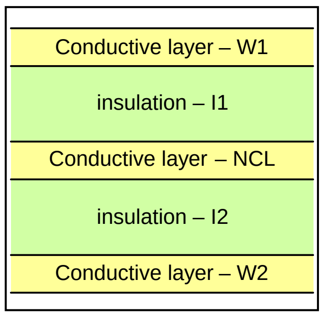
9.2.2 Multilayer planar transformers.

Despite very thin layer insulation capabilities and of anti-soldering mask measured in previous case of one layer planar transformer was found very good. To obtain higher resistivity against partial discharge air cavities must be excluded from the insulation system. Based on this idea planar transformers with three layer and multilayer structure were designed, Examples of conductor patterns and two types of the structure of these planar transformers are presented in Fig. 9.64.



a)



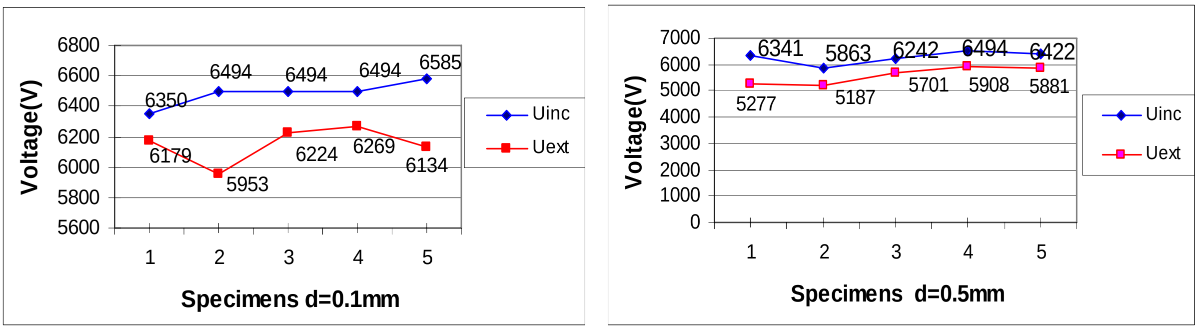


b) **c)**

Fig.9.64: a) Examples of multilayer structure of planar transformers with different distance between windings; **c)** three layer structure ; **b)** multilayer structure

PD activity in planar transformers with three layer structure described by means of evaluation U_{inc} and U_{ext} is presented on Fig. 9.65. Distances of conductors in transformer planar coils were: a) d=0.1mm and b) d=0.5mm.

It is seen that by excluding the gas phase from the insulation path PD inception and extinction voltages rise considerably. In case of lower distance of conductors in planar coil namely d=0.1mm the electrical field on both sides of insulation layer is more uniform which results in slightly higher values of U_{inc} and U_{ext} . Here should be noted that this observation is in contradiction with observation for one layer transformer, where the distance between conductors is in fact identical with the insulation distance.



a) **b)**

Fig.9.65 PD activity in planar transformers with three layer structure. Distance of conductors in transformer planar coils was: **a)** d=0.1mm and **b)** d=0.5mm.

9.2.3 Influence of thermal stress

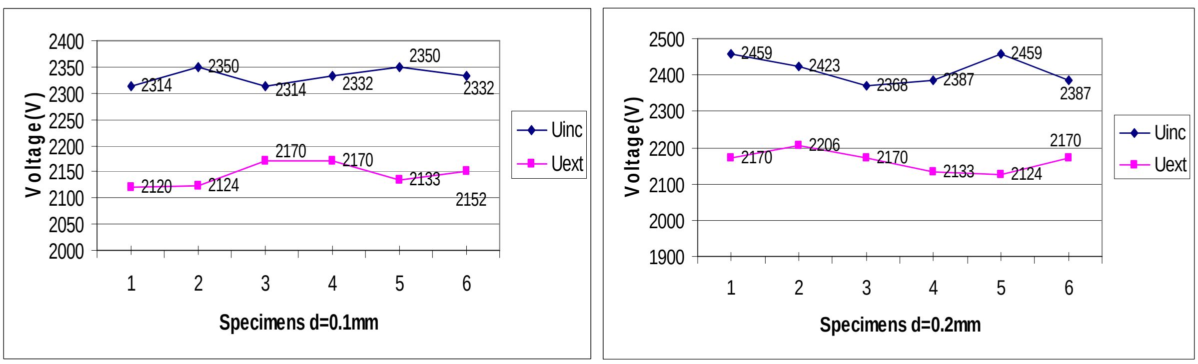
Investigated samples of one layer planar transformers were placed in thermal chamber during six months. The parameters of thermal cycling were:

Change of temperature: from 0 °C up to 100 °C;

One cycle time: 15 minutes / 4 cycles per hour.

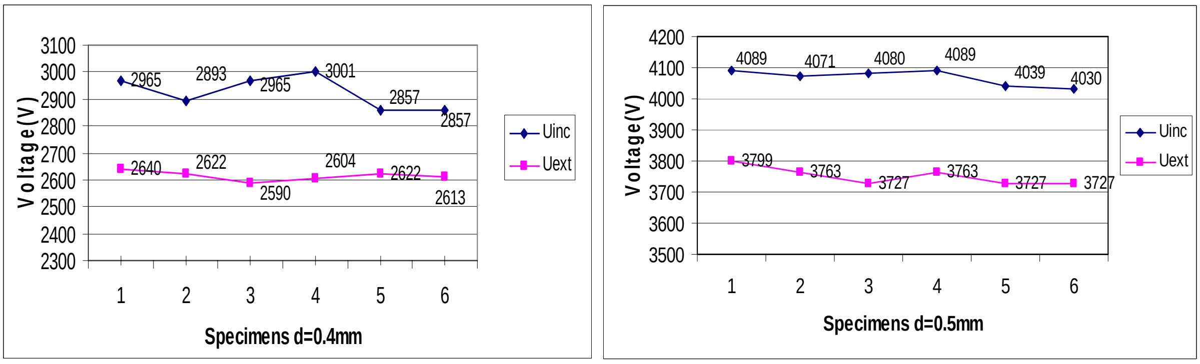
On figures Fig.9.66 and Fig 9.67 we can see the influence of thermal stress on PD activity in insulating system of one layer structure. Investigation of PD activity was performed the same way as described in chapter 9.2.1.

On the Fig 9.68 we can see comparisons of PD activity of the same specimens before and after placing specimens in thermal chamber. It is obvious that both U_{inc} and U_{ext} have drop in all samples and the drop is almost uniform. This is evidence for good quality of insulation system and sophisticated technological process.



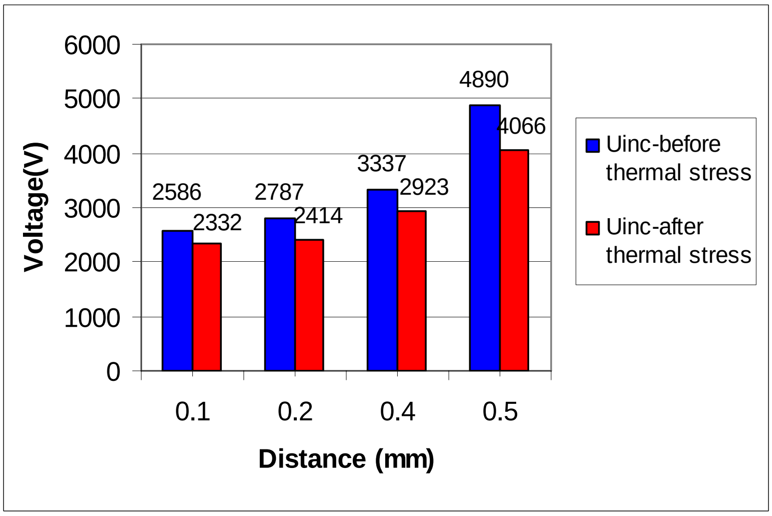
a) **b)**

Fig.9.66 Measurement of PD in planar transformers after thermal stress in case of different distance between interlaced conductors : a) d=0.1mm b) d=0.2mm

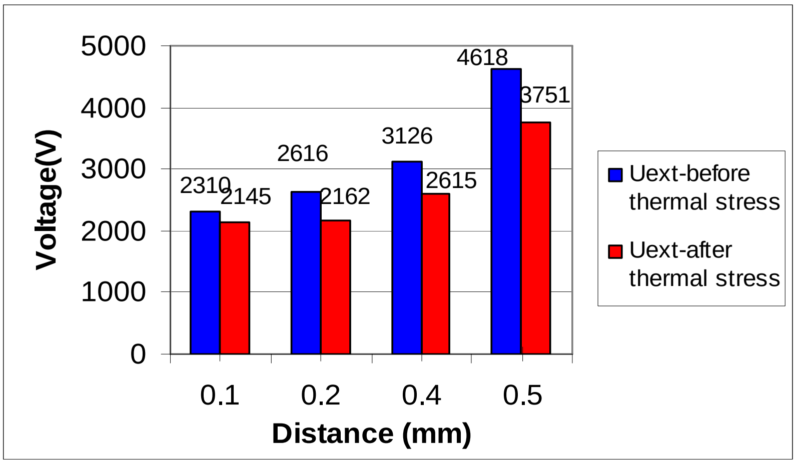


a) **b)**

Fig.9.67 Measurement of PD in planar transformers after thermal stress in case of different distance between interlaced conductors : **a)** d=0.4mm and **b)** d=0.5mm.



a)



b)

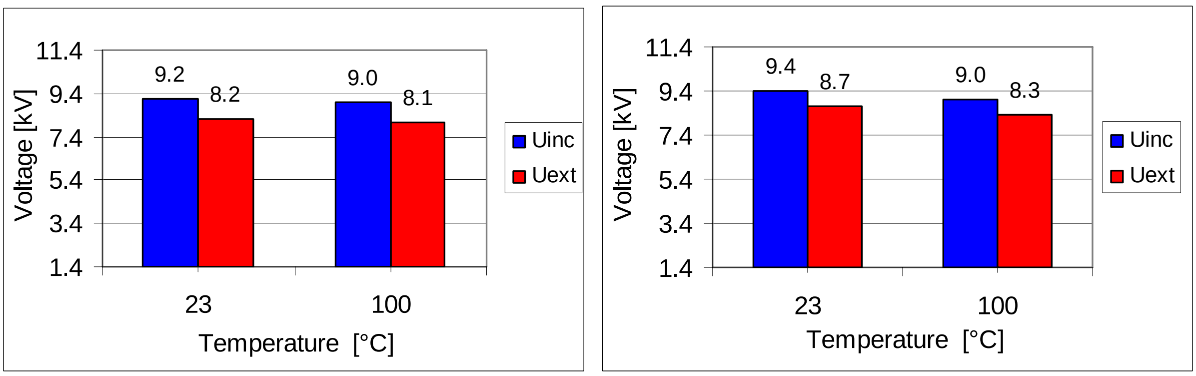
Fig.9.68 Comparison of voltage in planar transformers in one layer structure after and before thermal stress: **a)** U_{inc} and **b)** U_{ext}

To increase U_{inc} and U_{ext} voltage planar transformer with new multilayer insulation structure was designed. The structure of the insulation system is depicted on Fig.9.64 c). In the Tab.9.4 we can find dimensions of windings and PD parameters for temperatures 23 °C and 100 °C.

The distance between the coils, which is in fact the thickness of the insulation layer, is for respective coils 300 µm and 500 µm. Number of primary and secondary windings is equal and for different types of transformers is 28,5 and 37,5.

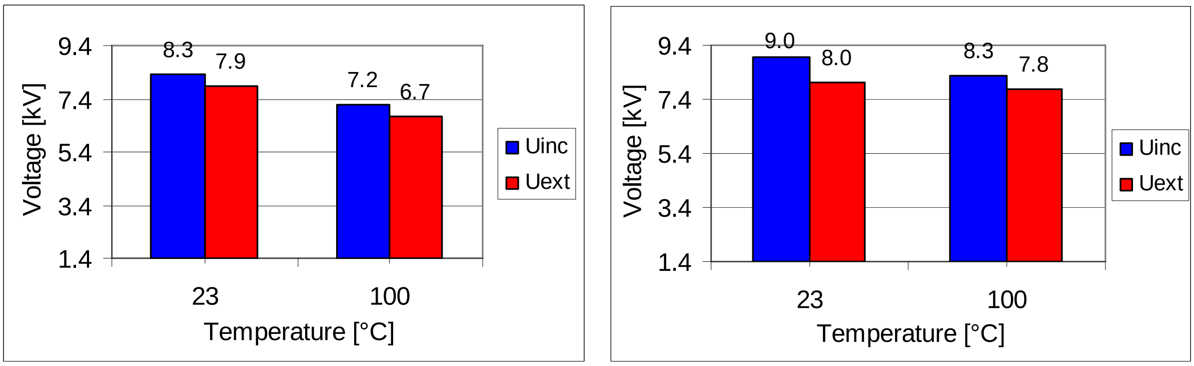
Tab.9.4 Basic parameters of planar transformers with multilayer insulation structure; U_{inc} and U_{ext} for temperature 23 °C and 100 °C,

	Distance	Size	a	d	N	F	T	U_{inc}	U_{ext}
Sample	µm	mm	mm	mm	-	kHz	°C	kV	kV
CSC 02w-01i	300	34,6 x 39	0.2	0.1	37.5	9.2	23	9.2	8.2
							100	9.0	8.1
CSC 03w-01i	300	34,6 x 39	0.3	0.1	28.5	9.2	23	8.3	7.9
							100	7.2	6.7
CSC 0103 03w-01i	300	34,6 x 29	0,2 / 0,1	0.1	37.5	9.2	23	9.9	9.0
							100	7.6	7.3
CSC 0203 03w-01i	300	34,6 x 35,8	0,3 / 0,1	0.1	28.5	9.2	23	9.3	8.3
							100	9.0	8.3
CSC 02w-01i	500	34,6 x 39	0.2	0.1	37.5	9.2	23	9.4	8.7
							100	9.0	8.3
CSC 03w-01i	500	34,6 x 39	0.3	0.1	28.5	9.2	23	9.0	8.0
							100	8.3	7.8
CSC 0103 03w-01i	500	34,6 x 29	0,2 / 0,1	0.1	37.5	9.2	23	9.8	8.9
							100	9.3	8.7
CSC 0203 03w-01i	500	34,6 x 35,8	0,3 / 0,1	0.1	28.5	9.2	23	9.7	8.8
							100	9.2	8.7



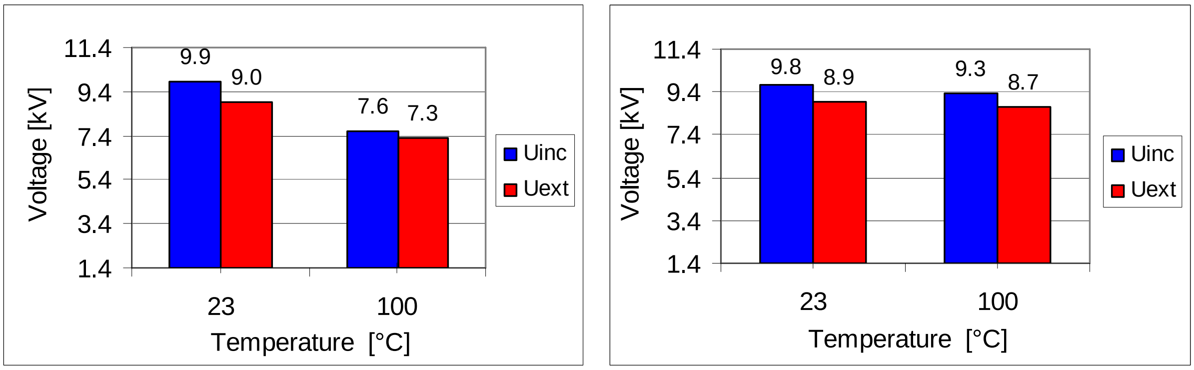
a) **b)**

Fig. 9.69: Planar transformer with multilayer insulation structure. PD activity represented by U_{inc} and U_{ext} for temperature 23 °C and 100 °C a) CSC 02w-01i ; distance of windings 300 µm and b) CSC 02w-01i ; distance of windings 500 µm.



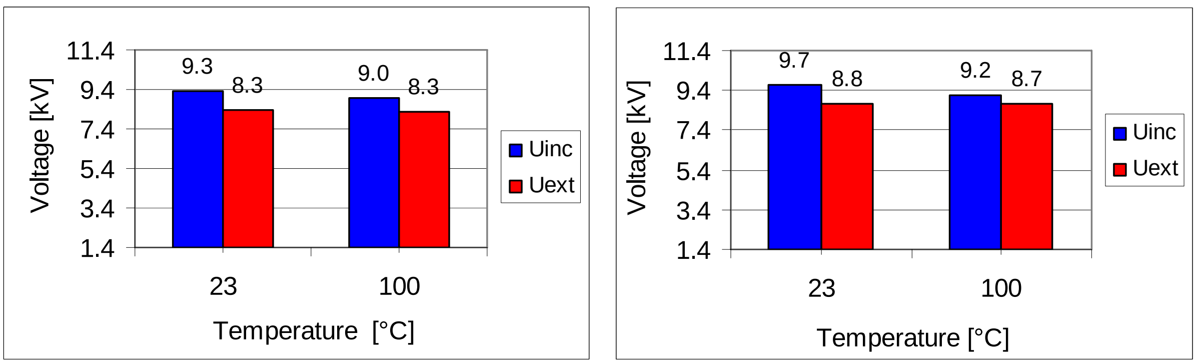
a) b)

Fig. 9.70 : Planar transformer with multilayer insulation structure. PD activity represented by U_{inc} and U_{ext} for temperature 23 ^{o}C and 100 ^{o}C a) CSC 03w-01i ; distance of windings 300 μm and b) CSC 03w-01i ; distance of windings 500 μm.



a) b)

Fig. 9.71 Planar transformer with multilayer insulation structure. PD activity represented by U_{inc} and U_{ext} for temperature 23 ^{o}C and 100 ^{o}C a) CSC 0103 03w-01i ; distance of windings 300 μm and b) CSC 0103 03w-01i ; distance of windings 500 μm.

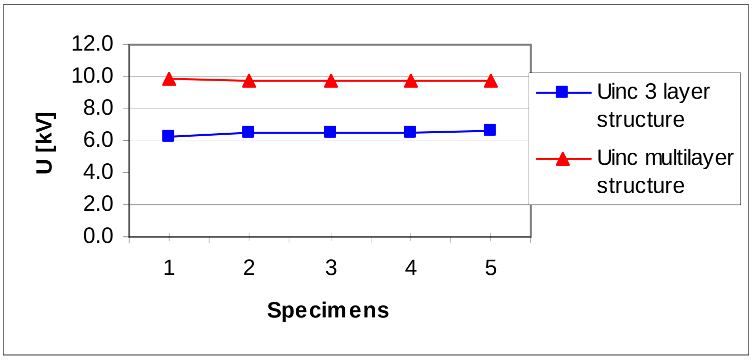


a) b)

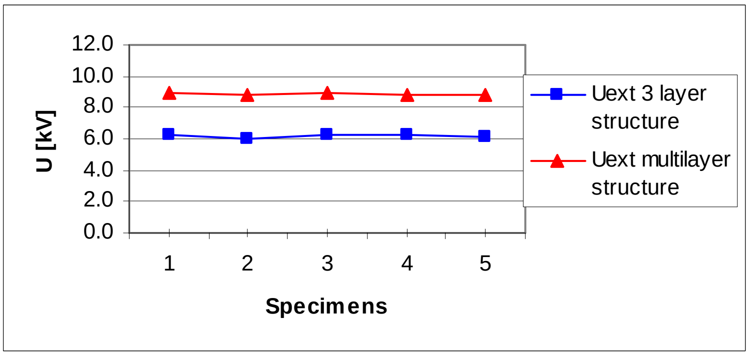
Fig. 9.72 Planar transformer with multilayer insulation structure. PD activity represented by U_{inc} and U_{ext} for temperature 23 ^{o}C and 100 ^{o}C a) CSC 0203 03w-01i ; distance of windings 300 μm and b) CSC 0203 03w-01i ; distance of windings 500 μm.

PD activity of planar transformer with multilayer insulation structure represented by U_{inc} and U_{ext} for temperature 23 °C and 100 °C for different conductor shapes and distance of windings 300 µm and 500 µm is presented on Fig.9.69, Fig.9.70, Fig.9.71 and Fig.9.72.

On Fig.9.73 there is comparison of U_{inc} and U_{ext} in planar transformers with 3 layer and multilayer configuration of isolation system. Distances between planar conductors in one layer plane is d=0.1mm. Temperature was 23 °C. It is clearly seen that both U_{inc} and U_{ext} by new multilayer structure are considerably higher.



a)



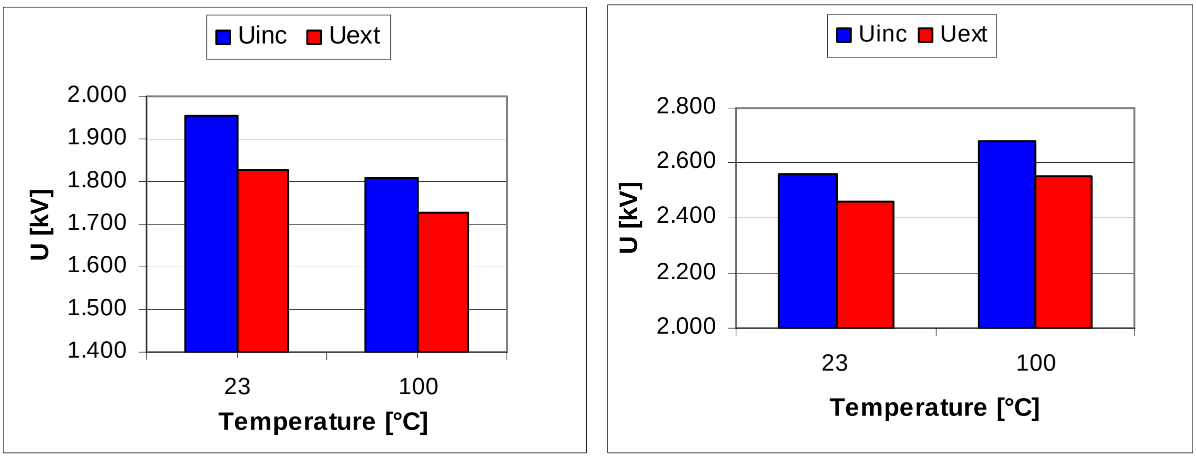
b)

Fig.9.73 Comparison of PD activity in planar transformers in 3 layer and multilayer configuration of insulation system; distance between planar conductors for both cases is d=0.1mm.
a) U_{inc} and b) U_{ext}.

9.3 Testing of pulse transformers

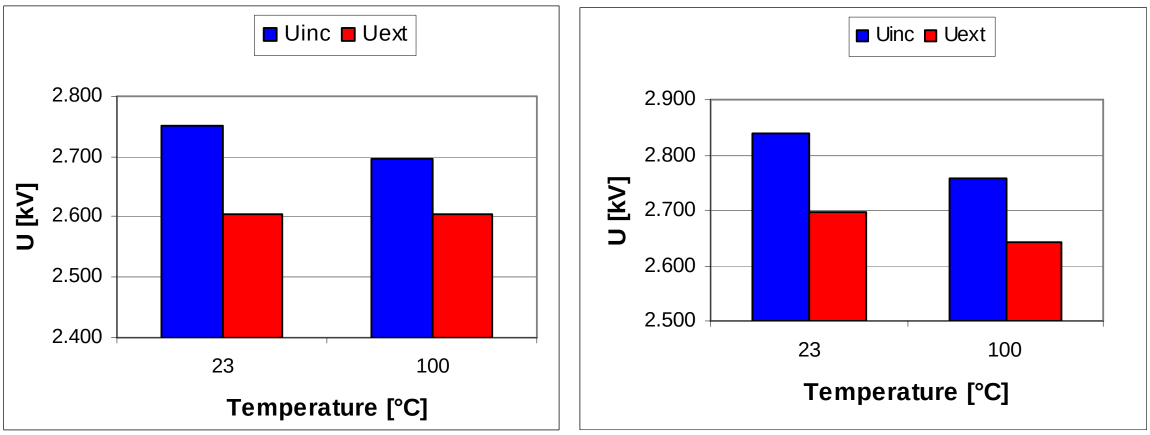
Toroidal pulse transformers are part of high voltage switch for the ozone generator working on the principle of dielectric barrier discharge. The power supply voltage of the switch is 3200 V and the SWITCH ON and SWITCH OFF times should be less than 100 ns.

To comply with the fabrication process these pulse transformers were designed on toroidal cores with an outer diameters of 10 mm and 15 mm and internal diameter 5 mm and 7 mm respectively. To ensure good magnetic coupling the winding was performed by twisted pair of conductors. Because of very short insulation distance such a make-up is very prone to partial discharge, nevertheless by proper insulation system design the PD activity can be suppressed dramatically.



a) **b)**

Fig.9.74: U_{inc} and U_{ext} at temperature 23 °C and 100 °C for toroidal pulse transformer:
a) before impregnation; **b)** after impregnation



a) **b)**

Fig.9.75: U_{inc} and U_{ext} at temperature 23 °C and 100 °C for pulse transformer:
a) after second impregnation; **b)** after third impregnation

First type of pulse transformer was made on toroidal core with outer diameter 10 mm and internal diameter 5 mm. Thee insulated conductor diameter was 0.25 mm and primary to secondary windings ratio was 16: 16.

Measurements were first performed at room temperature close to 23 ° C and than at temperature 100 ° C simulating the working conditions of toroidal transformers in equipment. Measurement was repeated three times and the mean values were used to make the assessment of the insulation system performance.

After that the evaluation of the impact of multiple impregnation on PD activity was carried out. Fig. 9.74 and Fig. 9.75 show the PD inception and extinction voltage for each impregnation step.

Exact values of U_{inc} and U_{ext} are shown in Tab.9.5. Percentage of increase of PD inception and extinction voltage values after respective impregnation step is shown in the Tab. 9.6 .

Tab. 9.5: Toroidal pulse transformer. U_{inc} and U_{ext} for temperatures 23 °C and 100 °C.
a) after first impregnation step in comparison with the state before impregnation
b) after second and third impregnation step.

a)

		no impregnation		impregnation 1x	
		Temperature		Temperature	
Voltage		23°C	100°C	23°C	100°C
U_{inc}	kV	1,954	1,809	2,560	2,678
U_{ext}	kV	1,827	1,728	2,461	2,556

b)

		impregnation 2x		impregnation 3x	
		Temperature		Temperature	
Voltage		23°C	100°C	23°C	100°C
U_{inc}	kV	2,750	2,696	2,840	2,759
U_{ext}	kV	2,605	2,605	2,696	2,641

Dependence given in table Tab.9.6 was verified by repeated measurement on several samples after each impregnation step. The greatest impact is always after the first impregnation, where the value of inception voltage increases more than 30%.

The change of the extinction voltage is slightly less but it is also very close to 30%. In a second impregnation, the increase is about 7% for inception and 6% for the extinction voltage. The values after the third impregnation changed only by 3 % for both inception and extinction voltage, however by some sample the change was much less pronounced.

Tab. 9.6: Toroidal pulse transformer. Percentage of change of U_{inc} and U_{ext} after respective impregnation step: **a)** at 23 °C ; **b)** at 100 °C

a)

rise of voltage	1. impregnation	2. impregnation	3. impregnation
U_{inc}	31,0	7,4	3,3
U_{ext}	34,7	5,9	3,5

b)

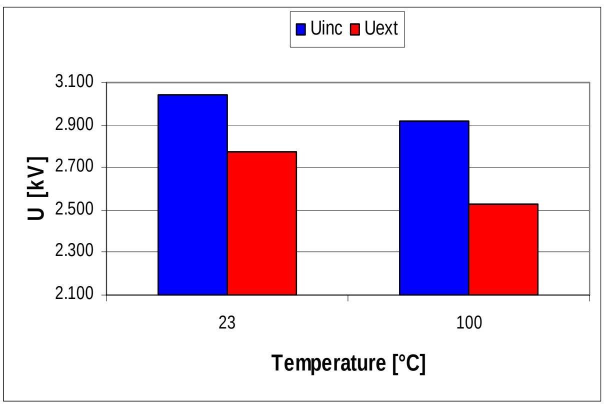
rise of voltage	1. impregnation	2. impregnation	3. impregnation
U_{inc}	32,7	6,4	4,0
U_{ext}	28,2	12,1	2,4

Fig.9.76: TAV pulse transformer. Toroidal core 10/5 mm. Conductor TAV 0,20 SM

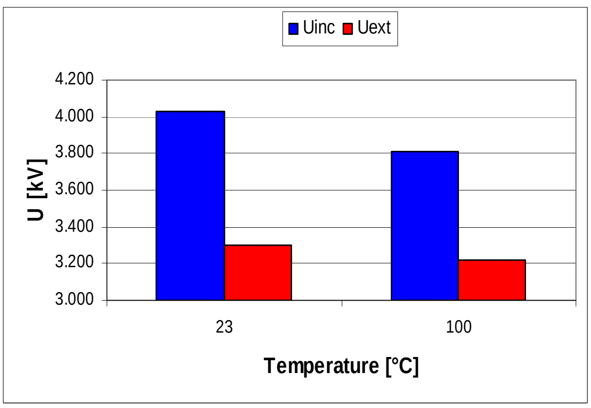
It is obvious that the PD activity obtained for first type of pulse transformer did not comply with the claim for working voltage of the switch declared as 3200 V. To ensure higher resistivity against PD new type of toroidal transformer was designed where twisted pair were made from special conductor with teflon insulation. This conductor labeled TAV 0.20 SM has wire with diameter 0,2 mm and the insulation strength of the teflon insulation is in this case more than 4 kV. This value is however valid for DC voltage and has no impact in respect to resistance of this wire insulation against partial discharge. The ratio of primary to secondary was 16 : 16 as in previous case.

Tab. 9.7: TAV pulse transformer. U_{inc} and U_{ext} for samples before and after first impregnation for temperatures 23 °C and 100 °C

		TAV-1 / no impregnation		TAV-1 / impregnation 1x	
		Temperature		Temperature	
Voltage		23°C	100°C	23°C	100°C
U_{inc}	kV	3,045	2,918	4,030	3,810
U_{ext}	kV	2,772	2,528	3,301	3,216



a)



b)

Fig.9.77: U_{inc} and U_{ext} at temperature 23 °C and 100 °C for TAV pulse transformer:
a) before impregnation; **b)** after first impregnation

Fig. 9.77 shows PD inception and extinction voltage before and after impregnation step. In comparison with previous type the PD inception and extinction voltages in no impregnated state are about one kV higher.

After impregnation the PD inception voltage reach value approximately 4 kV for both 23 ^{o}C and 100 ^{o}C. However the elevation of the U_{ext} is much less pronounced giving the lowest extinction voltage value 3,2 kV. Exact values are in table Tab. 9.7. Percentage of change of U_{inc} and U_{ext} after first impregnation in comparison with the state before impregnation for two different samples (TAV-1, TAV-2) is given in table Tab.9.8.

Tab. 9.8: TAV pulse transformer. Percentage of change of U_{inc} and U_{ext} after first impregnation in comparison with the state before impregnation for two different samples (TAV-1, TAV-2).

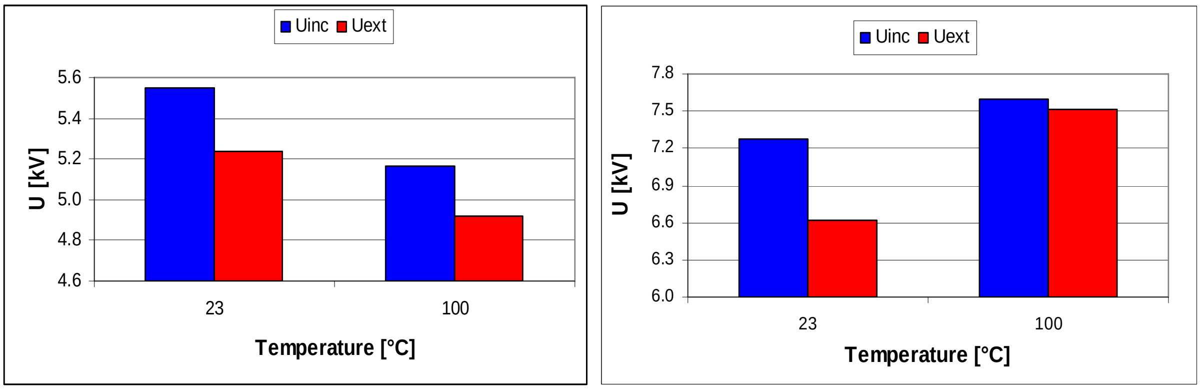
		TAV-1 / impregnation 1x		TAV-2 / impregnation 1x	
		Temperature	Temperature	Temperature	Temperature
rise of voltage		23°C	100°C	23°C	100°C
U_{inc}	%	28,5	30,2	32,3	30,6
U_{ext}	%	22,8	27,2	19,1	27,2

Results measured on the TAV pulse transformer indicate that using proper wire insulation system is possible to enhance PD resistivity of the insulation system. PD inception voltage increased more than 30% up to 4 kV and PD extinction voltage increased from about 19% up to 27 % giving the lowest U_{ext} value 3,2 kV. To ensure safe work of this transformer the maximal amplitude of working voltage should be less than the lowest U_{ext} – it means less than 3,2 kV.

Because the working voltage of respective equipment (ozone generator) is just 3,2 kV the PD resistance reached in case of TAV pulse transformer may be not sufficient. Therefore more enhanced insulation system was to find.

TAV toroidal pulse transformer with additional insulation was made on toroidal core with an external diameter of 15 mm and internal diameter 7 mm. The winding was made similar way, using the TAV 0.20 SM conductor but supplementary teflon insulation was added. The ratio of turns of primary to secondary was 8: 8. The impregnation technology was the same. The resulting device is depicted on Fig. 9.78.

Fig.9.78: TAV pulse transformer with additional insulation. Toroidal core 15/7 mm. Conductor TAV 0,20 SM with additional insulation.



a) **b)**

Fig.9.79: U_{inc} and U_{ext} at temperature 23 °C and 100 °C for TAV pulse transformer with additional insulation: **a)** before impregnation; **b)** after impregnation

Measurements performed on TAV pulse transformers with additional isolation revealed that this insulation system achieves significantly better parameters of both PD inception and extinction voltage compared to previous versions. As seen from the Fig.9.79 PD and from table Tab.9.9 inception and extinction voltages even in non impregnated state are much higher than for previous TAV pulse transformer after impregnation. After first impregnation step both U_{inc} and U_{ext} rise considerably, giving the lowest PD extinction value 6,6 kV. This voltage is in comparison with the corresponding U_{ext} measured for previous TAV transformer more than 100% higher.

Tab. 9.10 shows for TAV pulse transformer with additional insulation the percentage of change of U_{inc} and U_{ext} after first impregnation step. Note that for temperature 23°C the increase in U_{inc} and U_{ext} is approximately 30%, but at temperature 100 °C the increase was close to 50% for both U_{inc} and U_{ext} .

Tab. 9.9: TAV pulse transformer with additional insulation. U_{inc} and U_{ext} for samples before and after first impregnation for temperatures 23 °C and 100 °C

		no impregnation		impregnation 1x	
		Temperature		Temperature	
Voltage		23°C	100°C	23°C	100°C
U_{inc}	kV	5,547	5,167	7,279	7,599
U_{ext}	kV	5,239	4,917	6,620	7,508

Tab. 9.10: TAV pulse transformer with additional insulation. Percentage of change of U_{inc} and U_{ext} for samples after first impregnation in comparison with samples before impregnation.

		Temperature	Temperature
Rise of voltage		**23°C**	**100°C**
U_{inc}	%	31,2	47,1
U_{ext}	%	26,4	52,7

From previous PD experiments and design of three different type pulse transformers following conclusions may be drawn:

1) First impregnation brings the enhancement of PD resistivity approximately 30%. Further increasing of the number of impregnation has considerably smaller effect on the resistance to partial discharge activity.

2) When using a proper design both PD inception and PD extinction voltages can be elevated considerably. However careful PD testing and feedback engineering of insulation system is indispensable in this case.

3) High voltage test without PD measurement would let pass even the first type of the pulse transformer with unsatisfactory insulation properties. However the weak resistance against PD will undoubtedly result in breakdown of the device in short time - seemingly without any reason.

4) Change of the PD activity as consequence of change in temperature must be always taken into account.

Pulse transformers generally need small dimensions, excellent magnetic coupling and low stray inductance. This is difficult to achieve when implementing high working voltage or with demand on high voltage difference between primary and secondary windings.

As to resistance against partial discharge best results were achieved by planar transformers with multilayer insulation structure. However, here must be noted that the mounting of the planar transformer together with the ferrite core must be done carefully to prevent the PD between the planar coils and the ferrite core. Supplementary insulation must be used either under the ferrite core or on the whole planar coil surface as is demonstrated on the Fig. 9.80.

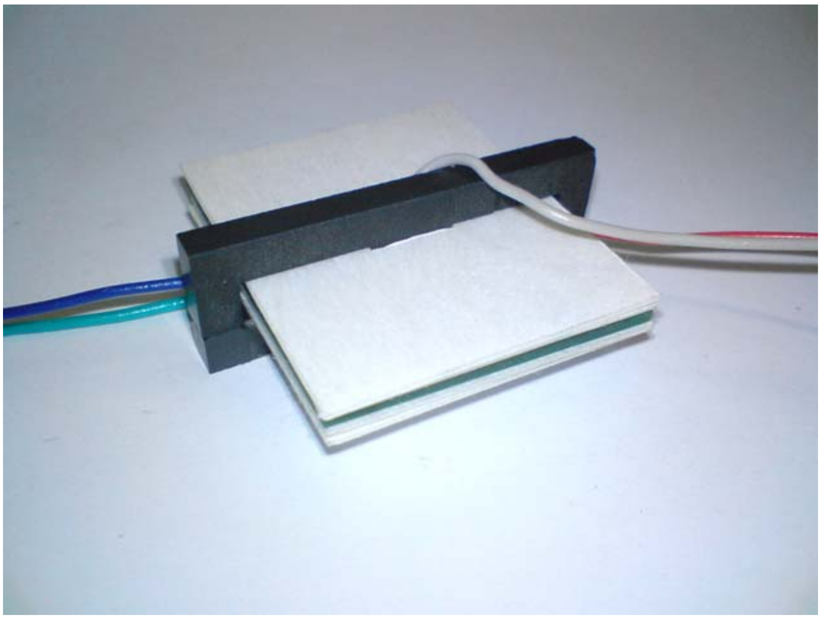


Fig.9.80: Planar transformer with multilayer structure. To prevent the inception of PD there is a need to ensure supplementary insulation between planar coils and ferrite core.

10. Conclusion

PD-testing is a generally recognized tool to verify the integrity of high-voltage insulation systems. For applications within low-voltage equipment, some modifications are necessary and also some simplifications are possible. In case of electronic devices PD there is due to extremely short distances a potential for high electric load. The risk of PD caused failure is here extremely high because of high working frequency and consequently high repetition rate of PD. In my thesis I therefore tried to elaborate a system for PD diagnostic of insulation in electronic equipments:

- In introductory chapters origin of PD is discussed and dependence of PD on operation condition of the electrical equipments is dealt shortly. Then in chapter *5 Influence of PD on electrical equipments* consequences of PD activity are summarized and in following chapter *6 Measurement of PD* is PD pulse acquisition is explained including the philosophy of testing.

- Workplace for PD diagnostic is described in chapter 8. Here also the main characteristics of measurement principles based on the method of amplitude analysis are introduced. PD detection principle and calibration procedure are explained and simple examples from PD testing on planar coils are given.

- The survey of the results of more than 500 experiments in the testing campaign is presented in chapter *9 PD testing*. PD activity in electronic devices and components in dependence of different working conditions was investigated and different possibilities of design of insulation systems on printed circuit boards are summarized.

As a rule, PD source is located in an insulation bulk and to place there the measuring device it is impossible. The PD registration equipment can be connected only to external parts of the controlled device. At passage through internal elements of the device the signal weakens, and his form disfigures. The degree of ceasing of a signal and distortion of his form depend on type of the signal source, on a place of his formation, on the design of the equipment, on used range of frequencies, on the way of connection, etc.

All this phenomena are important for proper assessment of PD activity. In frame of my work I therefore dealt with PD problematic as follows:

- PD diagnostic tool based on switched power supply was designed. Working frequency ranges from several hundreds of Hertz up to 100 kHz. The maximal amplitude of PD testing voltage is higher than 10 kV.

- For the workplace at department of microelectronics methods of PD measurement and calibration were elaborated. As the most convenient the method of Amplitude Analysis of PD pulses was chosen. After proper calibration this method facilitates an assessment of the charge transferred in single PD event. In most measurement this charge varied from several hundreds of pC until approximately 1000 pC depending on the insulation system. Consequently, PD free condition can be therefore estimated for transferred charge less than 20 pC which in our case gives the PD pulse amplitude of approximately 10 mV.

- More than 500 PD tests were made on different electronic devices, electronic components, in planar transformers, in components for high voltage gate drivers, in high voltage power converters, etc. The experience acquainted this way was of basic importance for 15 publications on national and international conferences.

- Possibilities of PD investigation tools were demonstrated on design of insulation systems on printed circuit boards, especially on design of different types of planar coils and transformers.

- Experience gained during PD testing facilitates understanding of correlation between PD measurement and device characteristics. This is of basic importance for good assessment of insulation properties of the insulation system and is useful when improving the insulation structure.

The main conclusions which may be extracted from experiment performed are:

1. The PD-test is a component test, but testing of equipments is also possible. For whole equipment, it is difficult to localize the PD source and its local PD level.

2. During type testing, the PD test will verify the proper design of the insulation system and the appropriate selection of the insulation materials and the manufacturing processes being used. Such tests are also very useful during development and design. By performing sampling and routine testing, the whole manufacturing process is evaluated, which is of fundamental importance for quality assurance.

3. The use of very high test voltages without measuring the PD always implies the risk of degradation of the solid insulation. Additionally, such tests can only show gross defects within the insulation system.

4, In order to avoid any risk of degradation, PD-testing should be performed with high sensitivity and with test voltages in the range of the PD-inception voltage.

5. The specified PD-extinction voltage can only be determined with limited accuracy, and this level is also influenced by additional parameters such as temperature and humidity, that may be often not taken into account during testing.

6. Low PD-levels have to be specified for the failure criterion. A reasonable compromise between desirable sensitivity and experimental practicality needs to be found for each case. For electronic devices the value is usually from 10 pC to 20 pC. Only in exceptional cases values of more than 20 pC are acceptable.

The results were published in [37 - 44].

The contribution of the work to the development of problematic of PD testing in electronic devices may be summarized as follows:

1. The workplace for PD diagnostic in electronic devices based on switched power supply was designed and made. Working frequency ranges from several hundreds of Hertz up to 100 kHz. The maximal amplitude of PD testing voltage is higher than 10 kV. Despite the simple design this equipment brings high repeatability and reliability of measurement. To time such equipment is not commercially available. The results were already published.

2. Methods of PD measurement and calibration were elaborated. Proper measurement and calibration will ease the use the PD diagnostic especially at workplaces dealing with design of electronic circuits which are not specialized in high voltage technique.

3. More than 500 PD tests were made and experience was acquainted in measurement of PD in electronic devices, electronic components, in planar transformers, in components for high voltage gate drivers, in high voltage power converters etc. Some results have been already published.

4. Experience gained during PD testing also contributed to better understanding of correlation of PD activity with properties of insulation system and other device characteristics. This is

indispensable for good assessment of the device properties and may help to improve the insulation structure.

5. In several experiments it was proved that PD testing may be used not only for high voltage equipments but also in case of low voltage applications and even in “non electric” applications, where PD can help to discover different material defects.

6. All results obtained in frame of this work may serve as a source of useful information for research and in manufacturing processes and instrumentation.

In future research there is advisable to focus more on investigations in insulation systems where PD measurement is a powerful tool for assessment of insulation properties. However, the sensitivity of the equipment which is to time not much below 10 mV may not be sufficient for such work. Therefore there is a need to ensure higher sensitivity of the data acquisition system and ensure more precise amplitude to discharge conversion.

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