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PARTIAL DISCHARGE IN ELECTRONIC EQUIPMENTS
ČÁSTEČNÉ VÝBOJE V ELEKTRONICKÝCH ZAŘÍZENÍCH

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1 INTRODUCTION

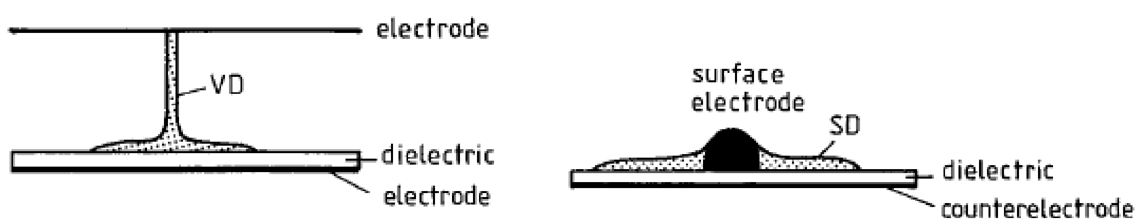
Partial Discharges (PD) is defined as an electrical discharge that only partially bridges the insulation between conductors and that may or may not occur adjacent to a conductor. PDs occur when the local electrical field intensity exceeds the dielectric strength of the insulation system involved, resulting 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).

In case of partial discharge there is always a dielectric layer between two metal electrodes. The discharge current stops after charging of this dielectric layer. Such type of discharge is therefore qualified as dielectric barrier discharge (DBD). Below we can see two configurations of dielectric barrier discharges.

The *Volume Discharge* (VD) electrodes arrangement consists of two parallel plates (see Fig. 1.1a). The micro-discharge takes place in thin channels which cross the discharge gap. Such micro-discharges 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. 1.1b). 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 here 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.



a) **b)**

Fig.1.1 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].

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.

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 corona discharge in gases, treeing and surface contamination, surface discharges at interfaces and internal discharges in voids or cavities within the dielectric.

PD phenomena accelerate the local degradation and can generate electrical trees. Although PD may initially be quite small damaging process causes gradually chemical decomposition and erosion of materials. Left unchecked, the damaged area can grow, eventually risking electrical breakdown.

Because partial discharge may decrease reliability and lifetime of devices and equipments the issue of PD diagnostics is very important. Naturally, PD diagnostic is nowadays well known method in high voltage high power technique but 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.

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 and separation of this signals and possibly location of a partial discharge (PD) source allow considerable improvement in diagnostics of solid insulation systems.

2 PURPOSES

In my thesis I tried to elaborate a system for PD diagnostic of insulation in electronic equipments. By the time when I start to work on my thesis, there were only few groups in Czech Republic dealing with the measurement of partial discharges issue and to my knowledge to the problematic of PD activity in electronic equipments here were only limited attention and practically no technical literature. 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 testing methods will ease the use of 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 improve the insulation structure.

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

3 METHODS

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 interpretation of results. By suitable conditions surface discharge 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.

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 soon 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.

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.

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. There are four analysis tools which can help us to detect PD: frequency response, acoustic analysis, tanδ measurement and amplitude analysis.

3.1 METHOD OF AMPLITUDE ANALYSIS

Circuit diagram for measurement PD using the method of amplitude analysis is shown in Fig. 3.1. This test circuit is mentioned in the IEC 60270 standard for PD measurement.

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 analysis of the charge distribution follows 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 specimens with high capacitance C_a . 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 . It is important to know that C_C must provide low impedance at the frequency corresponding to PD pulses. [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.

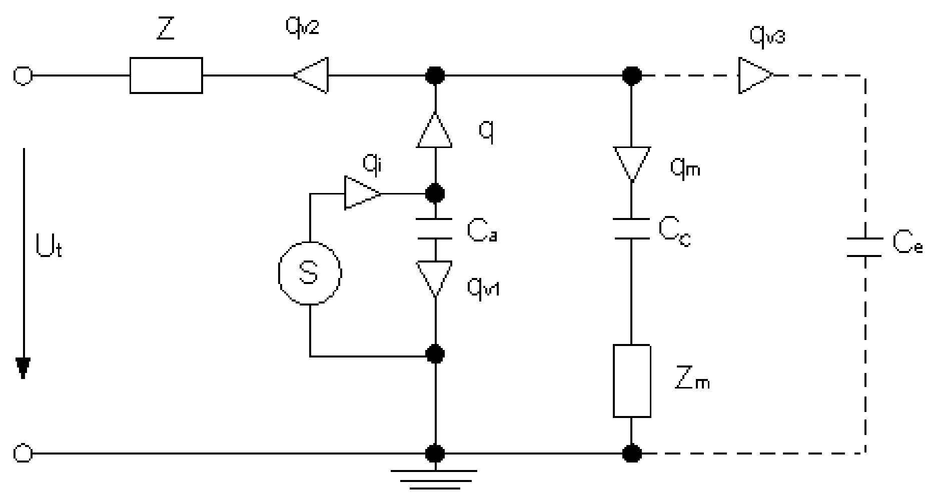


Fig. 3.1 Basic arrangement of PD - test circuits: U_t - Test voltage source; Z - impedance (Filter); S - PD source; C_a - Capacitance of the test specimen; C_C - Coupling capacitor; Z_m - Measuring impedance ; Ce - earth capacitance; q_i - Internal charge (not measurable); q - Apparent charge; q_{v1} - 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].

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.

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,

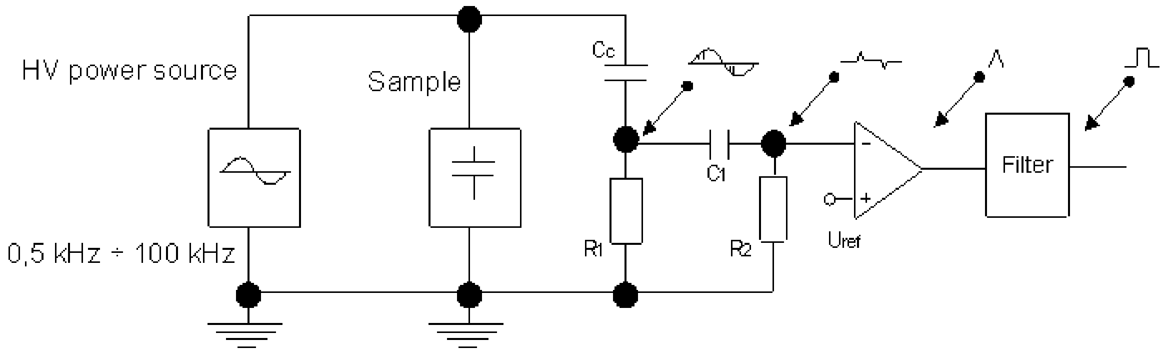


Fig.3.2 Circuit diagram for PD measurement.

3.2 CALIBRATION PROCEDURE

Before measuring a calibration of the PD-measuring equipment within the complete test circuit is required. When needed 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/noise 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.

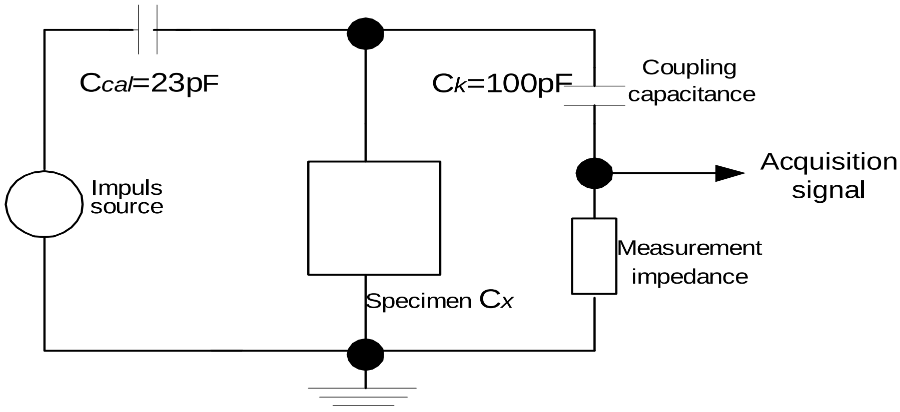
Finally, a calibration with the test specimen connected to the test circuit has to be performed. In the case of using the same test specimens, or in the case of test circuits with rather large capacitance of the coupling capacitor when compared with capacitance of the specimen ($C_C >> C_x$), this calibration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

To understand better the calibration procedure of PD it 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].

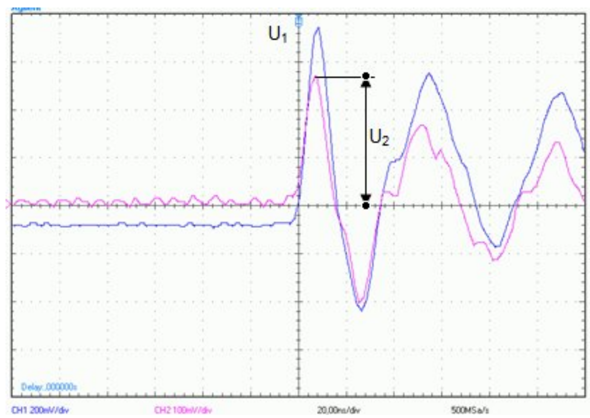
The calibration of the acquisition system consists in correlating the PD pulse voltage amplitude estimated by the instrument to the apparent charge associated to the PD. In turn, the apparent charge value is a measure of the real process caused by charge transfer inside the defect in the system insulation.

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.3.3. 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.



a)



b)

Fig.3.3 Calibration procedure. **a)** Principal scheme. **b)** Voltage response to the calibration pulse.

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.

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.

3.3 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 - one of the 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 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. In switched mode high voltage generator the floating channel is used to drive N-channel power MOSFET in the high side configuration.

The amplitude of testing voltage is controlled by power supply voltage. The frequency is from 500 Hz up to 100 kHz. Special oil transformers are used for different frequency bands.

4 RESULTS

PD-testing is a generally recognized tool to verify the integrity of high-voltage insulation systems. Due to extremely short distances there is a potential for high electric load also in case of electronic devices. The risk of PD caused failure is here extremely high because of high working frequency and consequently high repetition rate of PD.

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 investigated 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 300 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 8 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 engineering the insulation structure.

4.1 MAIN OBSERVATIONS

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.

In case of thermal stress testing samples were placed in thermal chamber during six months. The parameters of thermal cycling were as follows: *Change of temperature* - from 0 ^{o}C up to 100 ^{o}C ; *One cycle time* - 15 minutes / 4 cycles per hour.

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 can be 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.

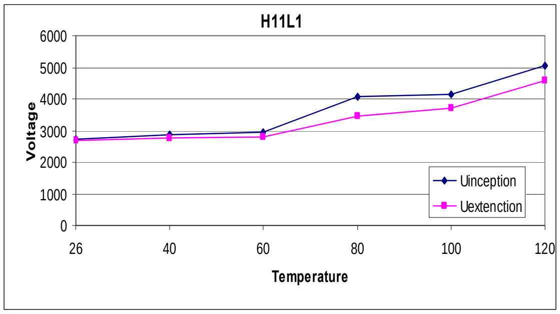
5. The specified PD-extinction voltage can only be determined with limited accuracy, and this level is also influenced by additional parameters such as temperature and humidity, that may be often not taken into account during testing.

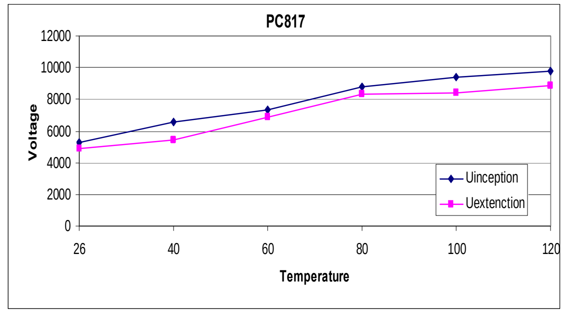
6. Low PD-levels have to be specified for the failure criterion. A reasonable compromise between desirable sensitivity and experimental practicality needs to be found for each case. For electronic devices this value is usually from 10 pC to 20 pC. Only in exceptional cases values of more than 20 pC are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

Some results were already published elsewhere. The list of related papers there is in following Chapter 7.

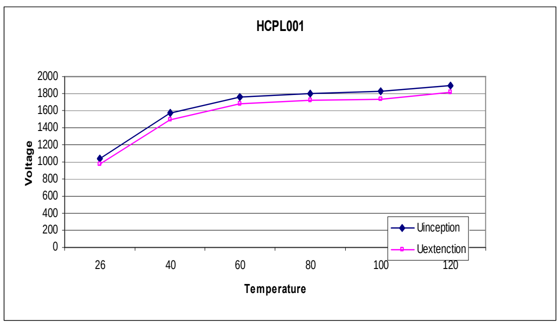
4.2 TESTING OF OPTOCOUPLERS

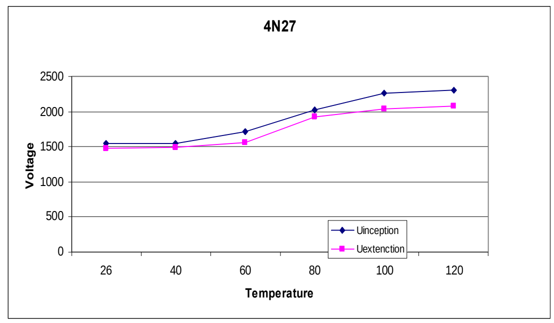
Main operational function of optocouplers is galvanic detachments of two circuits. The potential difference may range from few mV in data processing equipments up to several kV in power generation systems. There is also important to know whether the optocoupler serve only as galvanic detachment or if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





a) b)



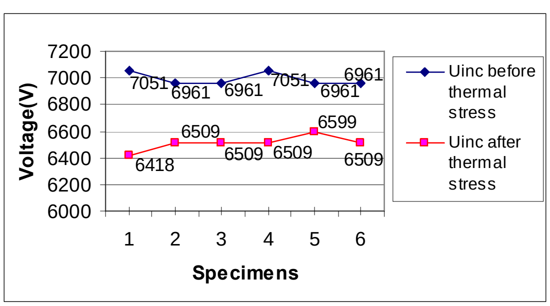


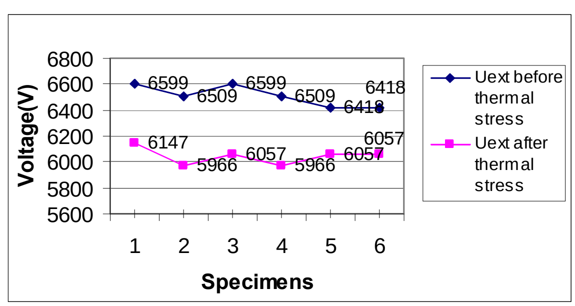
c) d)

Fig.4.1 *:* PD activity in insulation system of optocouplers. Temperature dependence of U_{inc} and U_{ext}.
a) H11L1 **b)** PC817**, c)** HCPL001 and **d)** 4N27.

Between many parameters which influence PD activity in insulation system of optoucuplers one of most important is temperature. Fig.4.1 shows the temperature influence on PD activity as measured by different types of optocouplers.

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 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.

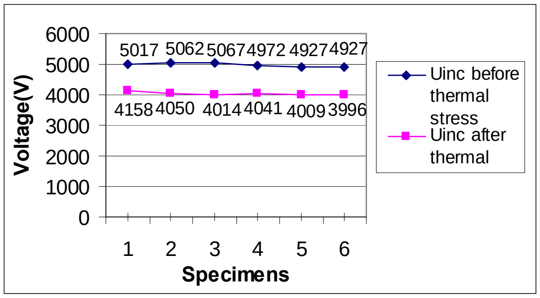




a) b)

Fig.4.2 PD activity in insulation system of optocupler PC 817 before and after thermal stress:
a) U_{inc} and **b)** U_{ext}

On Fig.4.2 and Fig.4.3 we can see the influence of thermal stress to different types of optocuplers. The specimens were placed in thermal chamber for 6 months.



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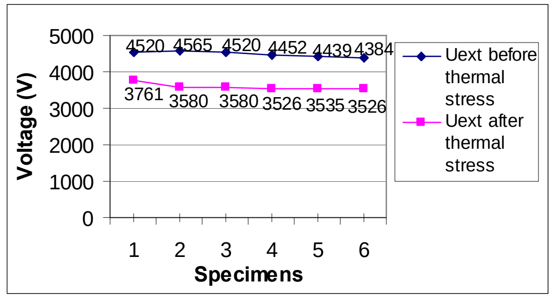


b)

Fig.4.3. PD activity in insulation system of optocupler HCPL601 before and after thermal stress: a) $\mathbf{U_{inc}}$ **and** b) $\mathbf{U_{ext}}$

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.

The test of PD activity in optocouplers have shown that between different samples of the same type exist differences with respect to the insulation characteristics. However, 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.

4.3 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 arbitrary arrangement of output taps.

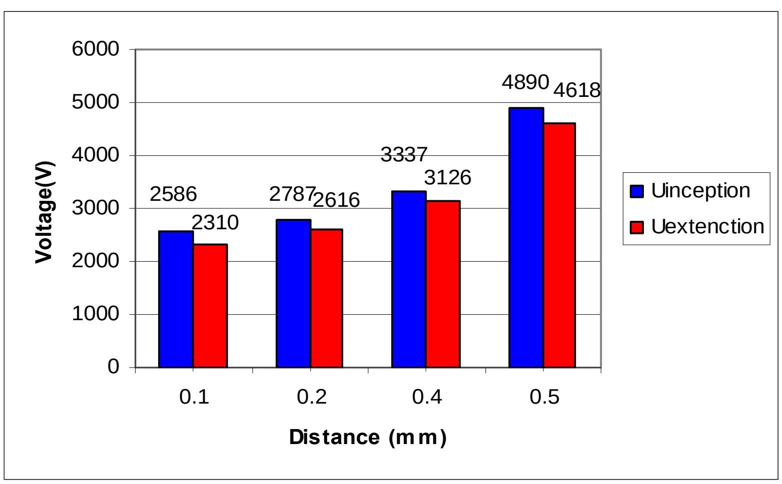


Fig.4.4 Planar transformers with the windings in one layer. The distance between conductors is in range from 0,2 mm up to 0,5 mm. Histogram of PD in planar transformers with different distance between coils for one layer structure.

First experiments were performed on one layer planar transformer. In this design the windings are placed on the same side of the PCB. Width of planar conductors was from 0.1mm to 0.2mm, distance between planar conductors was 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. Anti-soldering mask was used as surface treatment.

On Fig.4.4 the values of U_{inc} and U_{ext} for different distances between interlaced conductors in planar coils of this transformer are given. 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. In each experiment at means 6 samples were tested. The results on Fig. 4.4 are mean values taken from this measurements.

Fig.4.5 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) both values of value of U_{inc} and U_{ext} rapidly decrease.

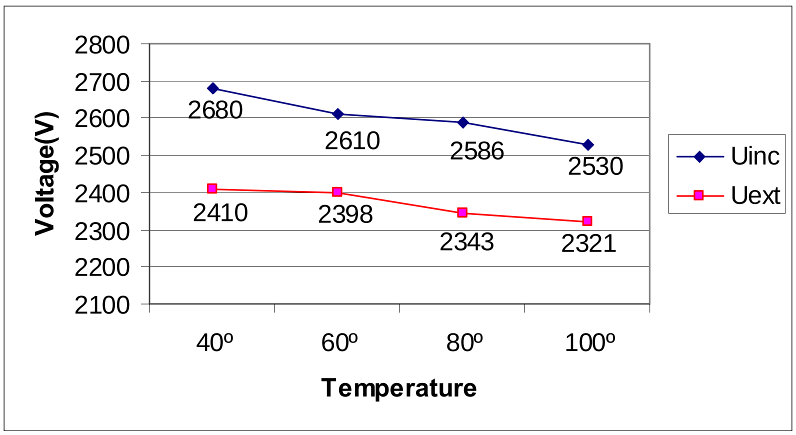


Fig.4.5 PD activity in insulation system of planar transformer: d=0.2mm (one layer structure). Temperature dependence of U_{inc} and U_{ext}.

On the Fig.4.6 and Fig 4.7 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.

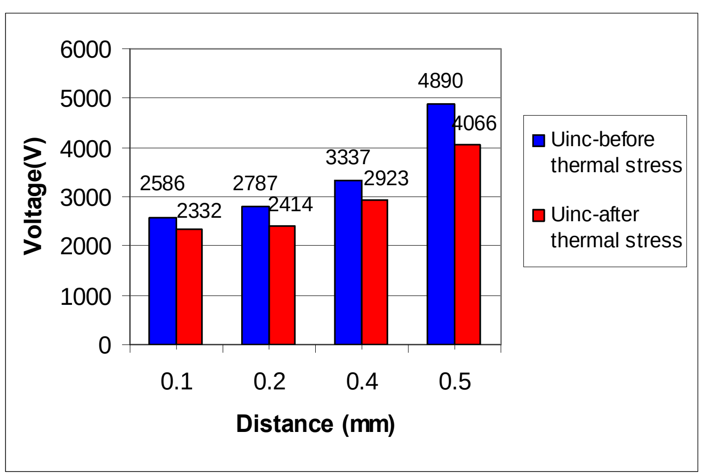


Fig.4.6 Comparison of U_{inc} in planar transformers in one layer structure after and before thermal stress.

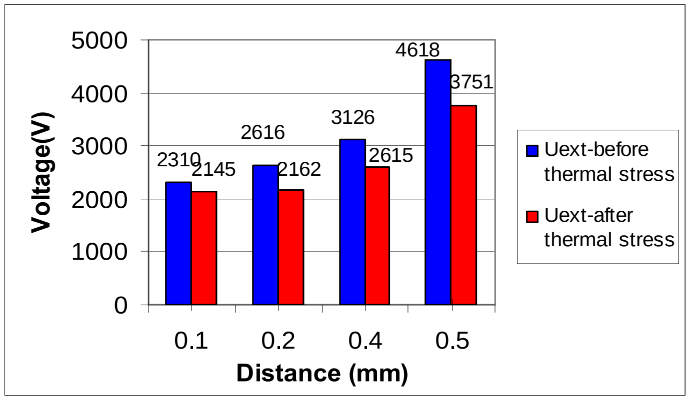
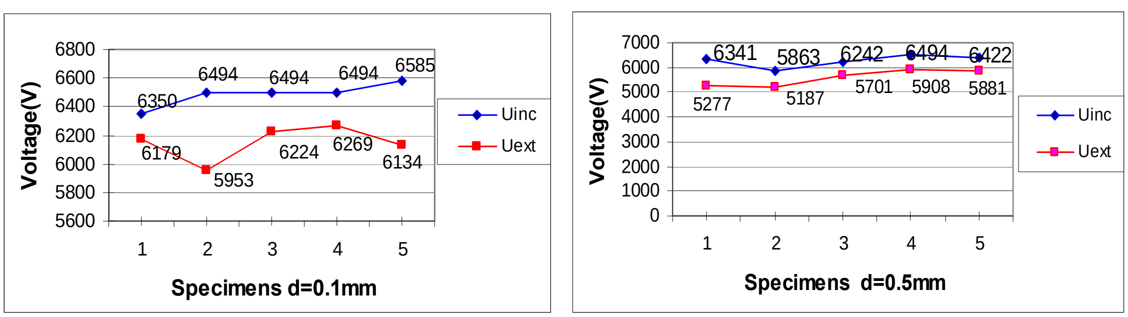


Fig.4.7 Comparison of U_{ext} in planar transformers in one layer structure after and before thermal stress.

Previous experiments have shown that despite very thin layer, insulation capabilities of anti-soldering mask are 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.

PD activity in planar transformers with three layer structure described by means of evaluation U_{inc} and U_{ext} is presented on Fig. 4.8. 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 quite different from observation for one layer transformer where the distance between conductors is in fact identical with the insulation distance.

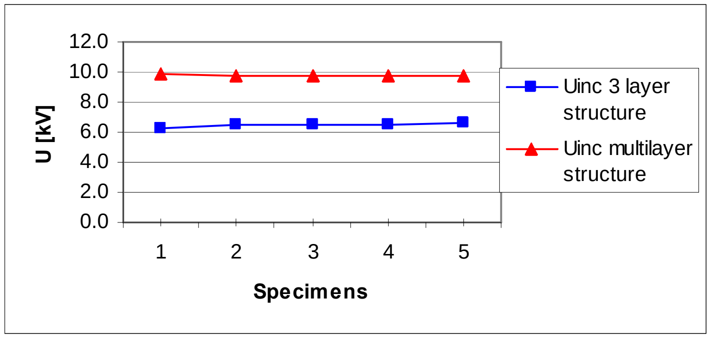


a) **b)**

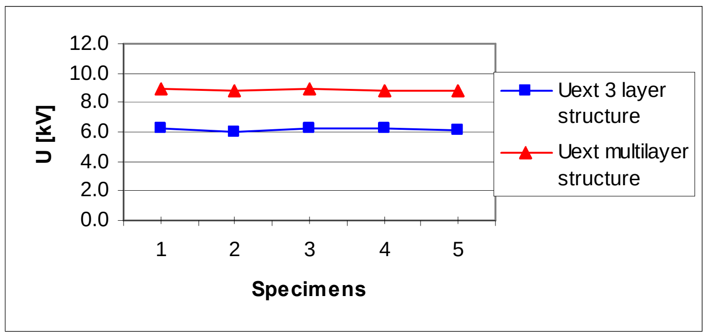
Fig.4.8 PD activity in planar transformers with three layer structure. Distance of conductors in transformer planar coils was: **a)** d=0.1mm and **b)** d=0.5mm.

To further increase of U_{inc} and U_{ext} voltage planar transformer with new multilayer insulation structure was designed. The distance between the coils, which is in fact the thickness of the insulation layer, was for respective coils 300 μm and 500 μm. Number of primary and secondary windings was equal and for different types of transformers was 28,5 and 37,5.

On Fig.4.9 there is a comparison of U_{inc} and U_{ext} in planar transformers with 3 layer and with multilayer configuration of isolation system. Distances between planar conductors in one layer plane is in both cases 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.4.9 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}

4.4 TESTING OF PULSE TRANSFORMERS AND IMPROVEMENT OF INSULATION SYSTEM

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 made on toroidal cores with an outer diameter 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.

Dependence of PD resistance on number of impregnation steps given in table Tab.4.1 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%. After the second impregnation step, 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. 4.1: Toroidal pulse transformer. Mean value of 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

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 was 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 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. 4.2: 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

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 for different samples and temperatures 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 found. TAV toroidal pulse transformer with additional insulation was therefore 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.

Measurements performed on TAV pulse transformers with additional isolation revealed that this insulation system achieves significantly better parameters in both PD inception and extinction voltage compared to previous versions. As seen from the table Tab.4.3 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.4.3 : TAV pulse transformer with additional insulation. U_{inc} and U_{ext} for samples before and after first impregnation for temperatures 23 ^{o}C and 100 ^{o}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

Observations which may be drawn from this example of application of PD tools to investigation and engineering of insulation systems are:

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

2) When using 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.

In comparison with pulse toroidal transformers planar transformers with multilayer insulation structure have much better insulation properties in respect to PD resistance. 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.

5 CONCLUSION

The contribution of my 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. Used testing methods will ease the exploitation of the PD diagnostic especially at workplaces dealing with design of electronic circuits which are not specialized in high voltage technique.

3. More than 300 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 summary, the workplace for PD testing in electronic devices was established and it was proven that exploitation of Pd diagnostic in testing of electronic equipments gives a powerful tool not only for assessment of insulation properties and for design of sophisticated insulation systems but also for assessment of quality of used materials and technologies.

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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 of insulation systems were demonstrated.