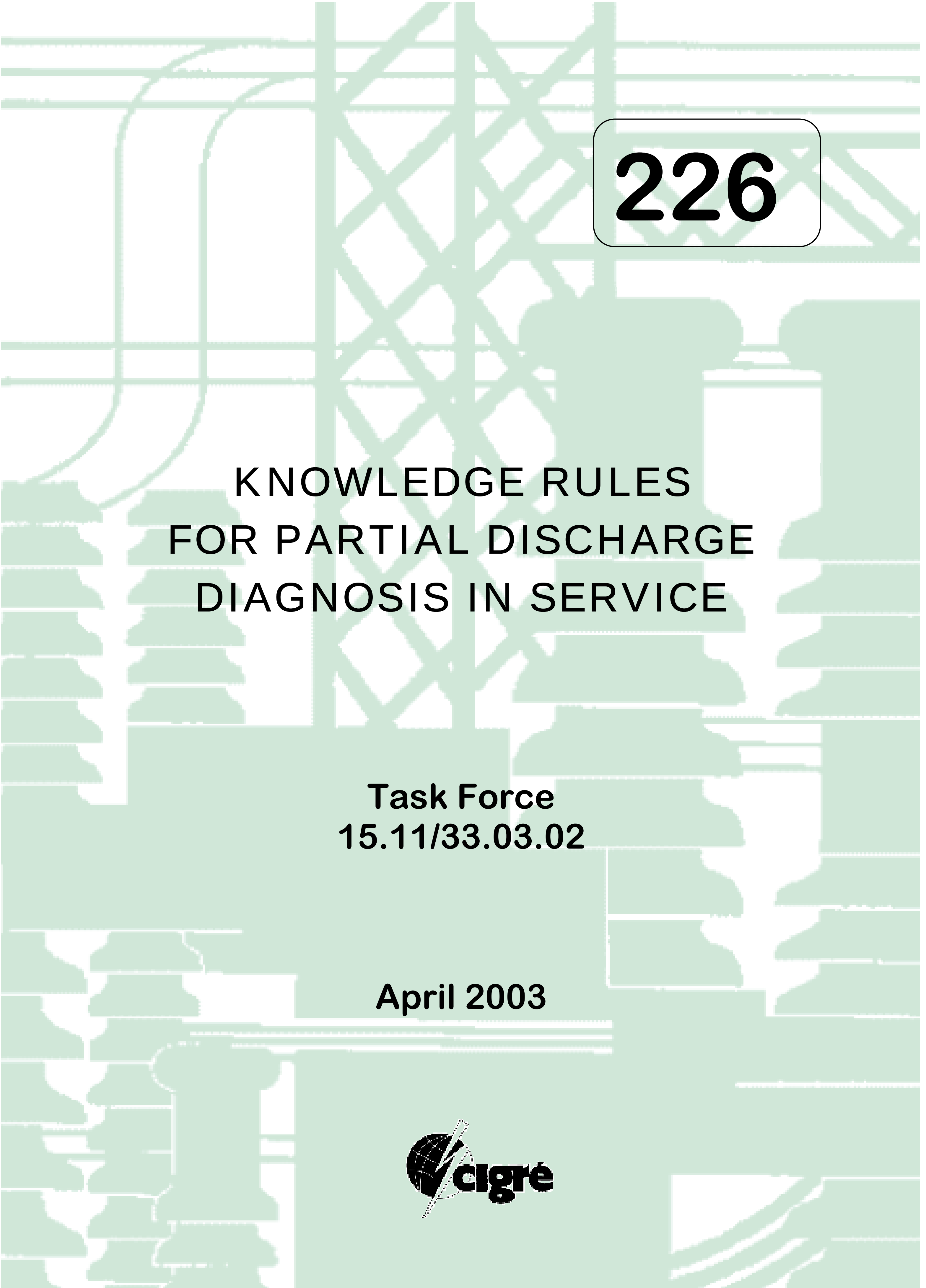

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KNOWLEDGE RULES FOR PARTIAL DISCHARGE DIAGNOSIS IN SERVICE

Task Force
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cigré

KNOWLEDGE RULES FOR PARTIAL DISCHARGE DIAGNOSIS IN SERVICE

Cigre TF 15.11/33.03.02

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PART I PARTIAL DISCHAGRES

PART II POWER TRANSFORMERS

PART III POWER CABLES

PART IV GAS INSULATED SUBSTATIONS

PART V GENERATOR STATOR INSULATION

PART I PARTIAL DISCHAGRES

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1.1 GENERAL

Liberalization of electricity markets brings about important changes in the working environment of power utilities. As a result, the network operators have to concentrate more on asset management to reduce costs, to postpone the investments, to optimise technical management keeping at the same time the reliability and power quality at high level. As a result of these changes, maintenance and investment costs for the power network are reduced. Furthermore, the operation loads of the existing network should be increased and the service life of existing network components should be maximized. On the other hand, a higher reliability of the power supply is required, and the claims for non-delivered energy in case of network component failures are increasing, see figure 1.1. An integral approach is applied based on selecting those issues where the largest cost savings can be reached and the most important risk reduction and performance improvements can be achieved. The latter implies in case of power cable systems, the use of risk assessment in making chooses between different maintenance techniques such as

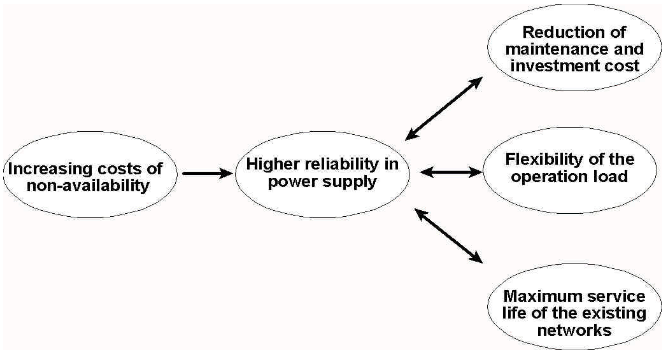


***Figure 1.1** Effects of liberalization on electricity markets.*

1. Corrective Maintenance (CM); *reaction only when failure occur*;
2. Time Based Maintenance (TBM); *preventive maintenance in fixed time periods;*
3. Condition Based Maintenance (CBM); *preventive maintenance depending on the actual conditions;*

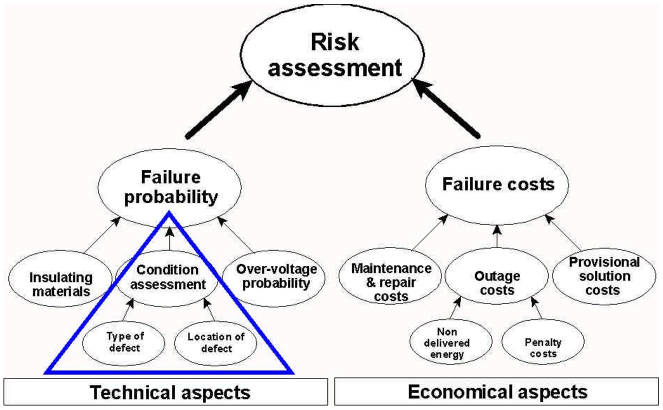


***Figure 1.2** The positioning of insulation condition assessment within risk assessment.*

In particular, to maintain the assets e.g. power cable, transformers, switch gear in dependence on their availability important detailed information on their actual insulation condition is necessary, see figure 1.2. Due to the service life of high voltage components the insulating materials are subject to structural changes. In most cases these changes can be seen as a degradation of the insulation properties in particular HV components. In order to detect changes in the insulation at an early stage and to gain insight to the maximum service life of a HV component, predictive maintenance is often recommended and in several cases already in use. In its turn the main goal of PD diagnosis is to recognise high voltage insulation problems by identify the insulation defect causing the discharge: e.g. internal or surface discharges, corona, treeing, etc,. This information in combination with knowledge rules is vital for estimating the harmfulness of the discharge.

1.2 INTRODUCTION

Due to the service life of high voltage components the insulating materials are exposed to structural changes. In most cases these changes can be seen as a degradation of the insulation properties of the particular HV equipment. In order to detect changes in the insulation at a early stage and also to get insight to the maximum service life of a HV component, predictive maintenance is often recommenced and in several cases already in use.

In the last ten years the use of digital PD measuring techniques for quality assurance in the works, during on-site testing as well as for monitoring purposes during service life of HV components like transformers, generators, cables and GIS has got increasing attention.

It is also known, that with modern sensitive PD off-line and on-line measuring techniques: the discharge process occurring in the insulation can be described by means of several digitally processed 1-, 2- and 3 dimensional PD quantities.

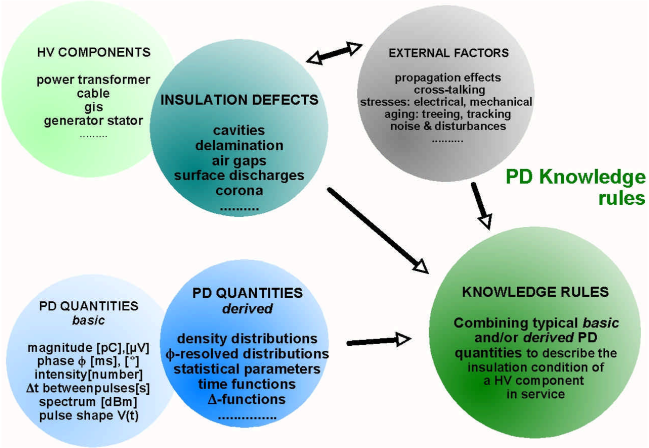


Figure 1.3 *General aspects of making PD knowledge rules.*

To support electrical engineers in interpreting PD measurements and recognizing aging processes in the insulation of a HV components, linkage between specific insulation characteristic with the combined information provided by particular measured PD quantities is necessary.

As a result, systematic knowledge rules can be formulated to support insulation condition assessment, see figure 1.3. In particular, to make on the basis of measurable and derivable quantities, for a particular type of HV component specific PD knowledge rules, several aspects have to be taken into account, e.g. typical insulation defects, and external factors like propagation effects, disturbances or cross-talking.

This brochure discusses the possibility of interpretation (knowledge) rules to support PD diagnostic of service aged HV components. Based on systematic experience from the field this brochure evaluates and classifies PD quantities, which are found useful for diagnosis monitoring of different HV components. In particular, for different insulation systems of HV components like instrument and power transformers, distribution and transmission power cables, GIS, generator stator insulation general characteristics of typical PD quantities are evaluated under the following restrictions:

a) Only by insulation defects induced degradation effects are taken into consideration.
b) No acceptance levels for go / no go decisions are discussed.
c) No special attention is paid to describe in detail particular detection and measuring techniques.
d) No application of post-processing technique e.g. neural networks, advanced statistics, wavelets, digital filtering, etc is discussed.

1.3 PHENOMENOLOGY

1.3.1 Electrical Partial Discharges

A partial discharge (PD) is a localised electrical discharge that only partially bridges the insulation between conductors and which can or can not occur to a conductor. Partial discharges are in general a consequence of local electric stress concentrations in the insulation or on the surface of the insulation. Generally such discharges appear as pulses having duration of less than 1 us. Corona is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation, but corona should not be used as a general term for all forms of PD.

A partial discharge occurs often within gas filled voids in solid or impregnated insulation or from sharp protrusions giving a field enhancement in gaseous, liquid or solid insulation systems of high voltage equipment. If the local field exceeds a certain limit determining the onset voltage and a seeding electron is present, then an electron avalanche will result.
This avalanche will for a partial discharge stop, either from the barrier effect of the cavity walls or from space charge effects when propagating in a gas or liquid. This process is very localised and transient in nature, with a typical duration of microseconds or less. However, although of very short duration, the high electron energies in the discharge can interact with any solid or liquid dielectric materials in the immediate vicinity and cause bond breaking of molecules, changes in the chemical properties and ablation of the material.
It is important to recall that it is not the real local discharge we measure. It is the charge this discharge induces on the nearby electrodes / terminals or even more complicated: the wave propagating from this induced charge to the detector. In the higher frequency regime the concept of discrete components are no longer valid, and the concept of dipoles and wave excitation much be taken into use.
As a result of such interaction the dielectric properties of the overall insulation may be impaired over time, with an accumulation of damage if the partial discharges continue. Such damage is, in effect, a component part of the “service-ageing” of the insulation.
Although the overall ageing process will have some other components and causes, partial discharges are major symptoms of defect induced insulation ageing. Because of this the detection and characterisation of partial discharge activity in insulation is an important requirement for the assessment of insulation condition.

1.3.2 Partial Discharge Processes

PD processes are the discharge development effects, which accompany each discharge event. These effects (e.g. current waveforms) depend on the material and electric field distribution and provide some means of PD characterisation.

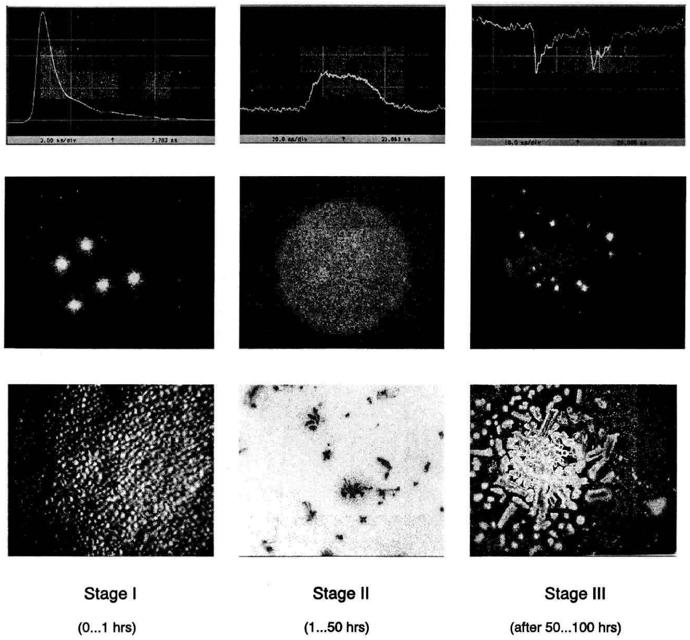


Figure 1.4 *Example of consecutive aging stages in the evolution of discharge mechanism described by pulse shape, optical image and effect on the dielectric surface [1].*

There are a very great variety of PD processes, which occur, in typical high voltage electrical insulation of equipment. This variety is due to the range of insulation materials used and to the various void or interface geometries, which can occur in the specific insulation system. Often the discharges will occur in a gaseous phase. This can be in the open volume of a gaseous insulation system, such as air or SF6, or it may be in gas filled voids on solids. It may also be in bubbles in liquids created by e.g. vaporisation of the liquid itself or of water drops. However, even if the discharges often are considered as gas discharges, electron avalanches may also occur in solids and in liquid. After the first avalanche has occurred cavities containing vapour or plasma may be formed. Then again the condition may favour gas discharges.

So we may often consider the discharges as essentially being gas discharges. These discharges occur - as stated above - when a certain field is exceeded and a seeding electron is present. Of gas discharges many types exist (e.g. glow discharges, Streamer, Townsend and leader discharges). Which ones occur depend on the field, its distribution, the gas type and the surfaces of surrounding metals / solids / liquids, see figure 1.4. This again determines the shape of the resulting current pulses. E.g. the current rise is faster in SF6 than in air or glow discharges do appear as pulse-less. Such characteristics may in principle be used for characterising a discharge.
Traditional PD detection systems with upper bandwidth in the 0.5 – 1 MHz range are not able to acquire the true shape of the current pulses and will thus not be able to provide a detailed outline of the PD "fingerprint". However, modern high frequency antennas, current transformers or *Rogowski* coil sensors give possibilities to depict the content of higher frequencies in the signals and thus allow acquisition of better details of the PD wave shape characteristics.

Figure 1.5 *Aging process in a resin cable joint caused by partial discharges and treeing [2]*

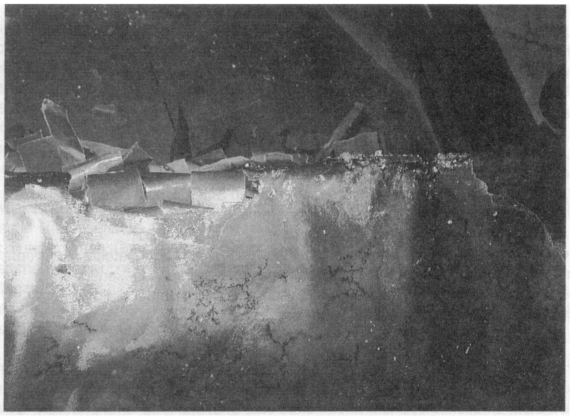


Figure 1.6 *Effect of 4 years PD activity in the paper insulation of a 400kV power transformer [3]*

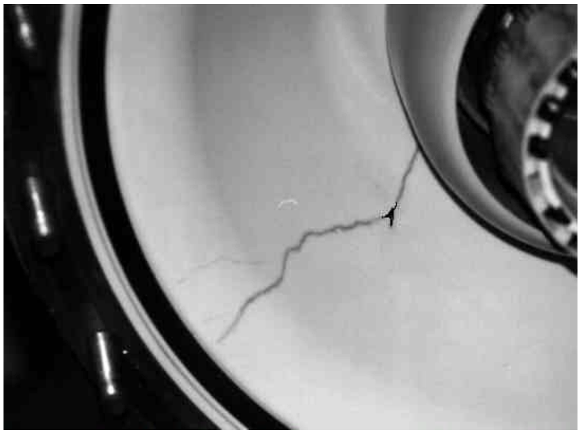


Figure 1.7 *Particle induced breakdown on the surface of a 400kV GIS spacer. [4]*

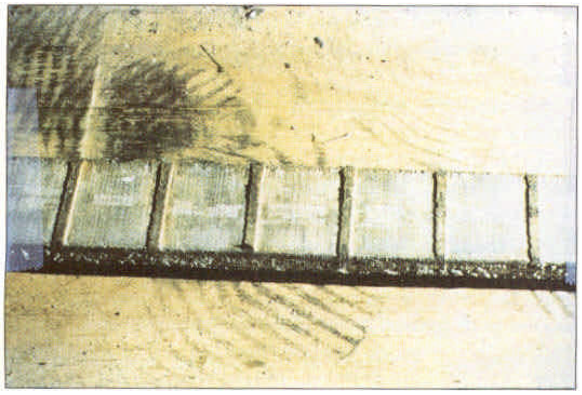


Figure 1.8 *Example of a generator coil removed from a stator bar that failed due to slot discharges. [5]*

1.3.3 Defect-induced Insulation Degradation

Defect-induced insulation degradation may have a symptom the partial discharge activity in high voltage insulation. The further degradation may result from interaction of the discharge product components with the general insulation material surrounding the defect. The phenomenon may be inherent (from the design or manufacturing process) or may develop in dependence of operation of the equipment (for example by high temperature, electrical and mechanical over stresses).
The harmfulness of PD's is determined by the ability of the high energy/high temperature PD products to permanently change and degrade the dielectric properties of the insulation material exposed to the partial discharge activity. The level of harmfulness is very material-dependent.

Electron energies or temperatures (not to be mistaken for the temperature of the surrounding gas molecules or plasma) in a partial discharge can get up in the 10 – 20 eV (ionisation energy). Depending on the bond type energies over some 5 eV are able to break chemical bonds of polymers. The interaction of electrons of high energies with solid insulation materials will cause bond breaking of the large molecules in surrounding solid / liquid. This change may be either or both of a simple ablation or erosion of the solid material walls exposed to the discharge, or a change in the chemical structure and properties of the solid insulation (for example, carbonisation of the material). As these effects are permanent and the discharge site is generally sealed, the integrated effects of such damage may eventually lead to catastrophic failure of the insulation, see figures 1.5-1.8.

The integrated effect of the partial discharges in the insulation degradation can sometimes produce an increase in the discharge magnitude and repetition rate and will also create some substantial changes in the associated discharge parameters like phase position. This changing nature of the discharge thus allows some relative means of assessment of condition if there is available some adequate knowledge of the impact of discharges in similar configurations and materials.

PD’s are inherently harmful in that the high electron energies and aggressive chemical by-products from cracked molecules can cause permanent damage to the insulation. In solids pitting and channel growth (i.e. electrical trees may result). In an impregnated insulation systems acids and dissolved gasses are formed and the solid may wear down with time. However, in some gas-insulated systems, notably air, the ionisation associated with PD’s (corona) will in normal circumstances not have any lasting effects because the air is exchanged with time. Air insulation is considered self-healing. . In the case of SF6 the situation is not so simple. There can be some permanent deterioration of the SF_6 gas, particularly if there are impurities like water present. Then fluoric acids may result. If the discharge occurs at the gas/spacer interface permanent damage is also expected to occur.

The ability of materials to resist the deleterious effects of PD’s varies greatly. Organic insulating materials have low resistance and suffer substantial deterioration. Inorganic materials such as mica and ceramics are much less affected by PD’s and are able to withstand PD levels much higher than those, which can be tolerated by organic materials. For example, the mica-based insulation used in large HV rotating machines will operate permanently with PD levels of thousands of pico-coloumbs, while cable insulation will not be able to tolerate levels of more than a few pC.

1.4 HV EQUIPMENT-SPECIFIC PD SIGNALS

Electrical PD signals as obtained at the sensor device(s) used for monitoring will have a number of possible components which can vary significantly from one item of equipment to another and will also and inevitably contain noise from electromagnetic interference coupled either conductively or radiatively to the system under test. In addition, there will be some sensor-imposed components in the signals, depending for example on the frequency response of the sensor system. Some sensor signals will give a true representation of the PD current flow as measured by the sensor, while other sensors will give an output signal which is a modified version only of the true PD current. It must also be remembered that the PD signal measured as the true waveform at the terminal of the equipment may not necessarily be the true PD current, because of modifications due to propagation and circuit effects within the dielectric.

1.4.1 PD Signals

The signals achieved from PD detectors are the basic measurement that is used to quantify the partial discharge and its characteristics. Three quantities will define the basic PD signal in any situation: PD magnitude, PD repetition rate and the phase angle of the PD relative to the applied voltage.

These quantities (particularly the magnitude) will be dependent to a degree on the material, the type of equipment under test (for example whether a transformer or a cable or rotating machine) and particularly on the type of sensor used. In general two type of PD responses can be used, see figure 1.9:

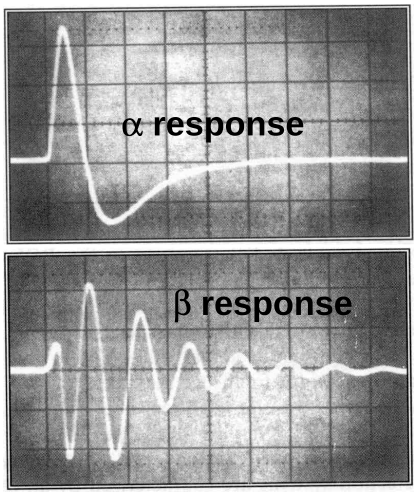


Figure 1.9 *Two type of PD pulses detected by a wide-band type system (a response) and by a narrow-band type system (b response) [6].*

1. Wide band PD measuring system; where in combination with the coupling device, the PD detection circuit is characterised by a transfer impedance $Z(f)$ having fixed values of the lower and upper limit frequencies f_1 and f_2, and adequate attenuation below f_1 and above $f_{2,}$. Recommended values $\Delta f = (f_2 - f_1) \approx f_2$. The response of these instruments to a (non-oscillating) partial discharge current pulse is in general a well-damped oscillation. Mostly, both the apparent charge q and polarity of the PD current pulse can be determined from this response.

2. Narrow band PD measuring system; these instruments are characterised by a small bandwidth Df and a mid-band frequency f_m, which can be varied over a wide frequency range, where the amplitude frequency spectrum of the PD current pulse is approximately constant. It is further recommended that the transfer impedance $Z(f)$ at frequencies of $f_m \pm Df$ should be 20 dB below the peak pass-band value. The response of these instruments to a partial discharge current pulse is a transient oscillation with the positive and negative peak values of its envelope proportional to the apparent charge, independent of the polarity of this charge.

While the repetition rate and phase of the PD's are less affected, the magnitude is very sensitive to all of the above parameters and thus calibration of the PD magnitude is a necessary adjunct to all PD testing. There is an increasing trend to higher frequency bandwidth monitoring of PD's and this is an important specification in the PD description.

With the three signal parameters above it is possible to perform a variety of post-test analyses which can be used to characterise the PD behaviour in any equipment item. This may take the form of, for example, determination of the IEC integrated PD parameters, PD statistical analysis or pattern analysis of the PD displays. Such processing is useful in monitoring equipment insulation over time to obtain trending details of the insulation condition. There is only ever likely to be a qualitative determination of insulation ageing based on use of such data in conjunction with previously obtained PD data of similar equipment types. Any more quantitative determination of the ageing of the insulation will require more detailed PD data, in particular the true PD waveform as this is the parameter which will be truly representative of the actual discharge processes that comprise the PD event.

1.4.2 PD Propagation and Attenuation Effects

In general PD's will occur at some location remote from the point of measurement and thus the signals detected by the PD sensor will propagate through equipment components before they get to the sensor. In particular for test objects with distributed capacitive and inductive elements PD's are then likely to suffer attenuation and dispersion effects depending on the losses of the signal transmission medium. PD signal dispersion is the effect of which take place the internal circuit and materials on the PD signals. These complex capacitive and inductive coupling phenomena can cause both attenuation of signal level and change in the pulse shape characteristics of the basic PD signal.
Also in HV equipment like GIS or stator insulation the PD signal may propagate along several paths in several modes. Through this propagation the signal may suffer radiation losses (attenuation and it may dissipate into heat (absorption). Likewise the different wave modes and frequencies may propagate at different velocities resulting in differences in the arrival time(dispersion) This will vary with design and material type.

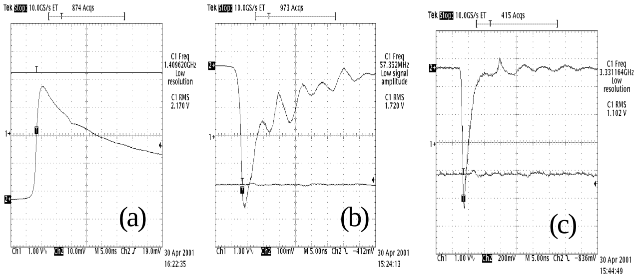


***Figure 1.10** Oscilloscopic records of typical PD pulse **s**hapes at a bandwidth of 500 MHz*
(a) point to plane discharge in air (25 ns/div)
(b) surface discharge in air (5 ns/div)
(c) void discharge in XLPE (5ns/div)

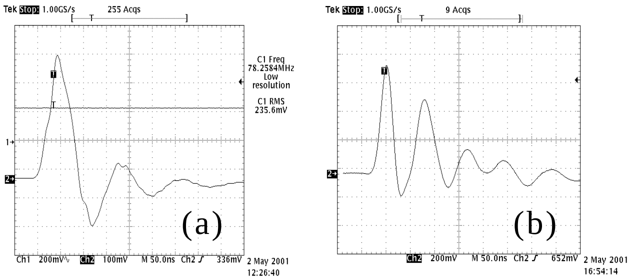


***Figure 1.11** Examples for PD pulse shapes received at the output of the measuring impedance*
(a) void discharge in the XLPE insulation of a cable termination (50 ns/div)
(b) void discharge in the epoxy resin insulation of an instrument transformer (50 ns/div)

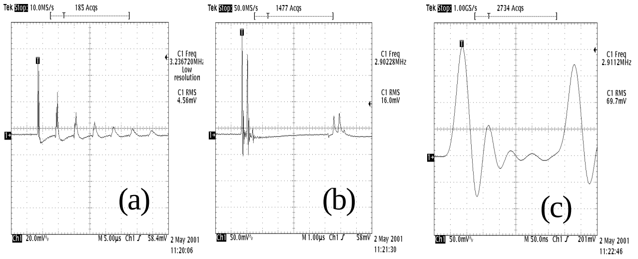


***Figure 1.12** Example of PD pulse response of a discharge event in a XLPE cable of 482 m length, PD position 451 m*

(a) overview at 5 ms/div
(b) increased time resolution at 1 us/div
(c) resolution of the direct and reflected pulse at 50 ns/div. The time difference between both is proportional to the distance of the PD source from the far cable end

The origin PD pulses are characterized by time parameters in the nanosecond-range. As an example a Figure 1.10 shows oscilloscopic record of typical pulse shapes, where the overall bandwidth was about 500 MHz, which corresponds to a step impulse rise time of 0.7 ns. Under real measuring conditions the fast PD pulses are strongly elongated and deteriorated. The main reasons for this are attenuation effects by passing the test object, where also oscillations may appear, and additionally the frequency response of the applied PD coupling unit. As an example Figure 1.11 shows the PD pulse response at the output of the measuring impedance as part of the coupling unit according to the IEC publication 60270. The PD source was a void in the XLPE insulation of a cable termination; i.e. the original pulse shape corresponds to those shown in Figure 1.12. That means, the origin rise time of about 1 ns is increased up to about 30 ns. The deterioration of PD pulses becomes even stronger for large test objects and especially for those having windings, such as generators or transformers. Under this condition also oscillations may appear, as evident from figure 1.11. Such oscillations may cause different readings if PD measuring devices of different processing principles are used.

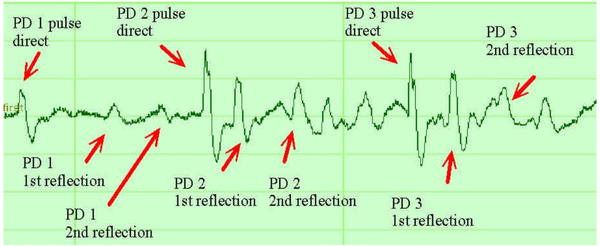


Figure 1.13 *Example of PD pulses propagating in a power cable. Each of the pulses is characterized by the 1st and the 2nd reflection. Based on the time difference between PD pulse direct and its 1st reflection the discharge site can be localized., e.g. PD1has different origin as PD2 and PD3 [7]*

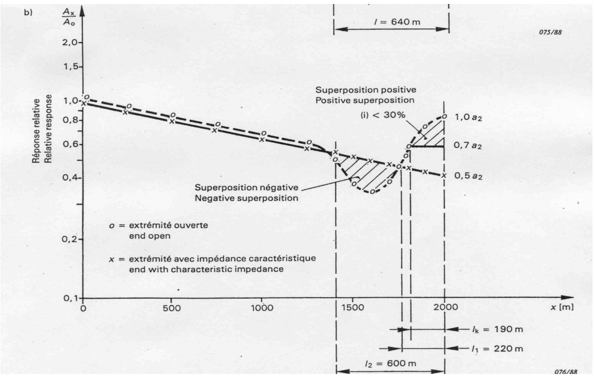


Figure 1.14 *Superposition and attenuation of PD pulses along the power cable [8].*

Due to the very fast PD pulses they may be reflected, if the travelling wave impedance of the test object changes along the propagation path. Such phenomena are well known for power cables and GIS / GIL. In this case a single PD event causes sequences of pulses (see figure 1.12) which may cause superposition errors. Depending of the PD fault site the reading of the PD detector may change, even if the apparent charge remains constant. Opposite to this disadvantage the appearing PD reflectogram (see figure 1.12) can advantageously be used for the PD fault location, using the well-known time domain refelctometry (TDR).
The propagation paths taken by electrical PD signals vary with the equipment type and with the transmission medium. Cables can be many kilometres long, the signal propagates in both directions with e.g. 150 m/µs and is gradually reduced in magnitude due to losses in the insulation and in the semiconductor. In stators in rotating machines the signal from deep down in the winding will partly be transported along the winding in the slot (the LF part) and partly couple capacitive via the stator head and also irradiate away (the HF part). Also in transformers the HV winding may consist of thousand meters or more of insulated conductors. The losses in the dielectric materials will affect the propagation and the frequency bandwidth of the sensor will also affect the detection. Time of flight analyses can be used with good effect for location of PD’s, but the attenuation and dispersion of the PD’s signals will limit the accuracy of the measurements and may also cause some problems in determining the actual PD waveforms. These effects are particularly apparent in HV cables, particularly in paper insulated cables where the losses in the insulation are relatively higher than in XLPE and EPR insulated cables, see figures 1.13-1.14. However even the low loss polymeric cables will have limits to the lengths over which PD’s can be detected with a good sensitivity.

1.4.3 PD Cross-talking

The radiative cross-talk is the signal coupling between phases and other nearby circuits which induces PD signals in neighbour healthy phases. In dependence on the energizing type: single phase excitation during testing or multiple phase excitation during service this may lead to complexity in interpretation of the PD sites. Furthermore in some equipment types (e.g. stators) inter-phase discharges may occur

Cross-talk is a problem in many items of equipment, but particularly where radiative, inductive or capacitive-coupled sensors are used in the high frequency regime signals will couple between phases. Generally the phantom PD's are recognizable by their lower magnitudes and by their phase relative to the voltage waveform. They can also sometimes be used to verify whether a signal is a true PD signal or just external interference.

As a consequence of the mutual influence of the three phases energizing, cross-talk may occur between the measuring terminals of the three-phase HV component, e.g. power transformer, generator stator bars, see figure 1.15. As a result, in all three phases PD activity will be observed and therefore the origin of PD activity has to be localized among three phases. True multi-channel analyses with coincidence filtration may be used to discriminate between true signals and cross-talk.

For this purpose a calibration matrix can be used, as described in IEC 76-3, appendix A. In particular, calibration impulses e.g. 500 pC have to be injected at the transformer terminals U, V, W and the response was measured at all three terminals, see the table below. It can be seen from the results in the table that discharges occurring at one phase of the transformer will be measured on the other two phases with a attenuation of approximately 35 as a result of cross-talk. Apart from attenuation, a phase shift is also expected when a PD-pattern is measured in more than one terminal as a result of cross-talk. Between the patterns from two different phases, a 120° phase shift occurs.

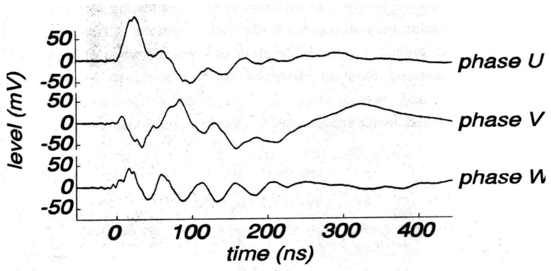


Figure 1.15 *Cross-talk between the phases of a turbo generator. PD pulse injected in the 11th bar of the phase U, and responses at the HV terminals of the three phases U, V and W, [9].*

Example of calibration matrix made for a power transformer.

PD calibration pulse injection between:	**PD magnitude / the phase shift detected on phase U**	**PD magnitude / the phase shift detected on phase V**	**PD magnitude / the phase shift detected on phase W**
U-Earth, 500 pC	500 pC / 0°	14 pC / 120 °	12 pC / 240°
V-Earth, 500 pC	15 pC / 240°	500 pC / 0°	14 pC / 120 °
W-Earth, 500 pC	11 pC / 120 °	15 pC / 240°	500 pC / 0°

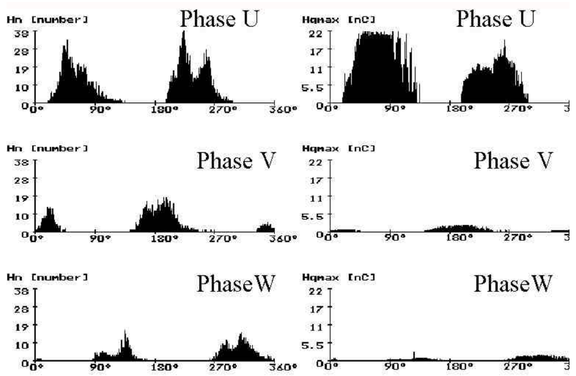


Figure 1.16 *PD phase-resolved pattern (left PD intensity* $H_n(f)$*, right PD magnitude* $H_{qmax}(f)$*) measured in phases U, V, W for PD activity in phase U [10]*

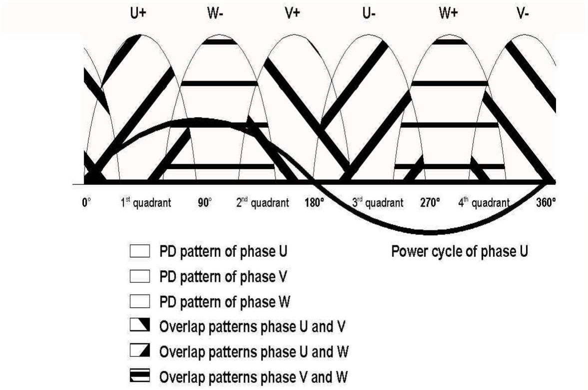


Figure 1.17 *Positions of the single-phase pattern with respect to the power frequency cycle of phase U. [11]*

The effect of cross-talk may influence the PD measurement significantly. In particular, PD patterns as mentioned in section 4.2 may occur in all three phases.

Moreover, making distinction between particular phases important is the way of energising the HV component.

Using single phase energising the cross-talk occurs only between the energised phase U and the no-energised phases V and W, see figure 1.16. It follows from this figure that the patterns of PD magnitude: $H_{qmax}(\phi)$ in comparison to phase U are in phases V and W attenuated.

On the contrary, the patterns of PD intensity $H_n(\phi)$ are not influenced by the attenuation of the PD level between the terminals. This makes the PD intensity $H_n(\phi)$ more attractive for analysing multi-terminal measurements.

Using multiple phase energising e.g. on-line, the measured PD patterns will reveal the single phase PD response together with PD responses from the other, see figure 1.17. It follows from this figure, that the position of the single phase patterns with respect to the power cycle of phase U is between the phases 120° shifted.

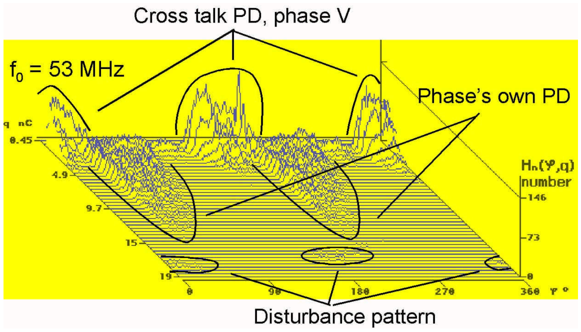


Figure 1.18 *Example of PD phase-resolved pattern on-line observed on phase W during measurements on a turbo generator. The pattern consists three types of data: Phase W own PD data; Cross-talk PD from phase V; external disturbances [11].*

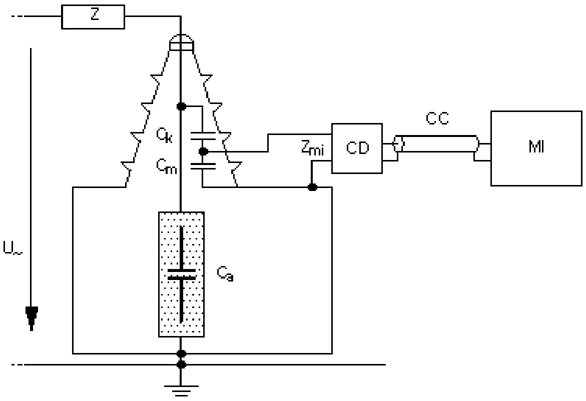


Figure 1.19 *PD detection circuit for measurement at a tapping of a bushing [6].*

Results of on-line measurements performed on a turbo-generator clearly illustrate this influence of the resonance frequency upon the following responses, see figure 1.18.

a) the *PD response of the measured phase*, i.e. the PD activity originating from that phase
b) the *cross-talk PD response*, i.e. the PD activity originating from the other phases;
c) the ***disturbance response***, i.e. disturbances originating from the power plant and from the generator itself (e.g. rotor excitation).

However, there is a risk that one may interpret as cross-talk signals occurring between phases. The driving voltage for such discharges will be out of phase with the line voltages. True inter-phase discharges will result in signals of opposite polarities at the respective phase terminals. Using a wide-band, well damped detector one may be able to recognise the pulse polarities.

1.5 PARTIAL DISCHARGE DIAGNOSIS

The use of discharge measurements for condition assessment of HV components depends on the method chosen for PD detection and quantities selected to evaluate the measuring information. A combination of both aspects results in PD diagnosis, which in its turn generates information suitable for making PD knowledge rules. In the last years a large variety of PD diagnostics have been introduced world-wide. In the next two sections basic information is given of diagnostics in use.

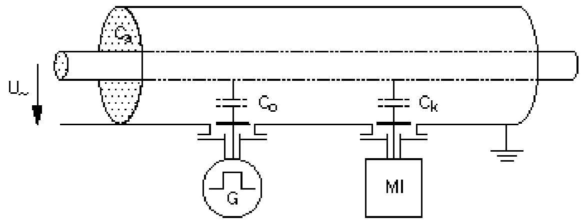


Figure 1.20 *PD detection circuit for measurement in GIS [6].*

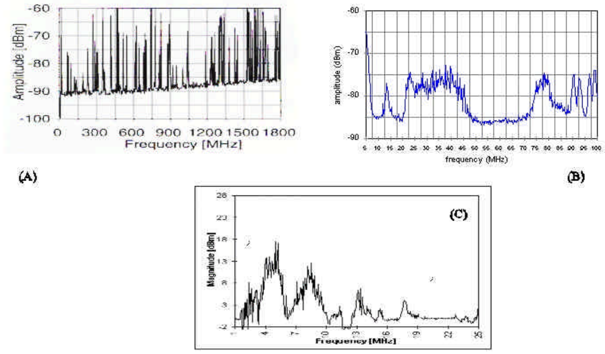


Figure 1.21 *Examples of PD spectrum observed using VHF/UHF PD detection methods for different discharges in HV components: (a) free moving particle in 345kV GIS; off-line detection, (b) internal discharges in a 11 years old 50 MVA turbo-generator; on-line detection (c) internal discharges in a 47 years old 50kV/10kV, 14 MVA power transformer; off-line detection.*

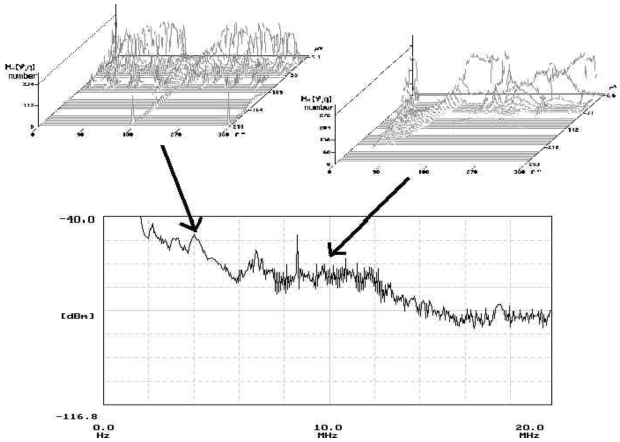


Figure 1.22 *Examples of PD spectrum observed using VHF/UHF PD detection method. It follows from this example that tuning the HF detection system to different frequencies can be used to make distinction between PD signals (see the PD pattern on right side) and disturbances (see the PD pattern on left side).*

1.5.1 Partial Discharge Detection

The result of the partial discharge is a localised electrical disturbance, modelled as a transient voltage collapse in a small volume of the insulation. It is possible to detect this voltage disturbance by electrical means either at the terminals of the equipment or by sensitive high frequency current monitors viewing the current in the equipment conductors. The characteristics of these PD transients, including their magnitude, their number and other various associated properties, such as the IEC integrated parameters defined in IEC 60270, provide a sensitive means of assessing the condition of the insulation.
Partial discharges can be detected by non-electrical means, most notably by acoustic monitoring of the ultrasonic disturbances produced by the pressure waves that accompany the partial discharge occurrence. However while the presence of such PD's can be determined by such techniques, they do not presently allow characterisation of the PD's. Such non-electrical means of detection will not be included in this discussion.
Generally, a discharge detection system measures the PD level, phase-resolved patterns and location of the discharges as a function of the applied voltage. Two principles are applied for the discharge detection process:

1. An IEC 60270 discharge detection with discharge activity measured in pC or nC by application of a defined band-pass integrator, see figure 1.19.

2. HF discharge detection with which the discharge activity is registered in mV by means of a broad band amplifier, see figure 1.20.

The 1st method is based on the detection of apparent charge of PD pulses in accordance to IEC 60270 recommendation. For this purpose the following assumptions are of importance:

a) The test object, is usually regarded as a capacitor C_a,
b) To detect PD signals a coupling capacitor C_k, is necessary, which shall be of low inductance design, and low PD level at the specified test voltage
c) To measure PD signals in [pC]/[nC] a detector with its input impedance (and sometimes, for balanced circuit arrangements, a second input impedance), a wide or narrow band-pass integrator is necessary.

The main goal of these systems is using information about the PD level in [pC], PD patterns to determine in a sensitive way the PD activity in a HV component. Due to the fact the presence of disturbances or noises may influence the detection not always this techniques are applicable outside screened labs or without special disturbance suppression tools.

The 2nd method is based on registration in [µV] and [mV] the HF voltage magnitude of PD pulses. In particular, using the fact that discharge pulses may contain energies in a very broad frequency band up to 3GHz the partial discharges can also be detected using measuring systems e.g. oscilloscopes providing very high bandwidth or by frequency selective instruments (as for example spectrum analysers) together with appropriate coupling devices e.g. *Rogowski* coil, HF current transformers, inductive or capacitive couplers. The different discharge measurement methods distinguish themselves also by the different frequencies of the test voltage applied. In particular depending on the type of HV component different frequency ranges can be used for this purpose:

a) high frequency (HF): up to 10 MHz,
b) very high frequency (VHF): up to 200 MHz,
c) ultra high frequency (UHF): up to 2 GHz,

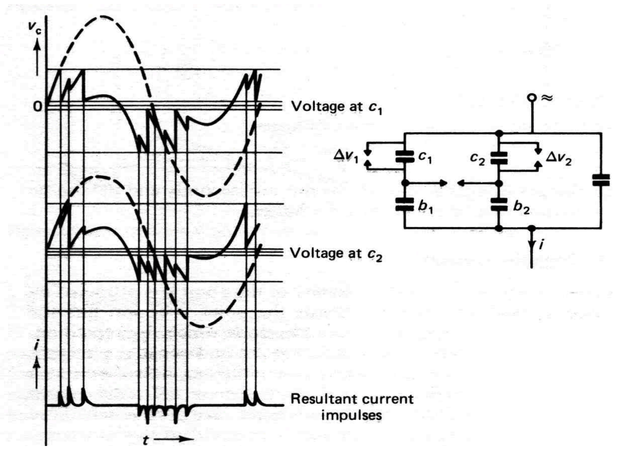
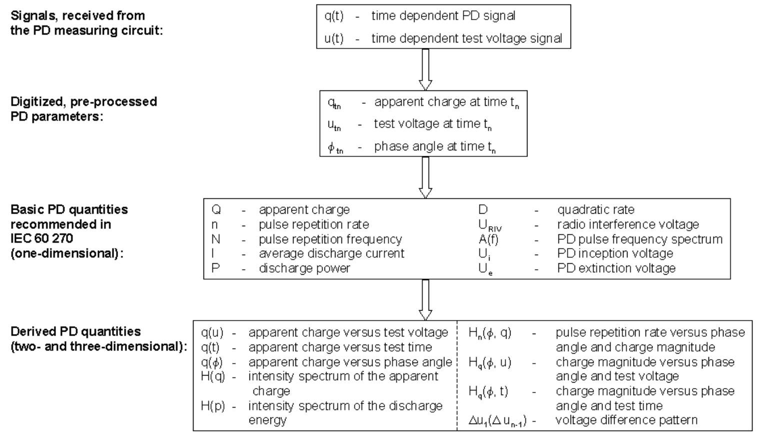


Figure 1.23 *Schematic recurrence of PD processes in the case of two discharging cavities [12].*

Due to the fact that HF measurements can not be calibrated in accordance to IEC 60270 recommendations it is not possible to measure the absolute value of the discharges in [pC] or [nC] but only in [µV] of [mV]. Nevertheless the sensitivity of HF couplers can be verified using methods described by Cigre WG 15.03.
The aim of HF, VHF or UHF applications is to measure and to quantify the shape or the frequency spectrum of partial discharge current or voltage pulses under on-site conditions where disturbances may be present. Due to the fact that discharging defects in HV components may have different PD spectrum, as the present disturbances this method is useful to discriminate between discharges and noises, see figures 1.21-1.22.



Signals, received from the PD measuring circuit:

q(t) - time dependent PD signal
u(t) - time dependent test voltage signal

Digitized, pre-processed PD parameters:

q_{tn} - apparent charge at time t_n
u_{tn} - test voltage at time t_n
ϕ_{tn} - phase angle at time t_n

Basic PD quantities recommended in IEC 60 270 (one-dimensional):

Q - apparent charge
n - pulse repetition rate
N - pulse repetition frequency
I - average discharge current
P - discharge power
D - quadratic rate
U_{RIV} - radio interference voltage
A(f) - PD pulse frequency spectrum
U_i - PD inception voltage
U_e - PD extinction voltage

Derived PD quantities (two- and three-dimensional):

q(u) - apparent charge versus test voltage
q(t) - apparent charge versus test time
q(ϕ) - apparent charge versus phase angle
H(q) - intensity spectrum of the apparent charge
H(p) - intensity spectrum of the discharge energy
$H_n(\phi, q)$ - pulse repetition rate versus phase angle and charge magnitude
$H_q(\phi, u)$ - charge magnitude versus phase angle and test voltage
$H_q(\phi, t)$ - charge magnitude versus phase angle and test time
$\Delta u_1(\Delta u_{n-1})$ - voltage difference pattern

Figure 1.24 *Principle of digital PD data processing to obtain PD quantities.*

Besides this distinction, there is a difference between on-line and off-line measurements. In case of off-line measurements the test object is taken out of service and electrically stressed by means of external power supplies: 50Hz, 0,1 Hz or oscillating waves (50Hz-500Hz). Using test voltages different form the line voltage important information about the inception / extinction characteristics of discharges in the insulation can be obtained.
In case of on-line PD measurements the test object is in service and the measurement system is detecting the high frequency (HF) discharge activity in the object concerned. Discharge detection at nominal voltage (on-line) only informs about the existence of PD only. On-line discharge measurements are strongly influenced by the actual HF disturbances in the grid. Consequently the measurement can be applied for checking large changes in discharge behaviour of the object.
Due to the fact that different methods for PD diagnosis are in use, in this brochure no distinction is made between systems using [pC] or [µV] as indicators of PD activity. More

detailed information about these detection methods will be given in the Cigre Brochure about PD detection and measurement techniques [13].

1.5.2 Partial Discharge Quantities

Partial discharges cause patterns of current impulses in the leads of a sample. This happens several times, during power frequency cycle.
As a result, groups of recurrent discharges, which occur during positive half and negative half of the voltage cycle, will be found. If a sample has several discharging sites, more discharges will occur within the same time intervals, see figure 1.23.
To describe the characteristics of a discharge many quantities have been introduced over the years. With regard to the observation time these quantities can be divided into three main groups:

a) Basic PD quantities (according to IEC 60270)
b) Derived PD quantities
c) Phase , amplitude -related derived quantities (PD pattern)

As well known, the sequences of PD pulses contain random events, which are characterized by a great variation in the magnitude and the phase angle. Those significant PD parameters are additionally strong influenced by the level of the applied AC test voltage. Therefore it is evident, that an informative diagnosis of insulation defects can only be achieved, if several PD quantities are measured and evaluated simultaneously showing principal of PD recurrence and classic way of PD evaluation [19], see figure 1.40.
The use of a computer-aided system offers the opportunity to store sequences of the discharge pulses and to post-process these in the course of time or as a function of the power frequency cycle.
In this way a complete data recording is made, and a basis is created for further evaluation and diagnosis of the insulating systems, see figure 1.24 showing possibilities of digital PD processing.

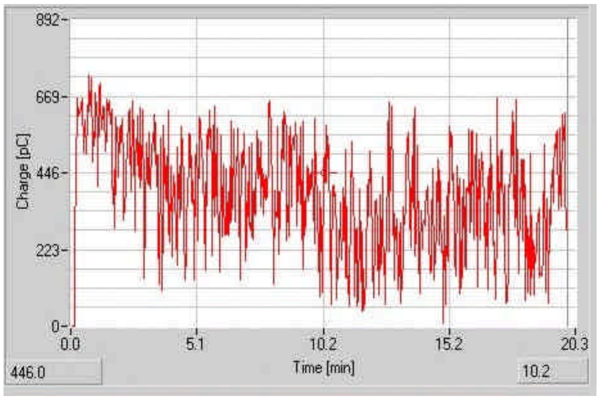


Figure 1.25 *Example of time-dependant changes in apparent charge magnitude measured off-line on a 30kV cable-sealing end.*

1.5.2.1 Basic PD quantities

A PD detector, which provides registration of discharge signals and the test voltage, may process in general the PD pulse in the frequency domain e.g. filtering, band-pass integration, or in the time domain e.g. pulse form, pulse phase-pattern, intensity. As a result for a PD phenomenon several parameters can be determined:

a) Discharge magnitude q_i; in [pC]. [nC], [μV],
b) PD pulse amplitudes in [μV] and [mV],

c) Discharge phase ϕ_i; in [ms], [°],
d) PD intensity N;
e) Time difference between successive PD pulses Δt [s];
f) Inception voltage difference between successive PD pulses ΔV [kV];

In addition, using wide band device e.g. digital scope or spectrum analyser the following parameters can be determined:

g) PD pulse shape;
h) PD pulse spectrum;

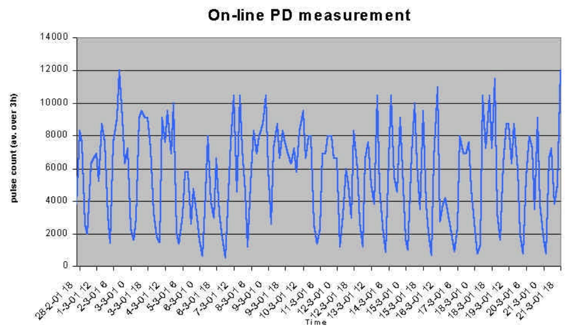


Figure 1.26 *Example of time-dependant changes in PD activity as observed on-line during 22 days of PD monitoring a distribution power cable. The intermitted changes with a one-day or few days period are result of operation load changes in the network.*

Once the PD data has been digitised and stored in the digital memory of the computer, those one-dimensional quantities are be combined to more complex quantities used as diagnostic tools. Such derived quantities are usually presented as two- and three-dimensional distributions, time functions or histograms, which exhibits typical PD patterns.

Digital PD measuring systems, which provides the registration of the basic parameters PD signal q(t) and test voltage signal u(t) simultaneously, may process in general the PD data in the time or frequency domain.

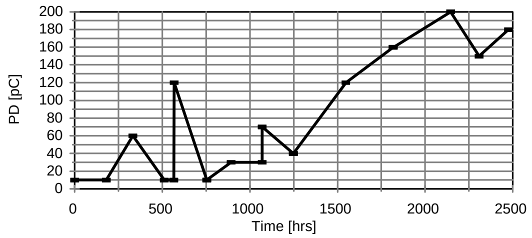


Figure 1.27 *Example of PD development at 4U0 till breakdown caused by internal defect ''grooves on the insulation core'' of Silicone Rubber Stress Cone of 20kV cable termination.[14]*

In the following sections, some of derived PD quantities as mentioned in figure 1.24 and which have been practically accepted are presented. Their and other PD quantities usefulness for making knowledge rules is discussed in parts II – V of this brochure.

1.5.2.2 Derived PD quantities

1.5.2.2.1 Time functions

It's known that the behaviour of discharges may be very complex due to their dependency to a wide range of conditions at the discharge site e.g. thermal or electrical stress. Moreover, depending on 'ageing effects' at the discharge site different types of behaviour can be observed in the course of time or in the function of the applied electric field.
In particular, the presence of time-dependant changes in PD behaviour can be explained in different ways (changes made by the presence of external noise or disturbances are not mentioned here):

a) PD process itself e.g. changes in inception conditions caused by discharge by-products, see figure 1.25. This type of changes is defect type dependant and it has temporary character and does not show any direct relation to the insulation degradation.

b) Changes in electrical or thermals load e.g. temperature / pressure effects, see figure 1.26. This type of changes has temporary character and does not show direct relation to insulation degradation.

c) Changes of the insulation around discharging defect, e.g. treeing, increase / decrease of conductivity, new discharging defects, see figure 1.27. This type of permanent changes may consist sometimes information about the defect induced insulation degradation.

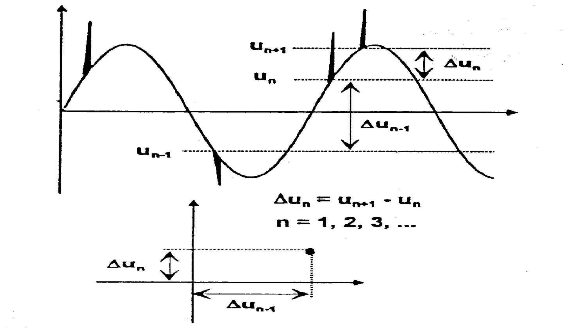


Figure 1.28 *Principal of voltage difference analysis, where the inception voltage of consequtive PD pulses are compared.*

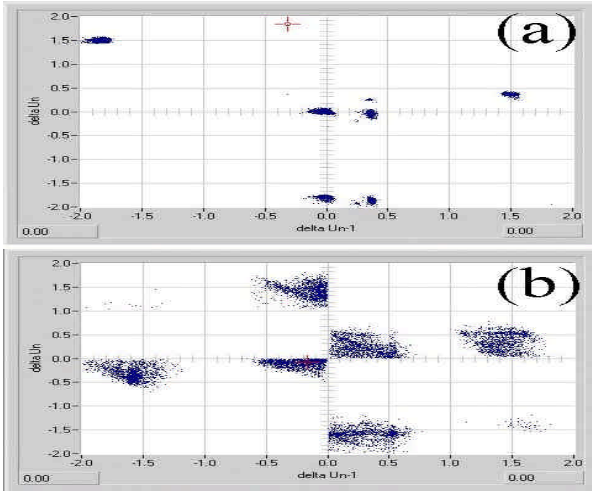


Figure 1.29 *Example of voltage difference analysis of discharges in cable sealing ends (a) for PD in a cavity (b) for surface dischagres.*

1.5.2.2.2 Δ-Functions

The occurrence of consecutive PD pulses in the function of the power frequency cycle (at ac stresses) and in the time (at dc stresses) can be also evaluated to obtain more information about discharge process.

At ac voltage stresses the difference in the inception of particular PD pulses can be used to describe more detailed the PD process self, see figure 1.28. Taking into account the following influencing factors

a) settings (e.g. threshold level) of the signal processing system;
b) the presence of multiple discharging processes;
c) the cross-talking effects,

since each data point contains information on the sequence of three consecutive pulses, characteristic patterns can be expected for different PD sources as evident from the figure 1.29.
At dc stresses the time to the previous discharge as a function of the discharge magnitude can be used to evaluate insulation condition.

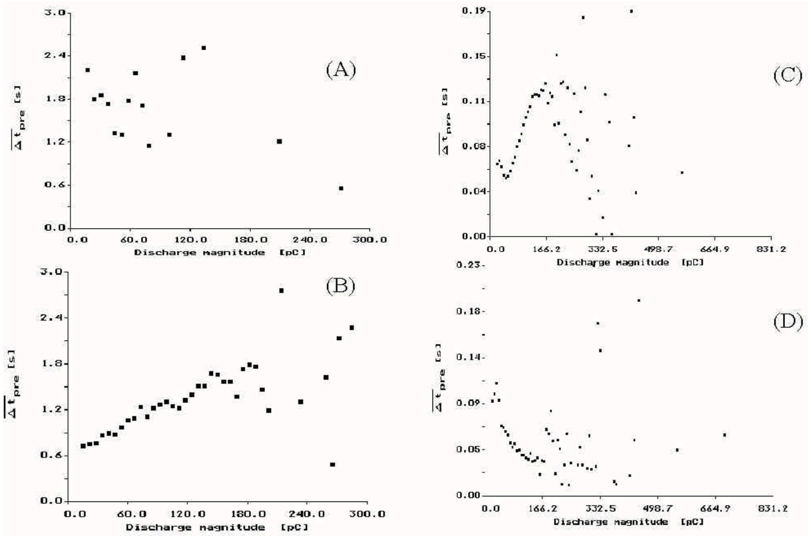


Figure 1.30. *Example of HVDC PD diagnosis of HV components: 75kV DC capacitor and a 150 kV DC capacitor.* ***(A)*** *PD behavior of a 75 kV capacitor; no internal defects;* ***(B)*** *PD behavior of a 75 kV capacitor; internal damage;* ***(C)*** *Internal defect before aging; the clear correlation between the time and the PD magnitude indicates the presence of a defect;* ***(D)*** *internal defect after aging where traces of surface discharges (carbonized paths) appeared on the outer wall of the phenolic paper cylinder; as compared to (A) the curve of the time and the PD magnitude shifts in its linear part from a positive to a negative rise [15].*

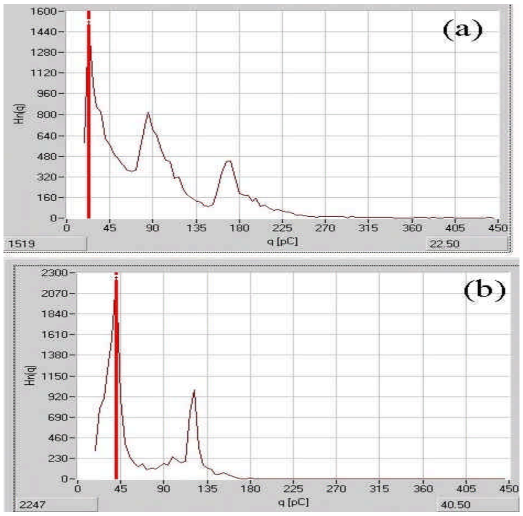


Figure 1.31 *Example of time-dependant changes in PD intensity spectra as measured off-line on a 30kV cable-sealing end: (a) at the beginning of the voltage stress; (b) after 20 minutes of voltages stress.*

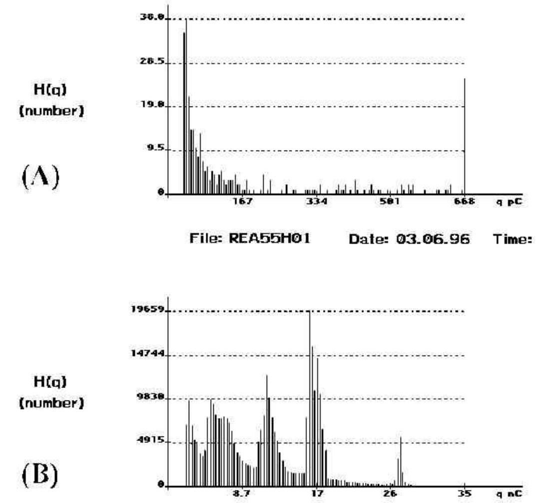


Figure 1.32 *PD intensity distribution H(q) as observed within 2 minutes for a power transformer without defects (A) and for a reactor containing discharges on a damaged screen inside the test objects (B) [11].*

Moreover, based on the assumption that in a "healthy" insulation PD are distributed randomly, see case (A) in figure 1.30 in the case of a discharging defect a clear correlation between PD magnitudes and the time between particular pulses occurs.

The example of PD evaluation of two DC capacitors shows that the different insulation conditions can evaluated using characteristics of the behaviour of)t and the PD magnitude.

1.5.2.2.3 Intensity histograms

Valuable information on the PD activity can also be achieved by histograms showing the intensity spectra of PD quantities, such as:

a) **H(q);** the intensity spectrum of the apparent charge magnitude, and

b) **H(p)** the intensity spectrum of the discharge energy

The observation of these PD intensity spectra can give interesting additional information about discharge sources. In figure 1.31 an example for changing the PD quantities during the test time is shown, see figure 1.25. This refers to laboratory tests of MV cable sealing ends, which have also been selected as `bed' by means of PD probing in service. It is evident, that the intensity spectra of the apparent charge magnitudes change significantly from the beginning to the end of the 20 minutes test time.

In figure 1.32 intensity spectra are shown of discharge magnitudes observed for a transformer in a 'good' condition and for a transformer showing internal defects. It follows from this example that the differences in the shape are clearly visible and it's clear that using this PD quantity additional information can be obtained to analyse different PD sources. Furthermore histograms of different PD basic quantities offer a good opportunity for further statistical evaluation e.g. using Weibull statistics [16] . Furthermore, derived from the PD-pulse height analysis NQN quantities can be used [17].

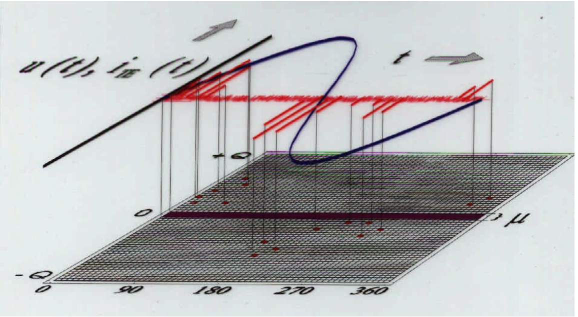


Figure 1.33 *PD signals occurrence in the function of the power frequency cycle resulting in PD phase-resolved pattern.*

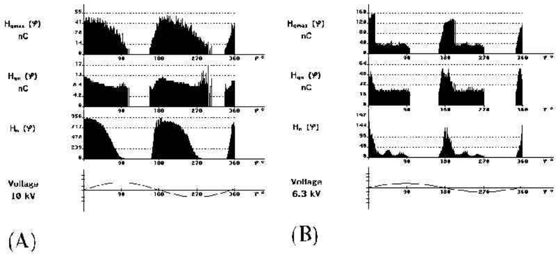


Figure 1.34 *Examples of PD patterns observed for 63 MW turbogenerators*

(A) *regular PD pattern: the sinus envelope of the two phase-resolved distributions $H_{qmax}(f)$, and $H_n(f)$ as well as the flat shape of the $H_{qn}(f)$ are typical for turbo-generators without insulation degradation.*

(B) ir-regular PD pattern: the phase-resolved distributions $H_{qmax}(f)$, $H_{qn}(f)$ and $H_n(f)$ are typical for 6MW and 63MW turbo-generators showing discharges in HV bushing [11].

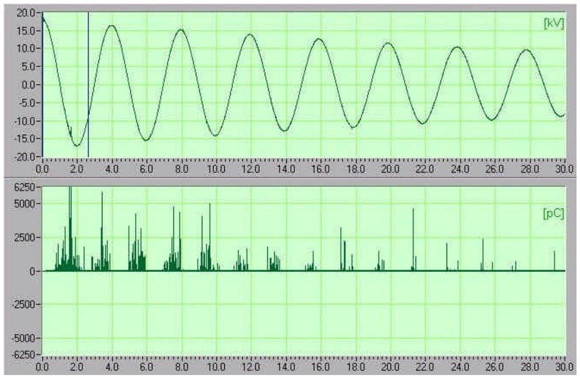


Figure 1.35 *Example of phase-resolved PD pattern observed using oscillating voltage waves (200 Hz) on a distribution power cable showing high PD activity in an epoxy filed joint [7].*

1.5.2.3 Phase-related derived quantities

Most frequently used PD quantity is the phase-resolved PD patterns, see figure 1.23. Due to the fact that PD pulse occurrence is related to momentary value of the power frequency cycle (0.. 360°), the moment of a PD inception can be described by its phase angel *f*.. If the observation of PD activity take place for several voltage cycles, through the whole (0.. 360°) angel axis phase-resolved quantities can be determined. Since the PD detection has been used for quality control of HV insulation by observing PD occurrence in function of applied voltage (see figure 1.23) the phase-resolved PD pattern has become indispensable element of modern digital PD diagnostic.

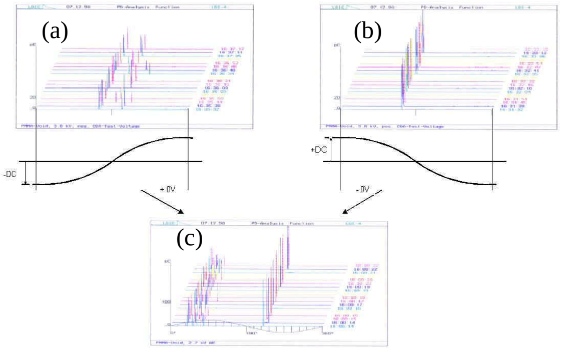


Figure 1.36 *Comparison of PD patterns of a void discharge in a 12 kV XLPE cable under different voltage stresses [18]*

- *a) Oscillating (80 Hz) voltage stress at 7.6 kV_{peak} negative DC charging voltage - positive sweep*
- *b) Oscillating (80 Hz) voltage stress at 7.6 kV_{peak} positive DC charging voltage - negative sweep*
- c) *Power frequency (50 Hz) voltage stress at 6.1 kV_{peak}*

Due to the fact that in the last years many digital PD analysers have been introduced for world-wide use, in the following two sections to illustrate the principals of making phase-resolved PD patterns only few examples will be shown.

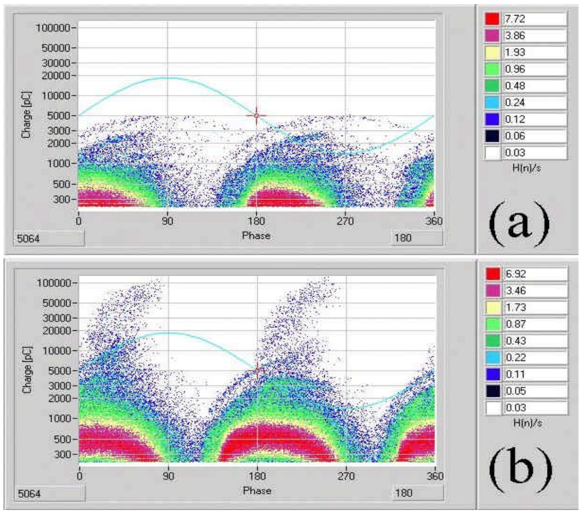


Figure 1.37 *Example of phase resolved PD patterns observed for a 16.5kV motor (a) at U_0=11.7kV, (b) at $2U_0$=23.4kV*

1.5.2.3.1 Two dimensional phase-resoled distributions

Using digital processing (see figure 1.34.) the PD magnitude and PD number observed throughout the whole cycle (0..360°) result in the following basic types of distributions:

a) $H_q(f)$: distribution of the discharges magnitudes (maximum or average value)
b) $H_n(f)$: distribution of the number of discharges.

In figure 1.34 examples of phase distributions are shown as observed for turbo-generators ‘good’ condition and with a presence of winding discharges. Looking at these distributions it's clear that its specific shape characterises each distribution. These shapes can be explained in terms of PD inception conditions.
PD phase-resolved patterns can occur not only during continuous ac energising but also during single ac voltage waves e.g. oscillating voltage waves with duration of hundreds of

milliseconds. Figure 1.35 shows an example of phase-resolved PD pattern of a power cable with a high PD activity in one of the epoxy filed joints. In combination with PD location by travelling waves the particular joint can be pinpointed.

In this respect it should be mentioned, that the phase-resolved PD patterns obtained for oscillating voltages are very similar to those appearing under continuous power frequency (50/60 Hz) voltage, if the frequency of the oscillating voltage ranges between 20 and 500 Hz. A practical example for the PD patterns of a void discharge in a 12 kV XLPE cable, subjected to both kinds of test voltages, is shown in figure 1.36. The upper both records refer to an oscillating voltage of about 80 Hz, which level was chosen close to the PD inception voltage (PDIV) of 7.6 kV_{peak} , i.e. the cable under test was charged by a DC source up to 7.6 kV. After triggering the discharging HV switch, the PD pattern was recorded for the first half-cycle of the appearing oscillating voltage, i.e. for the time interval when the test voltage sweeps from the polarity of the charging DC voltage to the opposite polarity. Each waterfall diagram shows the phase-resolved PD pattern of 18 test voltage shots. The lower record is obtained for the continuous ac voltage stress of 50 Hz. Here the test level was also chosen close to the PDIV. In this case it amounts 6.1 kV_{peak} , which corresponds to about 80 % of the above given PDIV for oscillating voltage.

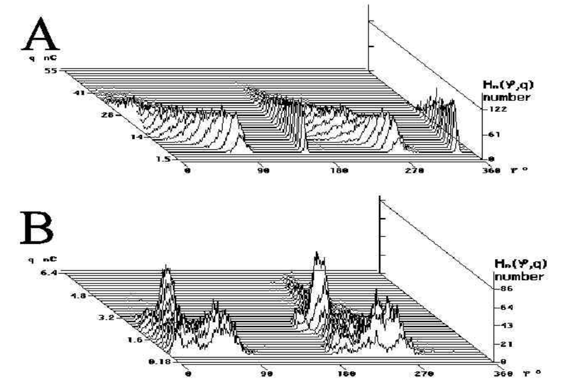


Figure 1.38 *Examples of PD patterns observed for :(A) regular PD pattern typical for turbo-generators in good condition, (B) ir-regular PD pattern as observed for end-winding discharges [11].*

For comparison purpose the phase-resolved PD patterns has also been monitored for 18 ac cycles, i.e. the measuring window for each record corresponds to 20 ms or 360^0 , respectively. As evident from figure 1.37, there is no significant difference in the characteristic PD patterns for both kinds of the applied test voltage, neither for the positive nor for the negative discharges. The only difference is, that the PDIV under ac voltage is about 20% lower. Due to this fact oscillating voltages can be considered as an alternative for conventional ac voltages with respect to cost-effective PD diagnosis tests of high capacitive HV apparatus, such as power cables, power capacitors and rotating machines.

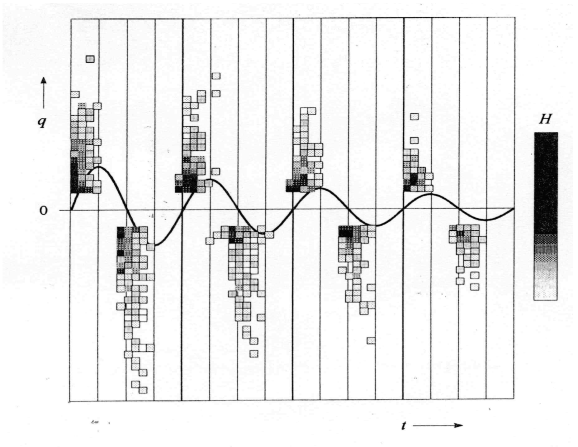


Figure 1.39 *Three dimensional phase-resolved PD pattern of an insulation defect in a 20 kV XLPE cable [19]*

1.5.2.3.2 Three dimensional phase-resoled distributions

Depending on specific application the phase-resolved quantities the phase-resolved distributions can further be combined with other variables like

a) measuring parameters e.g. PD intensity, or
b) testing parameters e.g. the level or duration of the applied voltage.

An typical example of such 3 dimensional quantity is the $H_n(f,q)$ distribution: where the PD magnitude and its intensity are combined.

In figure 1.36 examples of phase-resolved patterns as observed for the same stator bar insulation at two different voltage levels is shown. It follows from these graphs, that increase of the voltage stress may result directly in an increase of a certain PD activity (see the reed marked area).

Especially for HV components which are from the beginning due to their construction not discharge free e.g. power transformers, generator stators, PILC cable and accessories etc. its is difficult to make only on the base of PD magnitude changes a judgement of the insulation condition.

Therefore, giving information about possible changes also in the pattern the evaluation of $H_n(f,q)$ quantities has shown to be very useful. Example in figure 1.37 shows PD patterns observed for turbo-generators: **case A** with a regular PD pattern; where the outer and inner sinusoidal shapes of the 3D phase-resolved distribution $H_n(\phi,q)$ are typical for turbo-generators in good condition, **case B** with an ir-regular PD pattern; this $H_n(\phi,q)$ phase-resolved distribution was observed for end-winding discharges.

Three-dimensional phase-resolved distributions can be obtained not only for continuous ac voltages but also for the transient oscillating voltage.

A practical example, representing the $q(\phi, n)$ distribution of a void discharge in a 20 kV XLPE cable, is shown in figure 1.39. This looks also very similar to the PD patterns appearing under power frequency test voltage.

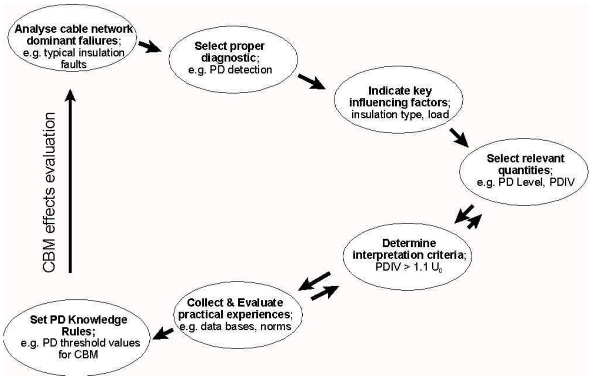


Figure 1.40 *Generation process for PD knowledge rules to support CBM.*

1.6 KNOWLEDGE RULES

1.6.1 General aspects

While the actual aging processes generated by the interaction of the partial discharges are still not well understood at the present time, there has been much information of a qualitative nature gathered over the years. In particular, taking into account particular components important aspects e.g. insulation type, defect type, load conditions etc. the detecting defects can be used in combination with PD knowledge rules to support the

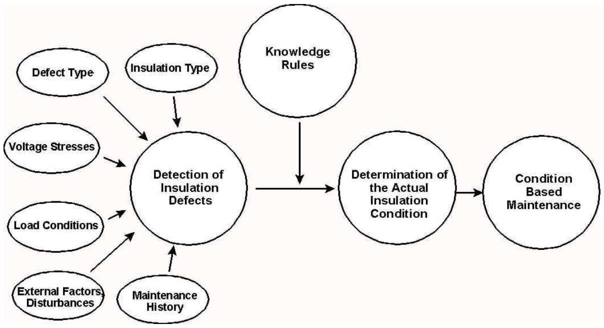


Figure 1.41 *Relationship between service condition specific factors, defect detection, knowledge rules and condition assessment to support CBM.*

decision process of CBM, see figure 1.40. With increasing age, the number of faults will increase and the power supply quality can deteriorate.

Important symptoms of this degradation process can be related to discharging local insulation imperfections or defects, which may occur in the particular HV component. As a result to support CBM by making meaningful PD knowledge rules systematic approach is necessary, see figure 1.41. In the following section using systematic field experiences for different PD diagnostics systematically used in the field the generation of PD knowledge rules will be discussed.

1.6.2 PD Interpretation Rules

Partial discharges are sensitive symptoms of possible discharging defects in the HV insulation. Already 30 years ago, it has been shown that using analog PD detectors, a combination of PD measuring quantities can be used to recognise discharging defects, see figure 5.1. At that time the major goal of using PD recognition was to find during acceptance tests the manufacturing faults. For this purpose Cigre WG 21.3 has developed a systematic supporting PD recognition.

Now, the situation has been slightly changed, see figure 1.42:

a) Advanced digital PD analysers are available;
b) There is much larger knowledge about the materials and aging processes;
c) Due to liberalization of the energy market and the introduction of condition based maintenance (CBM) there is more need to have diagnostics giving information about actual insulation condition of components in service.

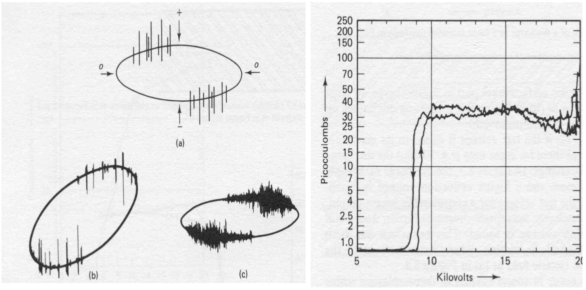


Figure 1.42 *PD pattern analysis; Left: PD pattern of dielectric bounded discharges a) formalized pattern b) and c) actual patterns; Right: X-Y diagram of discharges in a cavity of limited dimension, e.g. some square millimeters by 0.5 mm thickness [20]*

While the actual ageing processes generated by the interaction of the partial discharges are not well understood at the present time, there has been much information of a qualitative nature gathered over the years. There is thus available considerable informed knowledge-based data on such ageing effects.

The next sections are going to show that a lot of experience is available to evaluate PD measurements. With regard to the PD pulse spectrum, discharge magnitude and discharge phase-resolved patterns, as well as the repetition rate, different quantities have been discussed and their usefulness in the analysis of insulation defects is shown.

Moreover, with regard to particular type of HV component combining information about characteristics observed for each PD quantities can be used to support the interpretation of measuring data.

Based on within Cigre activities published results as well as in the literature available experiences the following HV components should be taken into consideration.

In particular, to evaluate for different components the effectiveness of PD diagnostics the following structure has to be used,:

1) *Insulation defects*: short description of general insulation problems (no particular construction problems) possible in this type of a HV component,
2) *PD processes and PD signals*: short description of HV component specific aspects important for PD measurement,
3) *Representative results*: typical ‘’good’’ and ‘’bad’’ examples of using PD quantities to detect insulation degradation,
4) *PD knowledge rules*: examples of combining PD quantities to determine certain insulation condition of a HV component
5) *Conclusion*: benefits / limitations of using PD diagnosis for this type of a HV component.

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PART II POWER TRANSFORMERS

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2.1 GENERAL

Partial discharges measurements are used as an optional commissioning test for transformers (IEC 60076-3) with an acceptance level of 300 / 500 pC at respectively 1,3×U_o and 1,5×U_o measured according to IEC60270. There are several ways of performing such a measurement [1].

For transformers in the field dissolved gas analyses (DGA) has - until recently - usually been the only tool for finding and investigating internal PD. Now, electric PD detection invoking standardized, or high frequency PD detection and acoustic PD detection and location are also taken in use for transformers in service. Compared to GIS and generators experience is still limited and no generally accepted rules for interpretation exist.

Chapter 2.2 briefly summarizes the findings of a recent CIGRE study on PD in transformers
Chapter 2.3 shows the characteristics on the basis of which the PD behavior will be evaluated.
Up to now there is not enough knowledge to determine the type of defect that causes a certain PD behavior. Chapter 2.4 describes laboratory work on models where the relationship between PD behavior and type of defect has been investigated.
Chapter 2.5 shows application of PD detection in on-line tests in order to establish the condition of the electrical insulation system. In a few points it shows the need for noise suppression in on-line situations, and a linking of actual defects to PD patterns.
Chapter 2.6 offers a standard format of cataloguing PD measurements, so that they can be collected in a database and easily be queried. If such a database is built, then it can be used for early recognition of incipient faults.

2.2 PREVIOUS CIGRE INVESTIGATIONS

In 1996 CIGRE WG 15.01 set up a taskforce to look into experience and feasibility of modern PD measurements and analyzing techniques. The TF reported in 2000 without drawing any final conclusions [10]. It was pointed out that the discharge magnitude and patterns among other things depended on:

- Voltage shape
- Location in winding
- Voltage class
- Frequency response and dynamic range of measuring equipment and the PD source
- Measuring time.

2.2.1 PD generating defects

In a well-designed transformer insulation, which is properly dried and impregnated, it is very difficult to initiate discharges. However, discharges do occur in transformers as found both from

PD-measurement during commissioning and from gas analyses from transformers in the field. To initiate discharges there has to be a defect in the insulation system. Such defects include:
Delamination may occur when thinner pressboard sheets are glued together to form thicker barriers. Voids within delaminations may remain for a very long time.
Voids may occur variously. They may occur in glue and in connections with enamelled thread, furthermore insufficient impregnation may give rise to voids. Sometimes (i.e. during commissioning) it is found that voids disappear from one day to the next, as gas is absorbed by the oil and the cavity is filled with oil. Voids may also occur in bushings. High moisture content combined with heat and high fields may create local high water vapour pressure and “puffing” effect of boards and winding insulation. Discharges in this spongy material may start thereafter.
Bubbles may occur due to gas evolution from discharges, and evaporation of water droplets. Experience shows that a gas bubble in an open oil volume will be ripped into smaller bubbles, which will quickly vanish when the first discharge occurs inside this bubble. Bubbles will therefore only exist at locations where they are supported mechanically by solid insulation (e.g. in wedges).
Free metallic particles may be left from the production process. Smaller particles will be carried by oil flow, while larger ones will sink to the bottom. Dielectrophoretic forces will attract high permittivity and conductive particles towards high stress regions. However, free particles can easily adhere to surfaces e.g. the surface of a winding.
Fixed metallic particles (e.g. in wood details, or fixed to paper in windings) may occur.
Moisture may occur due to ageing and may also be introduced into the insulation during site erection. Moisture will contribute in several ways to discharge inception and extinction. During a heating cycle in service (e.g. when energising a transformer that has been off-line), moisture may be pressed out of the solid insulation. Due to poor solubility in the oil there will be a super-saturation of the oil next to the cellulose surface resulting in water droplets and bubbles [11]. Evaporation of the water will give micro-bubbles giving rise to discharges. Increased moisture content in the cellulose will make the cellulose more conductive. In these conditions, cellulose fibres will start acting like metallic particles. Fibres sticking out from paper surfaces and fibres moving in the oil may initiate discharges. Increased moisture content will also increase the dielectric losses. During a cooling cycle, water may condense and be locally absorbed by pressboard. Pressboard has been seen to “puffed up” due to heat developed by dielectric losses and evaporation of water within the pressboard. As a consequence internal discharges may become prevalent in the cavities within the pressboard.
Bad connection of electrostatic shields will give large discharges because the capacitance of the defect is large. The “bad connection” will usually have a defined breakdown voltage (U_{BD}). The result is discharges appearing on the rising flank with voltage independent amplitudes ($Q= C\cdot U_{BD}$).
Static electrification will give rise to local charge deposition. The resulting field enhancement may initiate discharges. Discharge tracks due to such discharges have been seen along pressboard surfaces.
Surface tracking resulting from discharge propagation has been found along barrier surfaces and along supports. Carbonized tracks can act as conductive protrusions, and may over time increase in length.

2.2.2 PD patterns

The work did not conclude on which parameters were most suited as descriptors for PD patterns in transformer insulation. There was some scepticism about pattern recognition in general as patterns vary with instrument setting and with time and stress. However, the field was found quite immature and more experience has to be gathered to find the usefulness of these techniques.

From the independent investigations the following descriptors were suggested to be the more robust ones:

- *Phase angle of discharge pattern;* with phase mean, starting angle and phase width as statistical parameters.
- *The pulse repetition rate*
- *The discharge level* with the charge mean as a statistical parameter.
- *Polarity dependent differences in discharge level*
- *Temporal instability/ burst behaviour* is seen for many types of defects.

Due to the fact that with regard to PD occurrence in the insulation of power transformers systematic work has been performed within the scope of the CIGRE TF 15.01.04 [1] in this part based on current experiences with PD measurements on transformers examples of on-line PD detection and evaluation are shown.

PD detection has long been used for obtaining a Pass / Fail criterion for new or repaired transformers. Using an induced voltage test the PD behavior of the transformer was then evaluated.

2.3 FAIL/PASS TESTS FOR NEW TRANSFORMERS

It is known that on the base of one-hour induced voltage test of a power transformer important conclusions are made regarding insulation conditions of the test object. It is also known that these HV apparatus are not discharge free. On the contrary, a certain level of discharges <500 pC is allowed and most interpretations of the measuring results depend on the knowledge of test engineers.

The main goal of digital diagnosis support is to provide additional information about the PD process. In particular to indicate if the PD is a regular one (no deviation from a normal situation) or if it is irregular which means that discharging defects are present. To support this decision based on different PD quantities several discrimination criteria have been defined.

Table 2.1 and figure 2.1 show examples where the information's about particular PD quantities has been collected from the measurements and classified by a test engineer. For regular PD behavior and for irregular PD behavior examples are shown.

The questions asked in the data protocol have been designed to obtain an answer about the

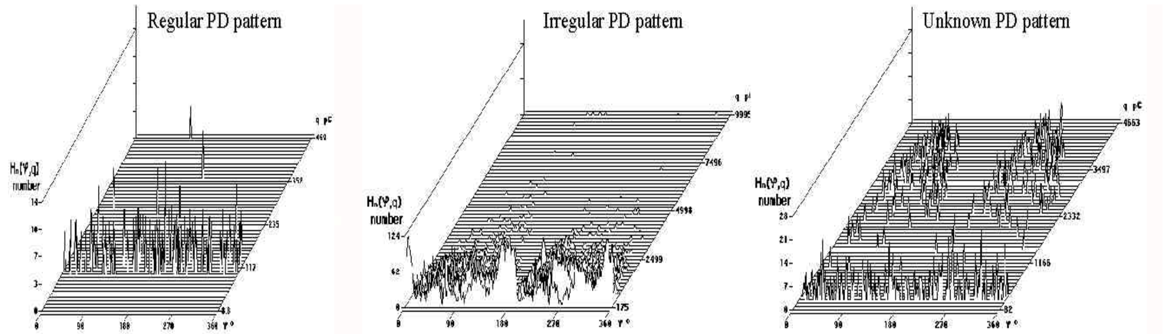


Figure 2-1: *Example of discrimination criteria for PD pattern analysis during induced voltage test of power transformers*
Regular PD pattern: *low PD magnitude; low PD intensity;*
Irregular PD pattern: *high PD magnitude; high PD intensity;*
Unknown PD pattern: *high PD magnitude; low PD intensity;*

presence of discharging defects in the transformer insulation.
Typical PD patterns will be used to support the data discrimination between regular and irregular PD patterns. All the information about PD magnitude, the PD time behavior, PD patterns etc. can be analyzed and weighted using knowledge rules generator of an expert system.

Table 2-1: *PD quantities and their characteristics used in interpretation rules for induced test on power transformers*

PD magnitude	*< 1 nC*	*> 1 nC*
PD intensity (number of impulses)	*low*	*high*
PD pattern data base recognition	*regular*	*irregular*
PD pattern change during and after enhanced voltage level	*no significant change*	*significant change*
PD magnitude during entire test	*low*	*high*
PD intensity during entire test	*low*	*high*
Number of the PD processes	*one*	*several*

2.4 PD DETECTION ON MODELS

2.4.1. Examples of PD activity in practical geometry's

This section describes a series of measurement performed at one laboratory. Some characteristics of possible fault conditions associated with oil-impregnated paper and pressboard insulation systems as utilized in large power and instrument transformers were studied. The fault conditions shown were designed to simulate in the laboratory those situations commonly encountered in practice [2].
For oil-impregnated systems, PD's may be initiated during proving tests in the factory when the equipment is new or they might develop at a much later stage during service. The types of fault condition associated with the first case include the following:

- trapped air in the insulation structure when filling with oil,
- presence of moisture due to insufficient dry-out,
- a design fault causing localized overstress, particularly at oil-solid interfaces,
- assembly fault causing overstress, e.g. broken shields or incorrect foil location.

Possible problems that may arise in service include the following:

- sparking caused by bad contact, which results in gas formation,
- surface tracking and gas formation from long-term deterioration of insulation,
- ingress of moisture due to lack of maintenance,
- contamination, e.g. chipped metal particles from cooling ducts or housing,
- high temperature caused by temporary sudden increase in load.

Compared to gaseous or solid insulation configurations, PD characterization for liquid systems with oil-impregnated cellulose material interfaces is probably more difficult due to the rapidly fluctuating behavior of the discharge activity. In such cases, highly dynamic conditions can arise depending on how the gas produced disturbs the existing insulation structure: i.e. whether it is absorbed in the oil, escaped from the system or locally trapped in the vicinity of the discharge source.

2.4.2 Discharge Patterns for Some Simple Fault Conditions

In most of the cases presented here, the same electrode system was used: a sphere-plane configuration with standard 3mm thick transformer pressboard(s) sandwiched in between as shown in figure 2.
Such an arrangement simulates practical situations where PD's may develop in an oil wedge formed by insulation interfaces. The HV electrode is a 12mm diameter brass sphere, wrapped in two layers of 0.06mm crepe paper and dried for 48 hours under vacuum at a temperature of 90°C. The earth electrode is a flat circular disc of 25mm diameter. The HV electrode can be adjusted so that there is either no gap or a small gap between it and the top of the pressboard.

2.4.2.1 Sparking

The presence of sparking is potentially dangerous since the high level of PD energy can cause burning to the insulation and also generating gas bubbles. In this test, of 30 minutes duration only, a stack of three pressboards was placed in between the sphere-plane electrode setup. The sample was tested at a stress of ~4kV/mm (rms) with no oil gap. This stress level is comparable to the operating design stress in practice (3-4.5kV/mm for paper and 3kV/mm for oil).

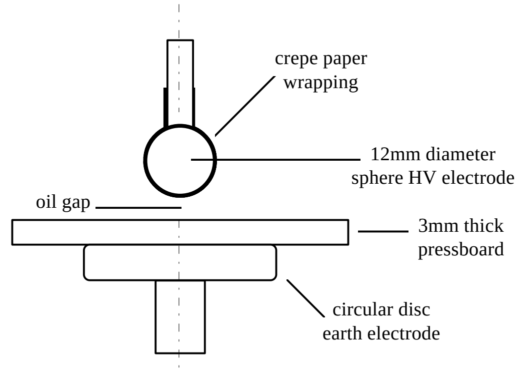


Figure 2-2: *Electrode Configuration*

Sparking and many gas bubbles could be seen coming from the area where the HV electrode touches the top pressboard. PD's occur over a very wide window (150°) starting from near the zero crossings. The PD activity varied during the 30-minute test. Initially there were some large PD's, up to 10nC, with a moderate repetition rate. Then the PD magnitude became somewhat smaller but the pulse repetition rate increased. Finally, the PD activity appeared to decrease both in magnitude and number. Visual examination of the top pressboard after the test revealed burnt track marks.

2.4.2.2 Tracking

Two pressboards were sandwiched between the electrodes. The bottom pressboard was new whereas the top one had burnt track marks (caused by the previous sparking test). The sample was subjected to a stress of ~4kV/mm (rms) with no oil gap. The discharge activity was surprisingly low, both in repetition rate (<20 pulse per second [pps]) and magnitude (<30 pC). However, some very large (few thousand pC) but intermittent PD's could be seen.

The pressboards were then slightly adjusted so that the HV electrode made contact with a section of the track mark. A very high discharge activity with magnitude up to 1200pC was obtained at a much lower stress of ~2.7kV/mm (rms). The overall repetition rate was high (~4000 pps) and a larger number of discharges occurred in the positive half-cycle.

2.4.2.3 Oil Contamination with Small Metal Particles

A number of tests were carried out to investigate the behavior of the PD patterns due to the presence of small metal particles. The particles were thin, sharp and about 4mm long. A dry pressboard section with the particles lying on top and near the center was placed on the ground electrode. The first test was done with no oil gap and with one particle.

Under the influence of the non-uniform electric field, the particle is charged and moves toward the HV electrode. As the field was increased the particle was dragged to the center of the electrode system and eventually the particle was able to stand up and bridge the oil wedge. However, there were no discharges generated.

Next, the HV electrode was moved to create a 6mm gap. As the voltage was raised, the particle was lifted up and was able to stand vertically on the pressboard. If the voltage was increased further, the particle rose against gravity and attached to the HV electrode, suspended vertically on one end and swinging. Discharges were observed at ~15kV or higher, with a charge of approximately.

With multiple particles there is greater discharge activity and there is also considerable interaction of particles, as shown in figure 2.3.

In a more practical simulation, a small amount of contaminated oil, extracted from a 390MVA generator transformer, was injected into the oil wedge and tested at the inception stress of ~3.7kV/mm (rms). This sample contained microscopic metal particles abraded from the transformer cooling ducts. Discharges up to 170 pC were recorded. The PD activity is confined to a relatively small window near the voltage peak.

2.4.2.4 Presence of Moisture

Moisture is always present in oil-impregnated materials. An untreated pressboard sample with about 4% moisture content was used. The sample was tested at the inception stress of ~8kV/mm (rms) with no oil gap. This is more than twice the normal operating stress.

The PD activity was reasonably steady during the 12-minute duration of the test with no failure. Large discharges up to 3nC were recorded with a moderate repetition rate (180pps). Discharges in the two half-cycles are of similar magnitudes but quite different patterns.

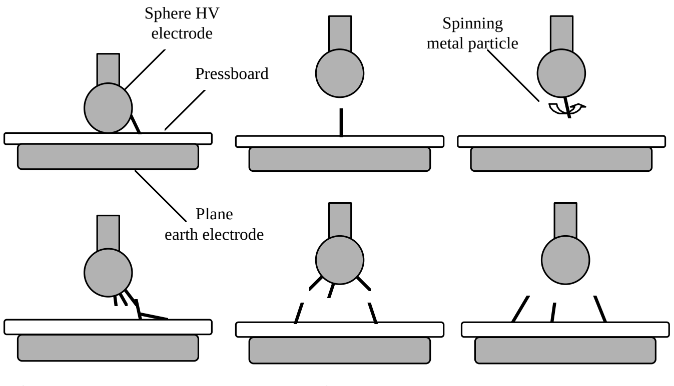


Figure 2-3: *Various scenarios of metal particle behavior*

2.4.2.5 Closed Cavity

This test simulates situations where gas bubbles produced by the discharges are trapped within the immediate area.

During the test, the generated gas accumulated in the cavity. Although the discharge patterns remain similar as the test progressed, the activity was less intense at the end of the test. The most intense discharge occurred at 45^{o} (and also at 225^{o} in the negative half-cycle) which corresponds to the pattern of so called “rabbit ear”.

2.5 ON-LINE PD DETECTION IN THE FIELD

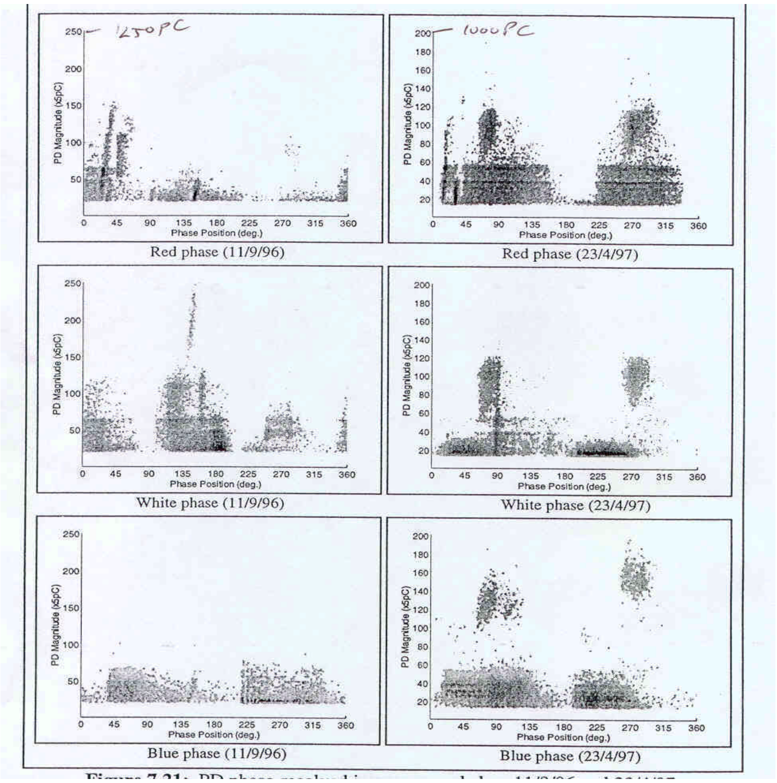
With regard to aging assessment of the transformer insulation the presence of external disturbances, e.g. corona makes very difficult to use PD measurements for this purpose, see figure 2.4. In particular the following experiences are published [2-7]:

1. In practice it is desirable to be able to detect internal defects less than a few hundred pC's. because this already may represent a dangerous level depending on the insulation system of the apparatus.

2. Repeatability of the test is highly dependent on the intensity and stability of partial discharges.

3. Comparison of measurement results is only possible among data acquired with the same hardware configuration (sensors and transformer) and sensor position.

4. Field measurements yielded more unfavorable results due to the size of equipment and adverse ambient noise. Noise suppression is very important and in several cases the main problem of field PD measurements.



Red phase (11/9/96)

Red phase (23/4/97)

White phase (11/9/96)

White phase (23/4/97)

Blue phase (11/9/96)

Blue phase (23/4/97)

Figure 2.4: *Examples of periodic on-line PD measurements to demonstrate the influence of the noise and external discharges. The significant increase of PD activity is mainly related to external corona discharges. It is desirable to detect on-line PD less than few hundred pC's because this may already represent a dangerous level*

5. PD detection was not sensitive to intense PD in the internal winding of a transformer, but problems in tap-changers and a mechanical problem were successfully detected.

6. The limitations of the technique might lead to erroneous or imprecise diagnostics, but it seems to be a viable method to increase the reliability of other techniques such as DGA.

For an interpretation of PD results two things are needed:

1. Detailed investigation of the behavior of the

PD-activity and localization of the PD-sources within the transformer under test,
2. Consideration of complementary information including additional diagnostic methods like frequency response analysis and recovery voltage measurement (RVM) as well as polarization and depolarization current measurement (PDC).

Furthermore according to [2-8] it can be concluded:

1. The off-line procedure described above has been applied successfully to several substation transformers (50 - 600 MVA) and seven 220 / 400 kV new autotransformers after installation. In all cases a detection sensitivity of better than 50 pC was achieved. For field measurements the detection sensitivity is much higher due to the different noise sources.

2. With the application of the presented method, two defects caused by the final on-site assembly of the new transformers and several critical PD-defects in old transformers have been detected. For the old units not only fatal defects with outages were prevented, but also cost-saving maintenance or refurbishment has been proposed.

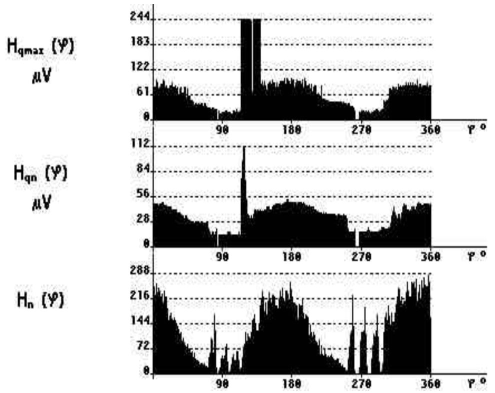


Figure 2-5: *Three-phase distributions of deduced quantities. From top to bottom: the maximum discharge plot* $H_{qmax}(f)$*; the mean discharge plot* $H_{qmean}(f)$*; the discharge number plot* $H_n(f)$

3. In the future, a consequent application of the described advanced diagnostic methods to new and service aged power transformers is highly desirable. More fundamental work is needed to fully understand all the complex physical and chemical processes relevant to the aging of transformer insulation systems.

2.6 PREPARATION FOR KNOWLEDGE RULES STORAGE AND CATALOGUING

2.6.1 Extraction of Parameters

Several authors have argued that many defects have their own specific patterns (amongst others), as can be assumed for defects in transformers. Based on this assumption this chapter will establish parameters that can be used to distinguish patterns from each other.

If such parameters are stored alongside the raw measurement data, then these parameters will enable easier comparison of patterns to other patterns in the same database. Secondly, knowledge rules could be built on the basis of certain combination of parameters.

Next to finding relevant parameters, it is necessary to devise a data format that is both easy to search manually and automatically. Independence of a specific computer platform or software program would be strongly desired to allow for easy interchange of data between interested parties, see for instance the CIGRE-Format as proposed in [8].

When for every discharge the basic quantities of discharge magnitude and phase angle are recorded, other deduced quantities can be obtained and several plots can be constructed. For the purpose of the characterization only the most important will be discussed. It has been known for many years that using 2-d phase resolved plots the occurrence of particular PD events can be displayed as function of the phase angle. The figure 2.5 shows from top to bottom:

- the maximum discharge plot, $H_{qmax}(\phi)$
- the mean discharge plot $H_{qmean}(\phi)$
- the discharge number plot $H_{n}(\phi)$.

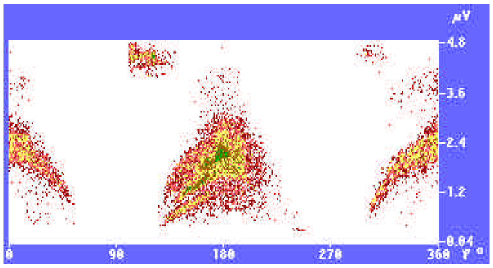


Figure 2.6: *The 3D-plot shows pulse magnitude and discharge intensity as a function of the phase angle. The pulse magnitude is found on the Y-axis and the intensity is shown in color-coding.)*

$H_{qmax}(\phi)$ shows the maximum discharge magnitude recorded at each phase angle during the measurement, $H_{qmean}(\phi)$ shows the average discharge magnitude recorded at each phase angle during the measurement and $H_{n}(\phi)$ shows the number of discharge recorded at each phase angle during the measurement time. Combining information of $H_{qmax}(\phi)$ and $H_{n}(\phi)$ in one 3-D plot results in the $H_{qmax-n}(\phi)$ distribution (figure 2.6). The 3-D plot is an important plot because it quickly gives an overview of phase relations and PD intensity. It also is able to show whether the difference in the average discharge magnitude and the maximum discharge magnitude is caused by

- a spread in pulse magnitude
- or whether it is caused by two discharge processes each having different pulse magnitudes occurring at the same phase angle.

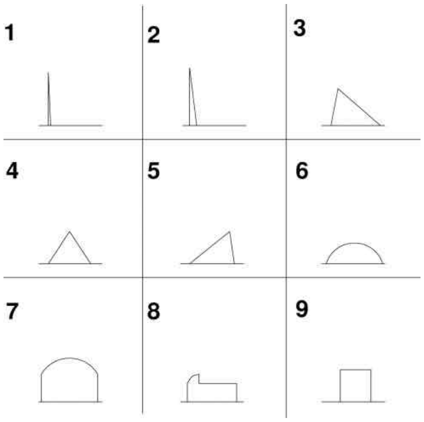


Figure 2.7: *Standard shapes used to classify the patterns in 2D-plots: (1) Narrow spike, (2) Wide spike, (3) Steep ascent, shallow descent, (4) Balanced ascent and descent, (5) Shallow ascent, steep descent, (6) Arclike, (7) Elevated arc, (8) "Baby stroller" , (9) Block*

2.6.2. Possible Parameters for Characterization and Identifications

Providing that one dominant PD phenomenon is active in the insulation for each of these plots certain patterns can be defined (figure 2.7). The shape of the measured patterns is compared to those predefined pattern shapes. By doing this for each plot a "pattern code" can be established. It is expected that this pattern code will be different for different defects. The reference patterns only cover half of the phase, instead of the more customary 360^{o} patterns. This is done to reduce the number of reference patterns needed. In this setup one reference pattern can be used to describe discharges in the positive half cycle, or discharges in the negative half-cycle or discharges in both cycles. In order to make a difference between these situations, an extra notation can be made to indicate that this is an symmetric or asymmetric pattern.

Similarly, for the 3D plots reference patterns shapes can also be defined. In the figure 2.8 several reference patterns are shown.

In transformers multiple patterns can be present simultaneously. When performing a

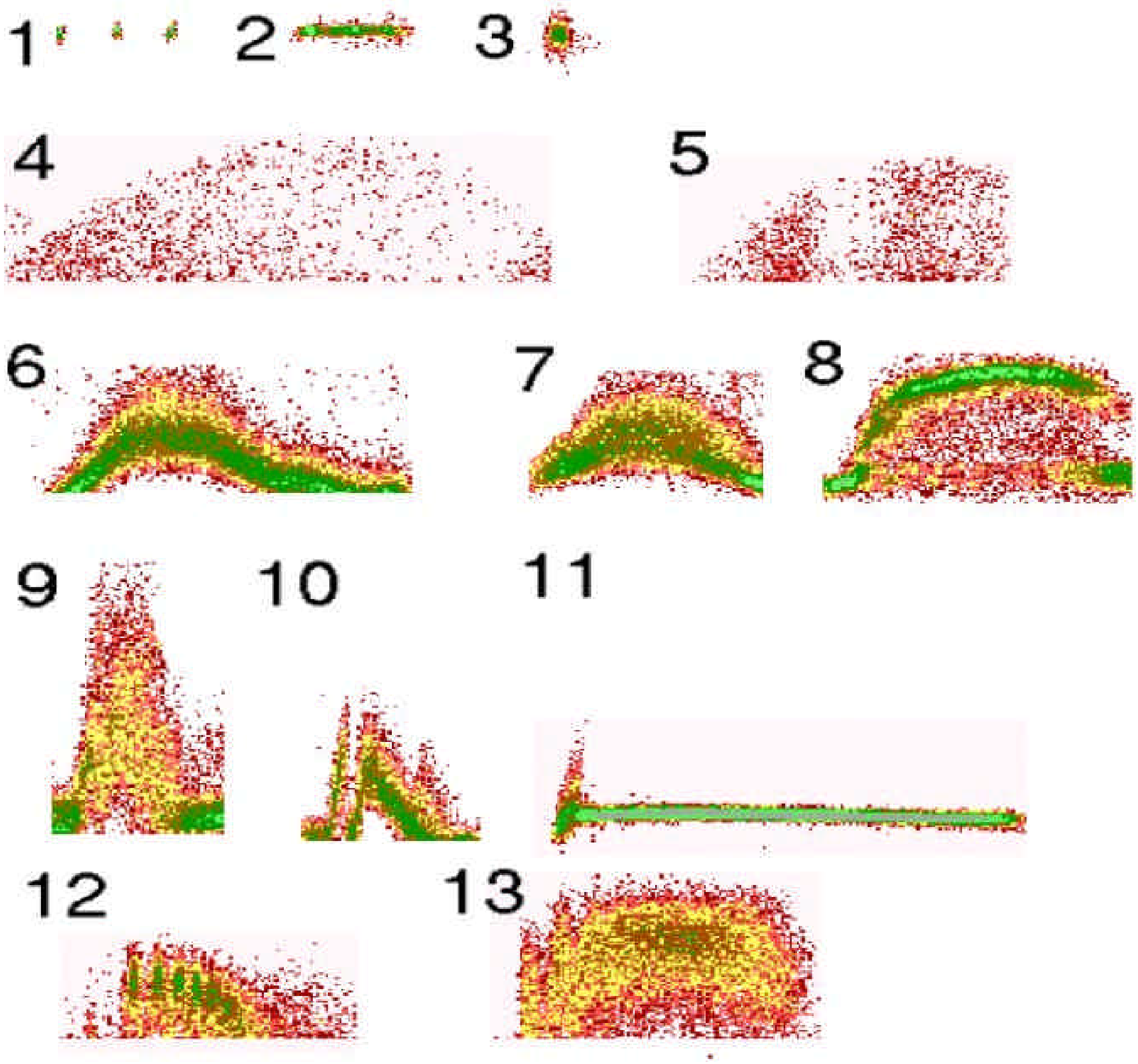


Figure 2.8: *Reference Patterns for 3D plots: (1) repetitive pulses of fixed magnitude, (2) band of pulses of fixed magnitude, (3) slight variation of phase angle and pulse magnitude, (4) Half sine, sparse, (5) Half sine, divided, (6) bow, left shifted top, (7) bow centered, (8) elevated bow, centered, (9) chimney, (10) rectangular triangle, (11) rabbits ear before a long band, (12) repetitive pulses, not fixed magnitude, (13) square*

measurement, those patterns will be recorded, as long as those patterns do not have overlapping phase angles, their respective contributions to the 2-D and 3-D plots can easily be distinguished. The description shown in this section will have a lot of redundancy, however, often PD patterns will have overlapping phase angles and this make it hard to separate the pattern shapes from each other. Some parameters will be difficult to establish and must be left blank. This causes the need for redundancy when describing the properties of a pattern.

The parameters of a measurement can be stored in a table where each pattern is mentioned, its characteristics are described and special remarks can be made. This table will have the generic shape shown in table 2.2. The header of the table shows the general transformer data, next the measurement name and properties are shown. Finally the patterns visible in the measurement are described one after another. While it is advisable to establish a standard for reading a measurement (for example the 3-D plot, from top to bottom, from left to right) it is not imperative since every pattern will be described sufficiently to allow for recognition in the plot.

Table 2.2 *Example of a transformer ID and general data followed by the measurement ID and general data followed by pattern 1 plus its data up to pattern n plus its data*

Transformer ID#		***Type***	***150/5010***	***Yd7d7***
Measurement method	VHF, 4.3 MHz	File name	Measurement7	
Winding	150 kV			
Phase	W	Phase reference		Positive zero
Pattern	1	magnitude	2.9 μV	Max
			2.8 μV	Mean
		Phase angle	30^o-75^o	45^o wide
		3D reference	2	
		$H_{qmax}(\phi)$	9	
		$H_{qmean}(\phi)$	9	
		$H_n(\phi)$	3	
			Intensity	12
	2	Magnitude	10 μV	Max
	n			
			intensity	

2.7 PRACTICAL EXAMPLES

Ideally, for a transformer having only one defect, only one pattern is visible in the measurement data. This pattern can then be compared to the reference patterns, (figure 2.9).
A table of pattern properties can be constructed that contains the relevant information regarding this measurement. Similar to this example, for every reference pattern a separate subset of relevant properties can be developed.

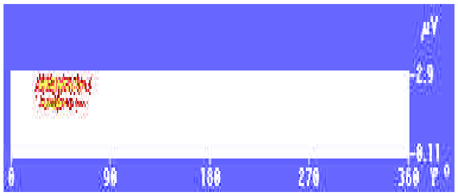


Figure 2.9 *Example of a single pattern*

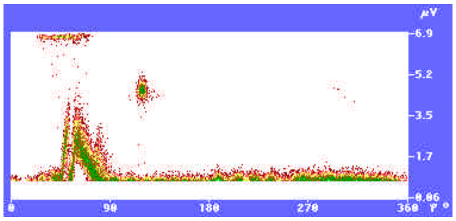


Figure 2.10 *Example of a multiple pattern.*

On-line measurements often show a combination of cross-talk, disturbances, multiple defects in the transformer (figure 2.10). Each of these can cause a pattern in your measurement and often one will see multiple patterns in one measurement. Such situations can be divided in two cases:

- The two patterns are completely separate, i.e. do not have overlapping phase angles
- The two patterns have overlapping phase angles

Case 1 is similar to "one pattern in a measurement", the only difference that more than one pattern should be specified in the table.

In case of situation 2, it is more difficult to attribute the correct reference patterns to the individual patterns. The figure 2.11 and Table 2.3 clearly show the problem. Patterns 1 and 2 in this figure are mixed, i.e. can be found at the same phase angles. This clearly influences the 2D distributions and therefore it is important to make a remark in the table that these patterns are mixed. By flagging the patterns in such a manner, a later data query can be told to ignore or connect less value to the affected properties. An attempt to separate their respective contributions to the 2D distributions is only possible if for one of the patterns its properties are intimately known.

Another point of notice is the "clipped flag for pattern 2. When querying the data, this will also warn that the shapes of the 3D and the $H_{qmax}(\phi)$ and $H_{qmean}(\phi)$ can be severely influenced by the clipping.

Table 2.3 *for multiple defects at mixed phase angles (measurement shown in figure 2.11).*

Transformer 7			***150/5010***	***Yd7d7***
Measurement method	VHF, 4.2 MHz	File name	Measment7	
Winding	150 kV			
Phase	W	Phase reference	?	Positive zero
Pattern	1	magnitude	4.6 µV	Max
				Mean
		Phase angle	45°-90°	45° wide
		3D reference	10	
		$H_{qmax}(\phi)$	3	
		$H_{qmean}(\phi)$	9	
		$H_{n}(\phi)$	4	
			Intensity	568
	2	Mixed with pattern magnitude	2 6.9 µV	Max
			6.7 µV	Mean
			Clipped	
		Phase angle	30°-70°	40° wide
		3D reference	2	
		$H_{qmax}(\phi)$	9	
		$H_{qmean}(\phi)$	3	
		$H_{n}(\phi)$	4	
			Intensity	568
		Mixed with pattern	1	
	1	magnitude	5.2 µV 4.2 µV	Max Mean
		Phase angle	120°-130°	10° wide
		3D reference	3	
		$H_{qmax}(\phi)$	9	
		$H_{qmean}(\phi)$	9	
		$H_{n}(\phi)$	4	
			Intensity	>20

For each measurement a table as shown in figure 2.11 can be made. Within such tables each pattern gets its own section for storing its attributes. Initially a catalogue of such measurements is not more than that. But once a pattern is identified as being linked to a defect this catalogue can then be searched for appearances of these patterns in other transformers.

In the case of dominant PD phenomena, for each pattern a "co-ordinate" can be computed, to allow an automated grouping of patterns. The following example shows attributes or combinations of attributes, which can be thought of, as significant:

- The maximum value of a pattern, divided by the mean value: $H_{qmax}(\phi)$ / $H_{qmean}(\phi)$
- This value could be used to distinguish between dispersed patterns, such as pattern 1 from Figure 2.11 and concentrated patterns (pattern 3 from figure 2.11)
- The pattern width
- The pattern starting phase angle
- The pattern center, which can be computed from the pattern width and the starting phase angle (starting angle+(width/2))
- This value could be used to recognize corona discharges from the same phase but at different magnitudes and pattern widths
- Each of the references, 3D, $H_{qmax}(\phi)H_{qmean}(\phi)H_{n}(\phi)$, in itself could be used as a value
- The intensity

2.8 REQUIREMANTS ON DATABASE OF PD PATTERN

For interpretation of PD patterns it is necessary to be able to store and classify PD patterns. A suggestion has been made for reference patterns for 2D PD plots and 3D PD plots.
A standardized data format for storing the characteristics of PD measurements is proposed.
Much research has been done in laboratory studies on artificial defects. In order to get full value from PD measurements, it is necessary to connect PD patterns from defects in samples with those from actual defects in transformers.
For linking PD patterns to defects in actual transformers a promising method would be to:

a) Put every new measurement in a database using a standardized data format.
b) Second, if a defect is actually detected and repaired, feedback should be given to database. In this way it will be possible to search for transformers that exhibit the same PD behavior as the damaged one.

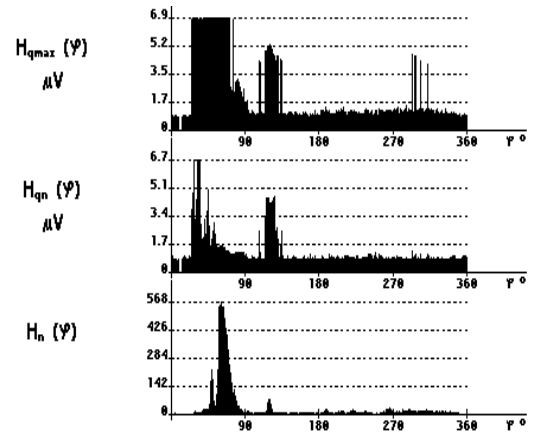


Figure 2.11 *Measurement belonging to Table 2.3*

Both steps are essential. There will be no real hope of linking PD patterns with defect if one of these steps is omitted.

2.9 CONCLUSIONS

1. For induced voltage tests on transformers table 2.1 and figure 2.1 show the criteria for a Pass/Fail conclusion.
2. In laboratory studies on models, several different PD patterns were found for several

different defect geometry’s.

3. Field measurements have shown the needs for noise suppression, but if present, then useful measurements can be made.
4. Better knowledge of the behavior of PD-activity and localization of PD sources in the transformer is needed.
5. A standardized data-format, for storing of PD measurements in (lightweight) databases is suggested.
6. By systematically storing PD measurements in a database, all measured transformers can be queried on the existence of a defect newly recognized in one transformer. In this way incipient faults can be detected in the whole transformer population of a utility.
7. To evaluate the effectiveness of PD analysis in power transformers the number of PD phenomena simultaneously active during the diagnosis has to be taken into account.

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PART III POWER CABLES

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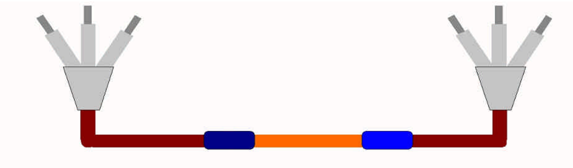
3.1 GENERAL

In the last ten years, to determine the insulation condition of the power cable grid, several on-site diagnostic measuring methods have been developed [1-16]. As a result, on the basis of on-site testing and measurements of partial discharges, important information is generated about discharging insulation defects. In particular, applying off-line test the PD has shown that PD knowledge rules can be defined to support condition-based maintenance [17-19]. To maintain the assets e.g. power cable in dependence on their availability important detailed information on their actual insulation condition of a cable section is necessary. In particular, the service life of single cable section elements has to be evaluated, see figure 3.1. The history, the operational and the laying conditions together with the importance of the cable circuit in the network are necessary conditions to decide to perform diagnostic testing. In its turn the main goal of PD diagnosis is to recognise high voltage insulation problems and to identify the insulation defect causing the discharge: e.g. internal or surface discharges, corona, treeing, etc, see figure 3.2. This information is vital for estimating the harmfulness of the discharge.



Cable Section:

- Cable parts
- Joints
- Terminations

- Different Types
- Different Ages
- Different History

Figure 3.1 *Important service life elements of a cables section.*

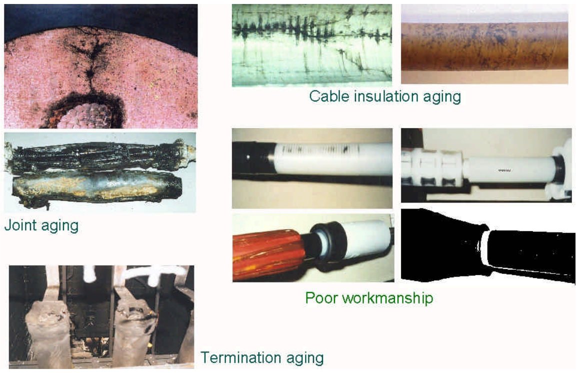


Figure 3.2 *Examples of power cable insulation defects.*

3.2 CABLE INSULATION DEFECTS

By registration of the disturbances in the power supply by network owners, statistical analysis can be made to indicate the major failure causes in the medium voltage power network. Figure 3.3 shows an example of statistical overview of the most important failure causes in a distribution cable network of a utility having almost 95% of the distribution power cable network exists of paper insulated lead cable (PILC). Approximately 43% of these breakdowns are caused by non-electrical external causes. This can be damages by digging activities for other types of underground cables (e.g. telephone, gas) or caused by movement of the soft wet ground in some parts utility area. But still, more than half of the breakdowns in the cable

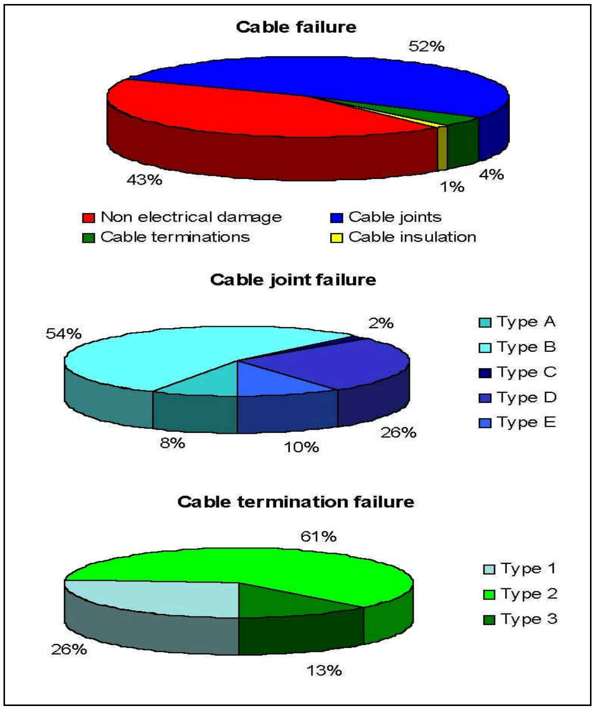


Figure 3.3 *Example of statistical distribution of cable failure causes.*

Figure 3.4 *Fault cause analysis of disturbed cable termination. Several sharp edges on the connector were found on all three phases.*

network is caused by internal fault in the insulation systems of the cable network. The majority of the electrical faults occur in the cable joints: 52%. The remaining breakdowns occur in the cable terminations (4%) and the insulation of the cable parts itself (1%). For many years now, failing joints and terminations are analysed to find the repetitive fault causes.

Visual inspection of the disturbed components gives insight in the different types of fault causes resulting in breakdowns. Figure 3.4 shows an example of the analysis of a disturbed mass filled cable termination, which showed on all three phases sharp edges on the conductor connectors to the switch gear. On the fault place, two phases were only insulated by the plastic cover of the termination, resulting in a breakdown after several years, caused by PD activity from the sharp edges. As a result of these visual inspections, a list of defects in the different elements of cable network can be made, as reflected in table 3.1.

Table 3.1: *Typical insulation defects for different types of power cable components.*

Cable type	**Accessories**	**Insulation**
PILC	Low oil level	Damage outer sheet
	Sharp edges on connectors	Tracking
	Moisture penetration	Internal damage (as a result of bending)
	Air / gas bubbles	
	Bad hardened resin	
XLPE	Sharp edges on connectors	Damage outer sheet
	Moisture penetration	
	Air / gas bubbles	
	Field grading movement	
	Bad hardened resin	
	Interface problems	
	Remaining semicone	

3.3 SELECTION OF ADVANCED DIAGNOSTICS

For many years, DC withstand testing was the only testing method applied in the MV power cables network, but nowadays also PD testing is applied. However, for some joints (resin filled), the DC voltage test combined with PD test is the best option. DC test for moisture penetration and PD test for sharp edges. Moisture penetration in the resin insulation, from the outside to the inside, does not result always in PD. Because the moistured part of the insulation material is conducting, the rest (dry part) of the resin is stressed with almost 99% of the applied DC voltage and breaks down. For the other types of joints and termination, PD testing at AC voltage stressing is the best diagnostic option, and is applied for almost two years now. As shown in table 3.2, partial discharges (PD) are sensitive symptoms of possible discharging weak spots (insulation defects, degradation products) in the HV insulation [19-22].

Table 3.2: *Typical insulation degradation processes of the power cable insulation.*

Accessories	interface problems → PD → tracking; bad hardening → cracking → PD; conductors problems → overheating → cracking → PD; local field concentrations → PD
Extruded Insulation	water trees → electrical trees → PD insulation voids → delamination → electrical trees → PD local field concentrations → PD
Paper/Oil Insulation	oil leaks → dry regions → overheating → PD water ingress → load effects → overheating → PD local field concentrations → PD

For water-tree aged cables PD detection is not an effective diagnostics tool. Other methods based on dielectric response e.g. return voltage, dissipation factor, dielectric spectroscopy or isothermal relaxation current are better analysis methods to be recommended [23].
Already 30 years ago, it has been shown that using analogue PD detectors, a combination of PD measuring quantities can be used to recognise discharging defects. In particular it was stated that any discharge larger than a certain q_0 measured below test voltage U_o leads to rejection of the object under test. In addition using phase-resolved PD patterns the recognition of defect is possible [ref. Cigre Electra No. 11, 1969]. At that time the major goal of using PD recognition was to find the manufacturing faults during acceptance tests. Nowadays, the situation has been slightly changed. In the last ten years, due to the fact that:

a) advanced digital PD analysers are available,
b) more knowledge about the materials and ageing processes is available;
c) due to liberalisation of the energy market and the introduction of condition based maintenance (CBM) there is more need to have diagnostics giving information about actual insulation condition of components in service.

the use of digital PD measuring techniques for quality assurance in the works, during on-site testing as well as for monitoring purposes during service life of HV components like cables have got increasing attention.

Table 3.3: *Standard methods for diagnostic testing of distribution power cables.*		
Voltage source	**PD detection**	**PD information**
50Hz ac energising: **on-line diagnosis**	VHF PD detection at power line frequency voltages	PD activity in the whole circuit at U_0 level
20Hz – 300Hz 50Hz ac energising: AC **off-line diagnosis**	Standardised (IEC) PD detection at sinusoidal power line frequency voltages	PD occurrence and location in the selected cable section at different voltage levels
0.1Hz ac energising: VLF **off-line diagnosis**	Standardised (IEC) PD detection at sinusoidal 0.1Hz voltage frequency	PD occurrence and location in the selected cable section at different voltage levels
50Hz..500Hz Damped ac voltages energising: DAC **off-line diagnosis**	Standardised (IEC) PD detection at damped sinusoidal voltages at 50Hz..500Hz frequencies	PD occurrence and location in the selected cable section at different voltage levels

Due to the fact that PD diagnosis of medium voltage cables is used as a non-destructive means of identifying critical weak points in a length of cable, the following requirements can be defined for such a diagnostic tool:

a) Non-destructive for the cable insulation and using AC voltage stress conditions;
b) Using standard and derived quantities;
c) Providing distinction between different types of insulation defects;
d) Providing PD site location: PD mapping;

As a result, PD diagnosis has two ultimate purposes
1. to conclude on the condition of the component measured,
2. to recommend
  a) about exchange of cable or accessory,
  b) to perform a more accurate on-site visual inspection,
  c) to retest within a certain time span.

From a physical point of view PD diagnosis tests of power cables should be performed under electrical stresses most similar to service condition. In order to decrease the capacitive power demand for energising the cable and hence to reduce the weight and costs of the test equipment, specific voltage shapes have been introduced and employed since 1985. As a result the most common applied excitation voltages are classified in table 3.3.
This report discusses systematic field experiences as obtained with all these methods whereas with regard to knowledge rules generation three methods will get special attention.

3.4 KEY INFLUENCES FACTORS

Due to the fact that different elements can be used during construction of a cable section, each cable section may represent a separate combination of elements like, see figure 3.1:

a) several different cable joints,
b) two or more different cable terminations,
c) different cable parts between particular joints / terminations.

These elements from the point of view of construction, insulation materials applied as well as due to different service conditions may age in different ways. In order to achieve a good end result it is necessary to have a number of sources of information, concerning the cable and accessories tested, available to support the operator in making a correct interpretation of the measured PD signals. The information has to be collected from the network owner:

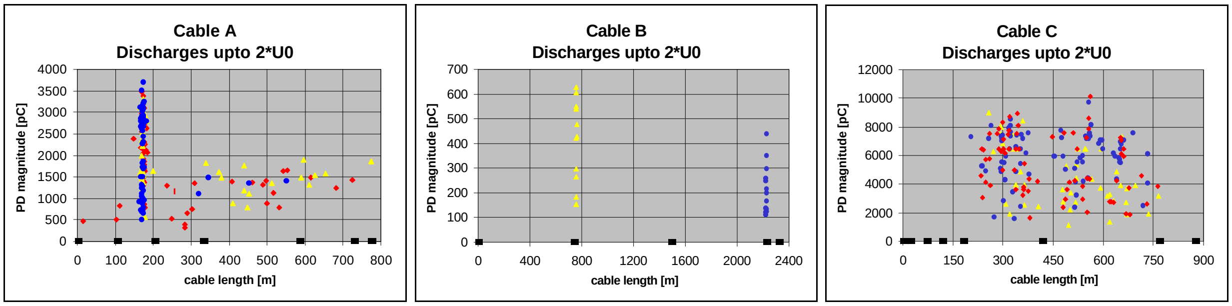


Figure 3.5 *Examples of different types of PD location in a distribution power cable*

(A) PD concentration in a cable part; in dependence on the PD magnitude as well as the concentration are conclusions regarding local insulation degradation could be made;

(B) PD concentrations in cable joints; ; in dependence on the PD magnitude as well as the concentration are conclusions regarding local insulation degradation could be made;

(C) PD concentration in the cable insulation only; due to temperature/pressure changes temporary PD activity may occur in the cable insulation, no indication on insulation degradation.

a) Type of cable and accessories
b) Accurate cable maps
c) Year of installation of cable and accessories
d) Current and "past" loading of cables
e) Operating history including failure behaviour
f) Installation conditions
g) Importance of the network

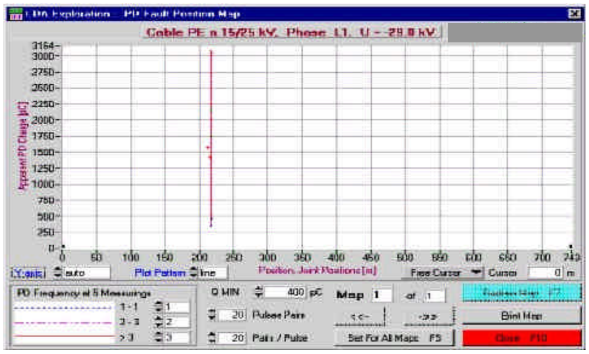


Figure 3.6 *PD fault position map of a 743 m long PE cable (15/25 kV) subjected to a damped AC voltage of 29 kV. The local concentration of strong PD-events at 216 m appear in a not correct assembled joint.*

As a result, prior interpreting the diagnostics results collecting relevant cable section specific technical information is of great importance, see figure 3.5. In particular, an example of similar discharge activity (PD ≅ 8.000 pC) as observed in two PILC cable sections is shown. In the 1st case (cable A) the concentrated PD activity indicates in the cable a discharging defect. In the 2nd case (cable C) no concentrations of PD are detected, but the PD activity is scattered over the full lengths of the two cable parts between 180 and 770 meters. This is temporarily PD activity (several hours) is caused by temperature / pressure changes, which are typical for synthetic oil impregnated cable insulation and occurs after disconnecting the cable section, and is not related to degradation of the insulation material.

Different to PILC cables XLPE and EPR insulated cables show mostly only sharp concentrations of single PD events, see figure 3.6 [26]. The reason for that is, that the cable insulation is usually

PD-free, because it is tested carefully after manufacturing in laboratory. Hence, PD may only appear in the accessories due to not correct assembling work after laying or longer service time.

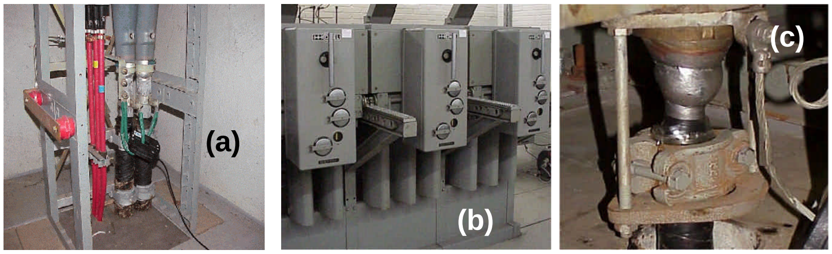


Figure 3.7: *Due to large construction diversity the accessibility for diagnostic systems can be different: (a) due to very open construction almost each of diagnostics systems can be connected (b, c) due to the cable termination is inside the switchgear the accessibility is limited.*

Selecting testing criteria have to be adapted to cable specific configuration. It is known that the XLPE cable insulation has to be PD free. Moreover, due to temporary over-voltages occurring during network operation the cable at U_0 service voltage has to stay PD free. As a result for the XLPE cable insulation, the PD inception and extinction voltages have to occur at higher levels than the service voltage U_0. Therefore it is of importance for XLPE cables to be able to detect this situation where due to over-voltage stress a permanent PD activity can be ignited.

Furthermore from practical point of few due to large diversity in physical accessibility to cable terminations and the possibility for a suitable sensor location it is of great importance to take into account the limitations in applying any sensitive PD diagnostics, see figure 3.7.

3.5 RELEVANT PD QUANTITES; Cable ’’fingerprint’’

Although the measurements can be carried out at preferred voltage levels, the following aspects should be considered:

1. A PD measurement should be performed at both U_0 as well as at 2 x U_0. Partial discharges measured at phase voltage appear constantly and therefore represent a great threat.
2. Partial discharges measured with coupled voltages only appear when there is an earth fault and then it is a question of how long the fault will last. A few minutes is not a problem but several hours duration is a threat.
3. When examining test results in cases where the PD inception voltage is < U_0, the growth in PD amplitude and the increase in PD intensity are of great importance.
4. For PD measurements with inception

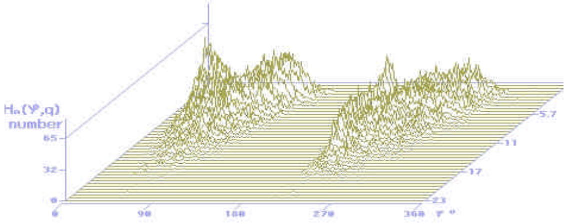


Figure 3.8 *Example of a PD ‘Finger print’ of a MV power cable as obtained using off-line diagnosis.*

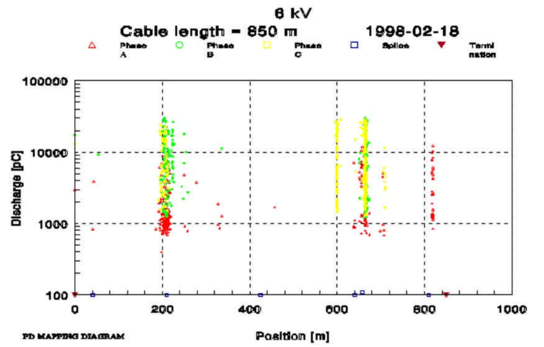


Figure 3.9 *Example of a PD ‘Finger print’ of a MV power cable as obtained using off-line diagnosis.*

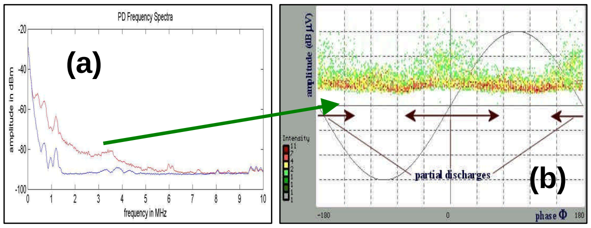
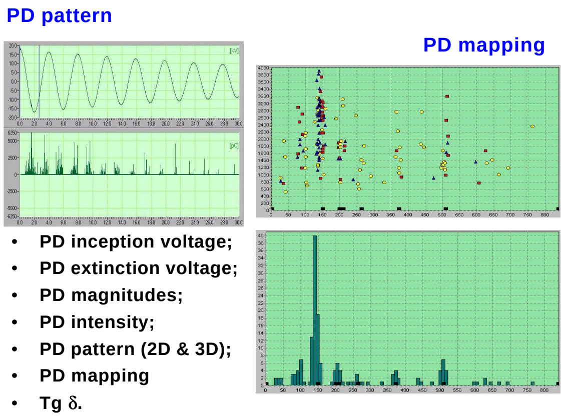


Figure 3.10 *Example of a PD 'Finger print' of a MV power cable as obtained using on-line diagnosis; (a) PD spectrum (b) PD pattern detected at a selected frequency e.g. 3.8MHz.*

voltages > U_0, the increase in PD intensity and PD level should be considered in relation to the permitted values and used as feedback to maintain non-destructive voltage levels.



- **PD inception voltage;**
- **PD extinction voltage;**
- **PD magnitudes;**
- **PD intensity;**
- **PD pattern (2D & 3D);**
- **PD mapping**
- **Tg δ.**

Figure 3.11 *Example of a PD 'Fingerprint' of a MV power cable section as obtained using off-line diagnosis.*

All relevant information from a PD cable measurement should be collected. To describe the PD process in the cable section under investigation diagnostics method generates several PD quantities, which can be divided into two groups:

1. basic quantities: e.g. PD level in [pC], [nC], PDIV in [kV], PDEV in [kV], PD spectrum;
2. derived quantities: e.g. q-V curve, phase-resolved PD pattern, PD magnitude/intensity mappings.

This PD information which can be determined at different voltage levels e.g. up to $2U_0$ is collected in a so-called PD 'fingerprint' of a power cable section. Examples of PD ´fingerprint´ as possible to obtain using different diagnostics are shown in figures 3.8-3.11. The characteristic of these quantities measured on different cable sections may vary in dependence on factors like type, age, service history, and location of the elements used.
Without any doubt, all diagnostics actions are to be considered as the indispensable final step in the complete PD field testing process, because those actions should be able to avoid service failures and consequently to contribute to improved reliability.

3.6 INTERPRETATION CRITERIA

For optimal interpretation of the results obtained from field measurements, it is important to study the results from several points of view, collected in the cable 'fingerprint'. In particular,

- the distinction between PD activity in the cable section under investigation and the discharges originating from outside the cable section e.g. switchgear, corona,
- characterisation of different discharging defects by typical PD patterns

are important issues. Combining these interpretation rules the ageing stage of a fault can be recollected.

Comparison of the measured ’fingerprint’ with a database of other measured cable sections, gives the opportunity to identify the criticality of a detected PD source and in this way optimise the planning of the possible replacements of cable parts or accessories.

In tables 3.4, 3.5 schematic example of interpretation rules for off-line PD measurements on distribution power cables are shown. In Table 3.7 schematic example is shown for off-line diagnosis of transmission power cables. These are rules of thumbs supporting the analysis of the measurement results from a cable section. Different aspects of the ‘fingerprint’ are used in these interpretation rules.

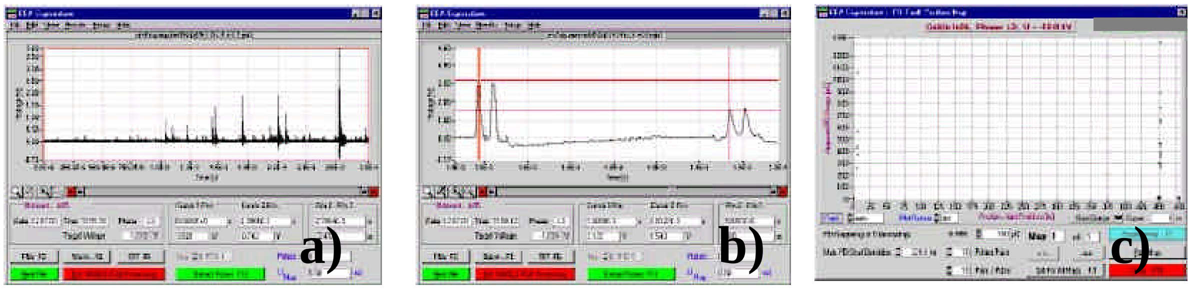


Figure 3.12 *Practical example for the location of PD sites in a 480 m long XLPE cable (12/20 kV) by means of a damped AC test voltage of 12 kV_{Peak} using the time domain reflectometry [27] a) Visualisation of the PD pattern appearing during the first half-cycle; b) Zoom of a single PD pulse selected from the record a), c) Created PD fault location map; PD failures in joints at 7m and 452 m*

Regarding the interpretation criteria of PD results the knowledge on the position of critical PD sources is very important. If PD diagnosis tests of distribution cables are executed off-line, the PD-site can be located by means of the time domain reflectometry (TDR). A practical example for a 480 m long XLPE cable is shown in figure 3.12. As already reported in chapter 3. for diagnostics of transmission cables (off-line and on-line) PD sensors can be integrated in the accessories. Because under this condition the maximum reading of the PD instrument is obtained, if the PD source is close to the sensor, the location of critical PD events in cable accessories bases on these criteria. A practical example, which refers to the identification of a PD failure in a prefabricated HV cable joint (110 kV) by using the directional sensor technology [26], is shown in figure 3-13.

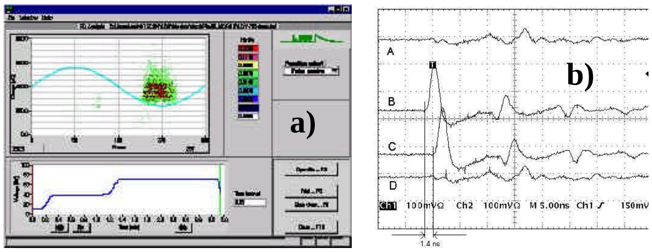


Figure 3-13 *Identification and location of a critical PD source in a pre-fabricated 110 kV XLPE cable joint during an after-laying test under power frequency AC voltage, using the directional coupler technology; (a) Visualisation of the phase-resolved PD pattern of the identified joint; (b) Output signals of the four ports (A, B, C, D) of the both integrated directional couplers [26]. Evaluating the time delay of 1.4 ns the PD source inside the joint could be pinpointed at a deviation from the real site less than 4 cm.*

Regarding the interpretation rule for the PD location, it is very important to keep in mind how a cable joint or cable termination is constructed, because the harmfulness of a defect is depending on the structure of the accessory.

The on-line based diagnosis method is at this moment under investigation and the interpretation rules can be only made to make a distinction between general PD activity in a cable circuit and the disturbances, see table 3.6.

Table 3.4: *Example No. 1 of interpretation rules for an off-line PD diagnostics on power cables.*

PD magnitude (depending on component)	high	low
PD value (depending on component)	high	low
PD density (depending on component)	high	low
PD pattern	dangerous type of discharges *****	less dangerous type of discharges *****
PD location	cable	accessory
Network condition	insulated neutral	solid earth
Installation condition	duct	direct buried
PD mapping	scattered PD	concentrated PD

***** *combining PD patterns to the dangerousness of discharge type requests special experiences*

Table 3.5: *Example No. 2 of interpretation rules for an off-line PD diagnostics on power cables.*

Inception & Extinction Voltage	> cable operating voltage	< cable operating voltage
PD magnitude	< typical values (e.g. < 4000 pC)	> typical values (e.g. < 4000 pC)
PD intensity	Low (e.g. < 5 pulses / period)	High (e.g. < 5 pulses / period)
PD pattern	harmful fault type *****	less harmful fault type *****
PD location	cable insulation	cable accessories
PD mapping	PD concentration	scattered PD location

***** *identifying the harmfulness of discharge type requests special experiences*

Table 3.6: *Example of interpretation rules for on-line PD diagnostics on power cables.*

VHF PD Spectrum	typical for PD activity	typical for disturbances
PD pattern	typical for PD activity	typical for disturbances and cross-talking effects *****

***** *analysing cross-talking effects requests special experiences*

Table 3.7: *Example of interpretation rules for combination of tan d and PD diagnosis to assess and classify the condition of PILC cable diagnostics on transmission power cables.*

Cable category	**PD at U_0 [pC]**		**tan δ at U_0 [x10^{-4}]**	**remarks**
A	PD ≤ 250	**and**	≤ 30	-
B	PD ≤ 1000	**and**	≤ 50	-
C	PD ≤ 1000 or Pd ≤ 5000 + no localisation	**and**	tan δ > 50 tan δ ≤ 80	Follow trend
D	Pd > 1000 + localisation	**and**	tan δ ≤ 80	Inspect/replace PD location
E	PD > 5000 + no localisation	**and/or**	tan δ > 80	Think about cable replacement

3.7 PRACTICAL EXPERENCES; Distribution Power Cables

3.7.1 Interpretation at Off-line Conditions

Relevant aspects, regarding the interpretation of the measurement data are discussed based on systematic examples from field measurements [21].

Especially for XLPE power cables it is of importance to know in the relation to U_0 of the cable the voltages PDIV, PDEV. If the voltage PDEV is lower than the operation voltage of the XLPE cable section, PD can occur continuously during service of the cable section, see figure 3.14. The detected PD source at PDIV (10kV = 1.1*U_0) has been located in phase L2 in the cable terminations.

Due to decreasing voltage at oscillating the PDEV can be determined. In this case, the PDEV is 0.9*U_0, lower than the nominal voltage. This means that in a case of just a small over-voltage, caused by for example switching, the PD source will be ignited and will be discharging continuously during

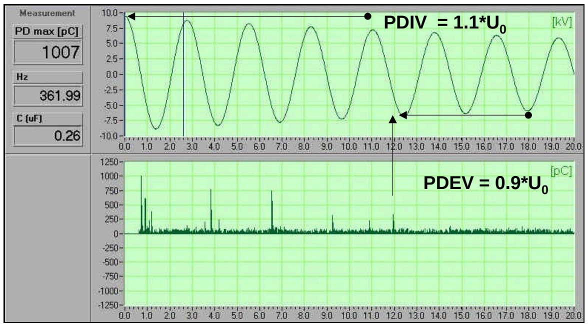


Figure 3.14 *PD measuring result where PDIV = 1.1 U_0 is just above U_0 and PDEV = 0.9U_0 is just below U_0.*

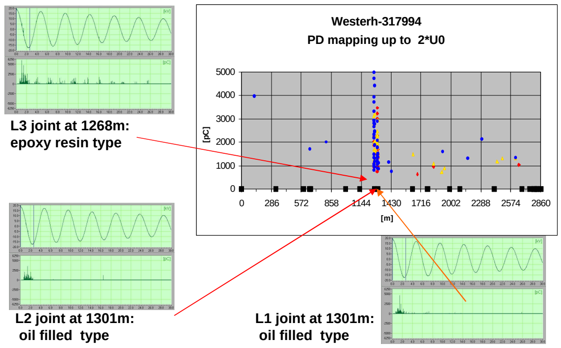
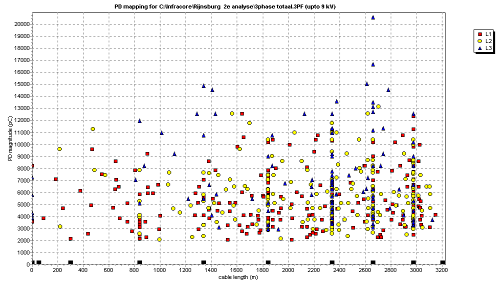
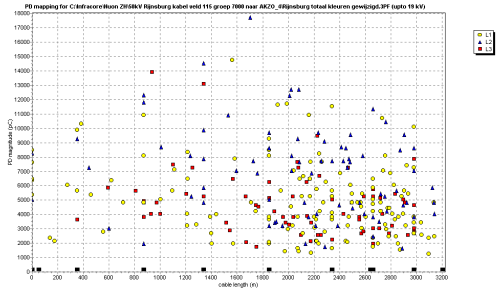


Figure 3.15 *PD diagnosis of a 22860m long 10 PILC cable showing discharge activity in different types of splice L3 located in the joint at 1268m. and splices L1 and L2 located in the joint at 1300m.*

operation.
Figure 3.15 shows the measuring results on a 3-phase PIL cable section with two aged joints. The PD pattern of phase L3 differs from L1 and L2; in L3 PD occurs in the negative as well as the positive side of the oscillating voltage. As known this refers to different PD source types, which is true in this particular case.
The PD mapping of the cable section in figure 3.15, shows that the detected PD is originating from two different types of joints at 1260 and 1300 m from the measuring side.
Due to the fact that for PILC insulation a certain PD level / intensity is allowed it is of importance to determine the criticality limits for PD activity. After discharges cross such a limit maintenance has to be performed resulting in improvement of insulation condition. In figure 3.16 an example of PD mappings made before and after maintenance indicated by bad insulation condition (too high PD activity in a number of splices) shows that evaluation PD levels in combination with PD intensity can be used to support the maintenance activities.



PD activity before the maintenance



PD activity after the maintenance

Figure 3.16 *PD mappings as made for a 3200m long 10kV PILC cable before and after maintenance: refilling all oil splices and replacement of one of the splices.*

To detect and to locate in power cables insulation discharging weak-spots, the principles of time dominie reflectometry (TDR) are generally used. In particular, using 1 sensor the actual discharge source location can be derived from the differences in arrival times of the first and reflected second pulse, see figure 3.17a. Due to attenuation and dispersion of the PD pulses travelling through the cable system the maximum length of cable circuits where the PD

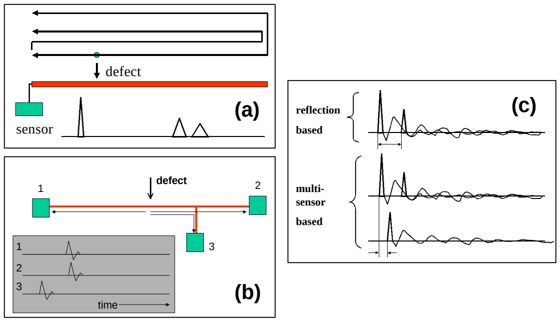


Figure 3.17 *Principals of signal processing of discharging defects in branched distribution power cable network. (a) single sensor PD detection on no-branched cable section; (b) synchronized multiple sensor PD detection on a branched cable network; (c) PD pulse shapes as detected in (a) and (b).*

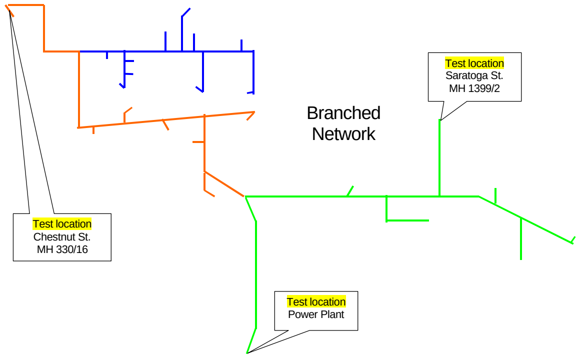


Figure 3.18 *Multi-terminal diagnosis of a branched distribution power cable network.*

activity can be located is about 4 km. With such a length of a cable the smallest measurable discharge s are in the range of 100pC to 1000pC depending on noise conditions. By applying sensors on both sides of the cable circuit the measurable cable length can be extended to 8 km. This increase is possible because the reflected partial discharge pulses do not have to travel up and down the cable anymore before they will be measured.

In a branched cable circuit sensors can be placed at several cable branch ends. Each of the sensors will receive partial discharge pulses that can be used to locate the discharge sources. The principles are similar to that of a long cable discussed above. Figure 3.17b shows the principle set-up in the case of working with three sensors.

A special case is a circuit with many branches, see figure 3.8. Here the diagnostic test can be done in two or more rounds. In a first round of testing, the weakest branches can be identified with only a few sensors (three or four), installed at the end of the longest branches. Weak branches without sensors have discharges that are seen on the T-splices only. In case of a dangerous discharge activity level at such a T-splice, this branch should be evaluated more closely by having a sensor at the end of this branch too in a next round of testing [24].

3.7.2 Interpretation at On-line Conditions

The diagnostics presented in section 3.7.1 work off-line, which means that during the test the cable section has to be disconnected from the network and energized by an external voltage source, e.g. 50 Hz AC, VLF or damped AC voltages. In that way, applying to the cable sample AC test voltages between PD inception voltage (PDIV) and $2U_0$ the discharge behavior of cable insulation can be analyzed to obtain most complete information about the insulation condition. This is in contrast to an on-line diagnosis where PD detection can only be performed at the line voltage U_0. According to experiences of a utility applying on regular base an off-line PD diagnosis about 10% of distribution power cables (PILC) as tested in the last two years up to voltage level of U_0 was showing discharges of negligible levels. As result applying an off-line diagnosis was not necessary at that time.

Therefore, to obtain more efficiency in applying these advanced off-line diagnostics, a certain pre-selection is preferred. This pre-selection can be done in different ways, e.g.:

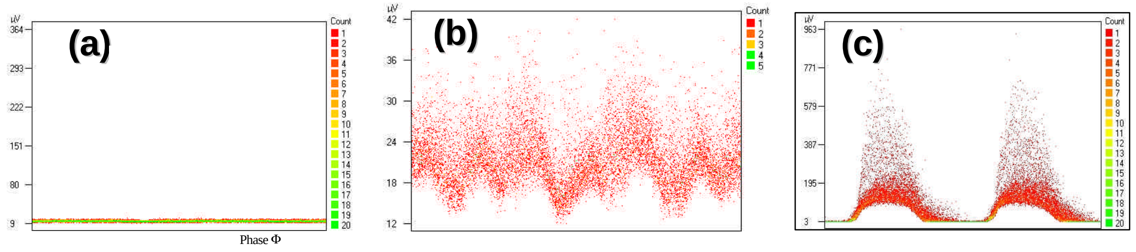


Figure 3.19: *Typical three types of PD pattern to obtain using on-line diagnosis: (a) No PD present at* U_0 *; (b) Disturbances at* U_0*; (c) PD present at* U_0*.*

a) Using failure history.
b) Identifying risky positions in the network.
c) On basis of an on-line diagnosis.

In particular, to support the off-line diagnosis by prioritising particular cable sections, on-line PD detection diagnostics can be a more and more interesting option [25,26]. Due to the fact that

a) distribution power cable-systems are complex systems consisting of different cable accessories and cable parts;
b) on-line energising may be accompanied by external disturbances;
c) the electrical (only U_0) and thermal (actual) load condition may influence the discharging defects;

before on-line methods will be applied, systematically investigation is still necessary.
In figure 3.19 three examples are show of PD patterns typical for on-line PD detection. It follows from this figure that especially two cases could be of benefit in prioritising the cable circuits for off-line in-depth diagnosis:

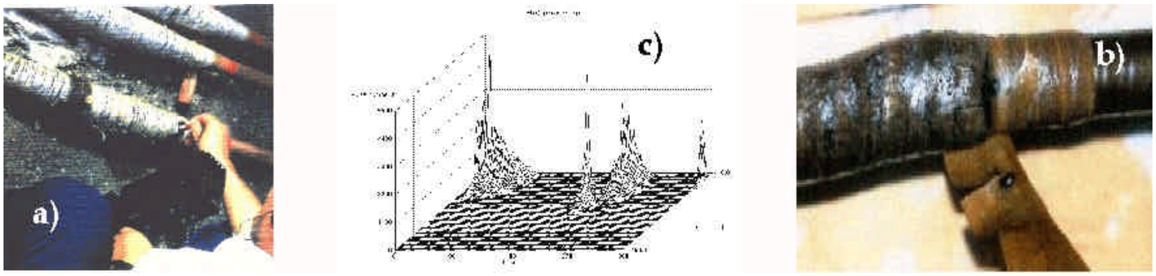


Figure 3.20 *Practical example for on-line PD probing of well accessible 20 kV cable joints; a) scanning the critical region of the cable joint by means of an UHF-sensor; b) visualisation of measured PD events of a defect joint, c) view of the identified PD degradation in the joint insulation.*

a) **‘’No PD present at U_0’’** to the lower the priority of an off-lien diagnosis;
b) **‘’PD present at U_0’’** – to consider an off-line diagnosis;

Unfortunately in the other case **“Disturbances at U_0’’** (20% of all on-line measurements) it is not possible till now to make any statements about the PD activity.
As already reported (see figure 3.3), the majority of electrical faults occur in the joints of MV power cables. Hence, for well accessible joints the UHF / VHF PD probe measuring technology can advantageously be used in order to improve significantly the signal-to-noise-ratio. A practical example for the PD probing is shown in figure 3.20 [28].
From the point of view of applicability of on-line PD detection to diagnosis of distribution power experiences at Nuon West have shown that the use of on-line and off-line PD diagnostics can be complementary and a combination can be of benefit for CBM.
Nevertheless, by using on-line PD diagnostics the following aspects have to be taken into account [26]:

1. Physical accessibility to cable termination and the possibility for a suitable sensor location.
2. The influence of disturbances in the network on PD signals originating from the cable section.

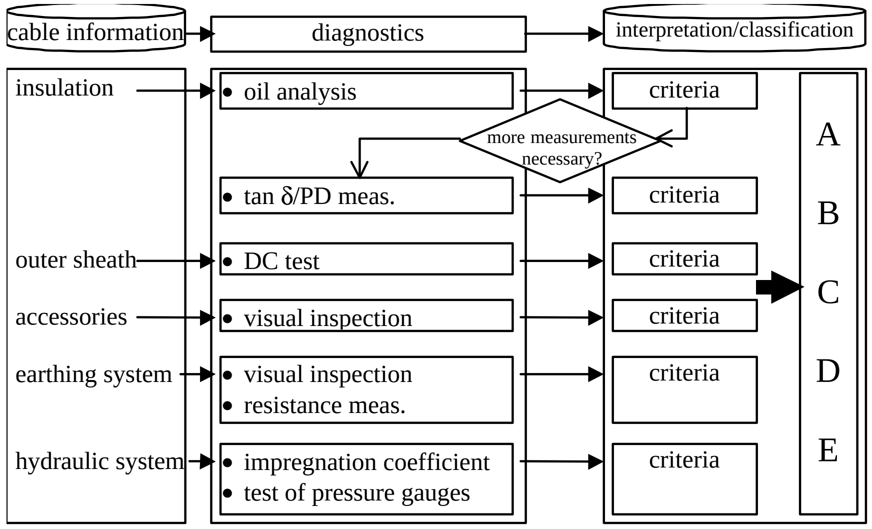


Figure 3.21 *Condition assessment of oil-filled cables.*

3. Interaction between PD activity and the thermal (load) conditions of the cable during PD test. It is know that changes in the operation conditions of a cable influence both the PD inception voltage and the PD amplitudes.
4. Distinction among phase-own PD sources. Presence of multiple PD sources in different phases and the cross-talking processes.
5. Importance of PD analysis at different voltage stresses e.g. PDIV, U_0, and up to $2U_0$.
6. The usual time domain reflectometry (TDR) can not be used for the location in the cable section of PD sites.

The longer the cable sections the higher the minimal detectable PD activity. It followed that above cable lengths of 0.5 km the cable must be tested at both ends.

3.8 PRACTICAL EXPERENCES; Transmission Power Cables

Approaching the CBM programs for HV cable networks (> 50kV) the following differences to MV cable systems (< 50kV) have to be considered [17]:

1. there is not one dominant failure process in HV cable networks, PD in the cable insulation cannot be seen as the only messenger for failures;
2. the complexity of cable systems in HV networks is often higher (e.g. oil-filled, gas-pressurised cable systems).

Not detection of PD, but the prevention and detection of ageing mechanisms that cause thermal instability, PD activity, leakage's and other degradation of the cable, is the main target for CBM on HV cable networks. This has resulted in the development of diagnostic packages to assess the condition of a certain cable type. Figure 3.21 summarises how CBM is applied to oil-filled cables. After a survey of all relevant information about the cables in the network, diagnostics are carried out to assess the condition of each cable. Interpretation is done based on criteria for each diagnostic. All results together are used for a classification of the cable into five possible categories, see table 3.8. A maintenance program and / or guideline for further operation of the cable is linked to each category. Depending on the category, the condition assessment is repeated once every 3 or 5 years.

Table 3.8: *Example of cable classification.*

Cable cat.	**Description**	**Availability in service**	**Expected time for CBM (h/y)**	**Expected life time (years)**
A	new cable in good condition	>99.9%	<24	>30
B	good condition but extra attention is required	>99%	<48	>25
C	stable situation, but moderate condition	>95%	<72	>15
D	In-stable situation	<50%	-	-
E	end of life	<95%	-	<3-5

The criteria for the interpretation of diagnostics are based on knowledge rules, which are under continuous development using among others:

a) available knowledge (literature) on cable ageing and diagnostics;
b) experience obtained by carrying out diagnostics;
c) research in the laboratory with (accelerated ageing) tests on field aged cable.
d) Table 3.9 shows an example of criteria for interpretation of oil analysis.

Table 3.9: *Reference values and criteria for oil analysis.*

AC electric strength	**Good** **> 50 kV/2,5 mm**	⇒	**Decreased** **< 30 kV/2,5mm**
tan δ	**Good**		**Increased**
40 °C	< 77·10-4	⇒	$> 125 \cdot 10^{-4}$
60 °C	< 168·10-4	⇒	$> 272 \cdot 10^{-4}$
80 °C	< 348·10-4	⇒	$> 563 \cdot 10^{-4}$
100 °C	< 459·10-4	⇒	$> 749 \cdot 10^{-4}$
DGA	**Good**		**Increased**
H_2	< 658 µl/l	⇒	> 1093 µl/l
CO	< 50 µl/l	⇒	> 78 µl/l
CH_4	< 19 µl/l	⇒	> 32 µl/l
C_2H_6	< 10 µl/l	⇒	> 17 µl/l
C_2H_4	< 5 µl/l	⇒	> 8 µl/l
C_2H_2	< 5 µl/l	⇒	> 8 µl/l
C_3H_8	< 12 µl/l	⇒	> 20 µl/l
C_3H_6	< 3 µl/l	⇒	> 5 µl/l
iso-C_4H_{10}	< 2 µl/l	⇒	> 3 µl/l
n-C_4H_{10}	< 34 µl/l	⇒	> 63 µl/l
CO_2	< 416 µl/l	⇒	> 577 µl/l

3.9 INSULATION CONDITION KNOWLEDGE RULES

3.9.1 Distribution Power Cables

After measuring and analysing PD activity in a cable section, the second step is to make a decision on the insulation condition of the tested cable sample. Using the measured PD quantities and their interpretation rules (tables 3.4-3.5) three condition classes can be derived from the analysis:

1. **cable section NOT OK**: weak spot in the cable section should be replaced;
2. **cable section NOT OK?**: trending on the cable component is required (e.g. 1 year 3 years);
3. **cable section OK**: no weak spots in the cable section, cable section is OK.

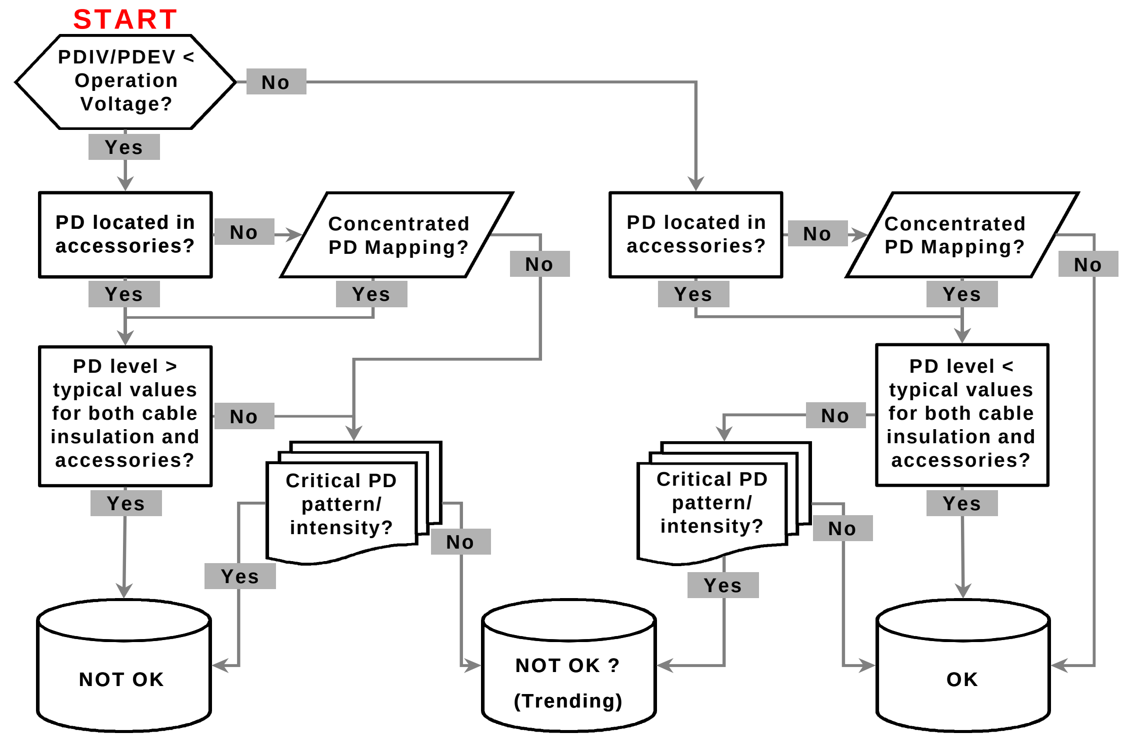


Figure 3.22 Decision diagram for diagnostic data analysis to categories the insulation condition in one of the three condition classes.

Figure 3.22 shows the decision diagram for power cables. Analysing the derived measurement data through the diagram, the cable systems insulation condition can be determined in one of the three classes. The decision diagram is based on all PD quantities for measurements on power cables. Not concentrated PD in the cable insulation is not an indication of ageing of the cable insulation materials, see figure 3.5.

For PILC related insulation, certain levels of PD can be accepted in the cable insulation, joint and termination, depending on the design of the component. Also, XLPE related accessories could stand certain PD levels (generally lower pC levels compared to PILC). However, XLPE cable insulation is required to be PD free (PDIV>$1.3U_0$, PDEV>$1.1U_0$), where the background noise during the measurement is not allowed to exceed 20pC. The typical PD values for the different components can be derived from the statistical analysis of all required measurement data in a database, see figure 3.23-24. As a result for particular components threshold values can be derived to support the CBM, see table 3.10. In particular the insulation condition assessment of a power cable based on the PD quantities the evaluation can be performed in two ways:

Table 3.10: Indication of some typical PD levels for different types of cable insulation and accessories based on experiences from the Netherlands.

Cable element	**Type**	**Trend values**
insulation	PILC	10.000pC
	XLPE	<20 pC
splices	Oil-joint	5.000pC
	Type 1(resin insulation	500pC (asymmetric)
	(oil insulation)	>10.000 pC
	(oil / resin insulation)	5.000 pC
	Type 2 (resin insulation)	4.000 pC
terminations	Oil-termination	6.000 pC
	Dry termination	3.500 pC
	Type 3 termination	250 pC

a) comparing actual values to those obtained for the particular cable section in the past and analysing / trending the differences in the terms of critical changes increases / decreases, see figure 3.25.

b) comparing actual values to those obtained once for similar cable sections or particular elements and evaluating the similarities / differences in insulation conditions, see table 3.10.

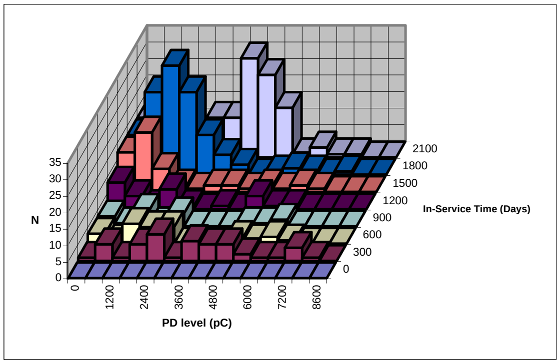


Figure 3.23 *PD frequency distribution versus service life calculated from the measurement values in a certain time interval. As a result aging effects could become visible e.g. after 1550 days of service discharging defects become visible.*

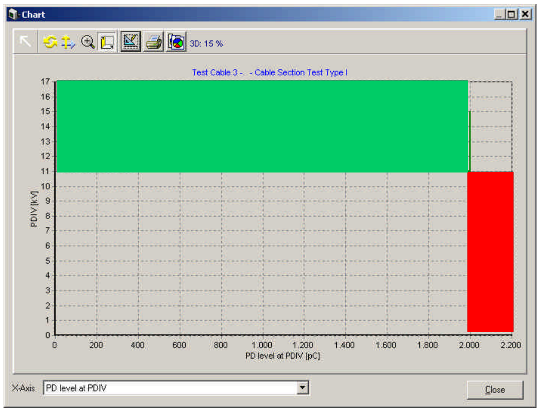


Figure 3.24 *Trending two diagnostics quantities PDIV and PD level; Green area means the degradation process is not critical for the insulation condition; reed are means increased risk of failure.*

Defects generating PD's over a long period may result in a failure. It is very important to collect all data received from PD diagnostic testing. Such data have to be analysed in a statistical way and per discharging location parameters such as discharge number, intensity, density, pattern and

phases involved have to be recorded. Typical defects often, but not always, show typical discharging parameters. Using the systematic application of PD diagnostics can result in

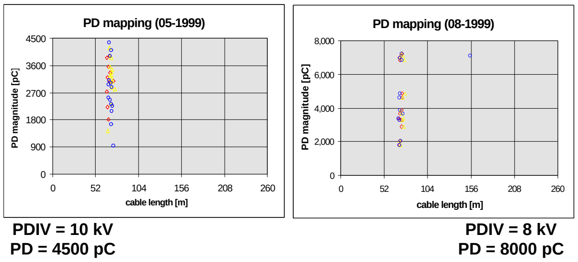


Figure 3.25 *Example of insulation ageing assessment in a PILC distribution power cable using PD diagnosis applied in a time inteval of 3 months. Due to the decrease in the PD inception voltage and the increase in the PD magnitude between the measurements with a time interval of three months, it was clear that the cable insulation at 90 m was degrading.*

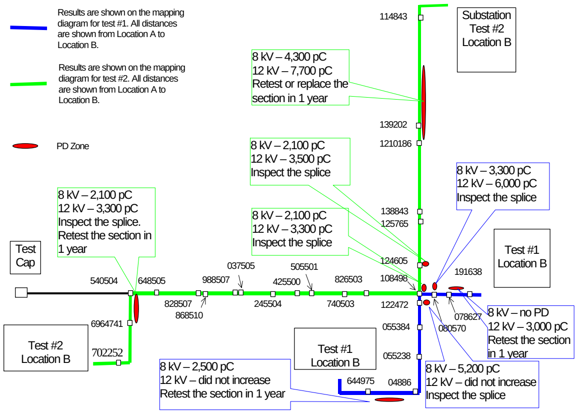


Figure 3.26 *Example of insulation condition assessment of a branched cable circuit. Based on the database experiences critical parts of the cable network are indicated.*

database and in knowledge rules which are of considerable value [18], see figure 3.26. But it is extremely important, that network owners co-operate.

Cable parts and accessories that were replaced on the basis of recommendations or due to unforeseen failures have to be dissected with the purpose to verify the recommendation and to understand ageing of the network. Such visual inspections are not required after each replacement. Especially in the beginning of replacement based on diagnostic testing results, such feedback is extremely important to obtain optimal knowledge rules and confidence in the results. These knowledge rules describe the effect of discharge activity on the behaviour of typical components, like splices, terminations and cable.

The knowledge rule is the key of the transfer of measured pC into the degree of severity of the measured defect, resulting in recommendations to repair or to exchange components.

3.9.2 Transmission Power Cables

As stated in section 9, knowledge rules are necessary to define criteria. The criteria are used to

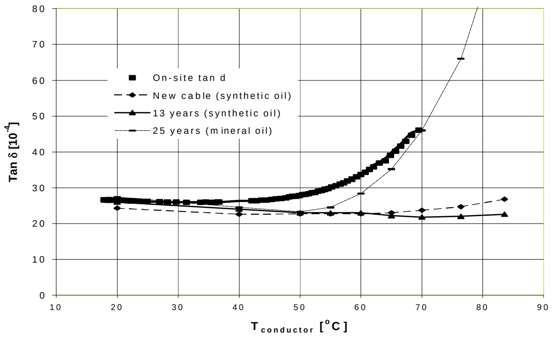


Figure 3.27 *Tan δ measurements, the maximum safe conductor temperature for the cable in service is 60°C.*

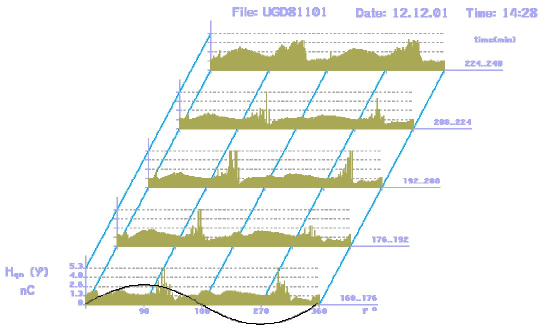


Figure 3.28 *Development of PD during accelerated ageing at 2.5U_0 of external gas-pressurized cable (failure after 240 minutes).*

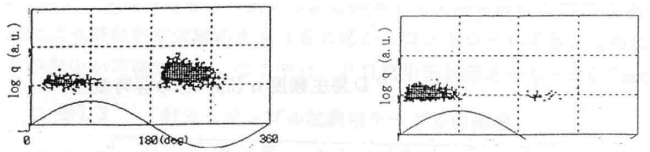
make an interpretation of measurement results, to define necessary actions, and to classify cables into a certain category. Two examples of development or improvement of knowledge rules will be given in the following.

Combination of laboratory research and field measurements to define the critical operating temperature of an 150 kV external gas-pressurised cable system:

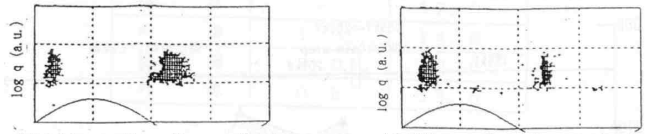
1. literature research and laboratory measurements on new and field aged cable to characterise the thermal behaviour of external gas-pressurised cable;
2. development of diagnostic program to apply measurements in the field;
3. on-site tan δ measurements together with heating of the cable conductor and temperature measurements;
4. interpretation of results to define guidelines for operation of the cable (e.g. maximum load capacity), see figure 3.27.

Accelerated ageing tests in parallel with tan δ and PD measurements on field aged cable to develop knowledge rules for critical tan δ and PD levels, and to estimate time to failure:

1. field aged cable is tested in the laboratory under high voltage (> 2·U_0);
2. during the accelerated ageing tan δ and PD are measured continuously;
3. after breakdown, the measured data are used to determine the fault cause (thermal or electrical?) and to derive several relations like PD / tan δ level ↔ remaining time to breakdown, PD pattern ↔ fault



(a) 3 min after voltage application (b) 5 min after voltage application



(c) 1.3 hours after voltage application (d) 13 hours after voltage application

Figure 3.29 *Changing of the* ϕ-q-n *pattern in the investigated 275 kV XLPE power cable joint specimen with*

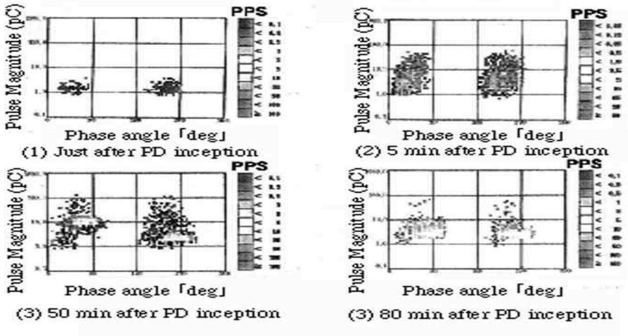


Figure 3.30 *The f-q-n patterns of 275kV XLPE power cable specimen due to a needle-shaped void*

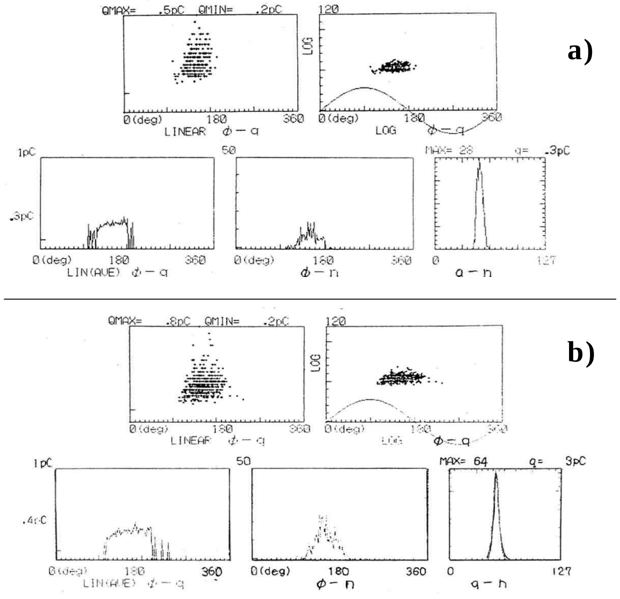


Figure 3.31 *The* ϕ-q-n *patterns of a 66 kV XLPE power cable specimen with a 6 mm cotton fiber at 70 kV (7 kV/mm); a) after 40 hours and b) after 315 hours voltage application.*

cause (see figure 3.28).

According to long experience of XLPE power cable utilization, most probable defects in XLPE power cables are selected to be knife scar in the outer semiconducting layer, needle shaped void in the insulation layer, and cotton fiber in the insulation layer.

In the following on the base of typical examples the PD behavior of those discharging defects in a cable joint insulation will be presented [29-33].

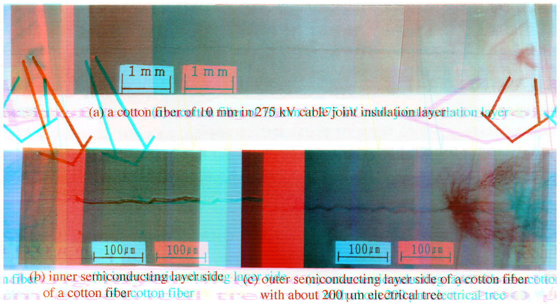


Figure 3.32 *Tree growth in the 275 kV XLPE power cable joint specimen with a 10 mm cotton fiber defect*

In figure 3.29 the ϕ-q-n patterns during the first 10 hours are shown. The PD pulse pattern changed rapidly and became almost steady state after 2-3 hours voltage application with keeping polarity asymmetry.

Typical ϕ-q-n patterns of a needle-shaped void is shown in figure 3.30. After 2 min of voltage application q-max reached 2 pC and then about 100 pC just before its breakdown after 81 min.

The PD occurrence of a cotton fiber in the insulation of a XLPE power cable joint specimen is shown in figure 3.31. Patterns after 40 hours (a) and 315 hours (b) show almost the same polarity asymmetry and the pulse occurrence characteristics at the voltage phase angle among 90-180 degree.
The presence of cotton fibers may result in treeing activity.
In figure 3.32 an example of a tree growth of about 200 μm is shown which was found in the outer semiconducting layer side of the cotton fiber.

3.10 CONCLUDING REMARKS

The discussion in the previous chapters has shown that

a) Studying fault statistic and providing visual inspection of disturbed components results in the identification of dominant faults. As most of these dominant faults will be PD related, PD measurements on power cables are an useful diagnostic tool;
b) Using PD diagnostics, important information can be collected in the PD ‘fingerprint’ of a cable section, containing PD inception / extinction voltage, PD levels, PD patterns and PD locations;
c) Standard interpretation rules which are used in a decision diagram, can be used for optimal decision-making on the insulation condition of a cable section;
d) Trend-analysis and databases are important tools for condition assessment

Despite the availability of different advanced PD diagnostics several interpretation pitfalls need to be mentioned also:

a) The main objective of a diagnostic measurement is to reach conclusions about the severity and location of possible defects or potential failures, based on the measured information. The degree of severity always relates to the question: *“Is this component going to fail soon and when will that be”?*
b) So far it was not possible to translate accurately the diagnostic information into remaining life estimation. Interpretation of the measured insulation condition is dependent upon the situation i.e. what is valid for one particular cable network situation is not necessarily applicable for another.
c) The network-owner has to accept a so-called “risk of failure”, based on the measured information and collected experience laid down in knowledge rules.
d) These knowledge rules prescribe the typical behaviour of materials or combination of different materials under a particular service regime. They are the basis of the recommendation criteria and they should avoid that all decision power about interpretation of measuring results has to be in the mind of the operator only.

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PART IV GAS INSULATED SUBSTATIONS

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4.1. GENERAL

With regard to PD occurrence in the insulation of gas insulated substations (GIS), systematic work has been performed within the scope of the Cigre WG 15.03 [1] Therefore, in this part, based on current experiences with PD measurements on GIS examples of on-line PD detection and evaluation are shown. Acceptance tests and periodic off-line measurements of SF_6 gas insulated test objects are restricted to measurement of PD inception voltage (in kV) and maximum discharge magnitude in pC and comparing these to the test specifications. The test objects may be GIS substations or GIS components such as switchgear, disconnectors and bus bars. If the permitted PD level is exceeded then the main goal of evaluation in GIS is to localize the discharge source. For periodic inspection it is also possible to use VHF/UHF sensors to measure PD signals on-line [9].

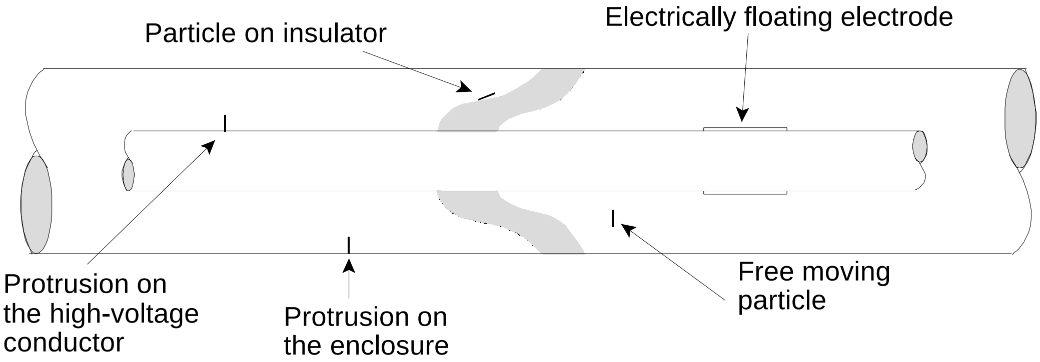

Figure 4.1: *Examples of possible insulation defects in GIS.*

The main objective of a PD measurement, whether it is based upon IEC 60270 or VHF/UHF, is to assist with recognition and localization of the discharging defect. To support the evaluation process during a measurement it is possible to use reference PD patterns of typical defects. Some examples of typical GIS defects are described below.

4.2. TYPICAL DEFECTS

Accidentally particles can be introduced into the insulation gas during operation of the GIS, in particular by moving parts inside a GIS or due to vibrations. Besides the influence of moisture, four important types of insulation defects are shown in figure 4.1 [10]:

1. Protrusions;
2. Particles fixed to an insulator surface;
3. Free moving particles;
4. Electrically floating parts.

4.2.1. Protrusion Fixed to the HV Conductor or Enclosure

Protrusions fixed to the conductor (HV protrusion) can be introduced during assembly, e.g. by scratching of parts or during service life, due to operation of contacts. Protrusions can be very dangerous because they locally increase the electric-field strength. It is known that protrusions can get corona stabilized at AC voltage and do not cause breakdown under steady state conditions. However, due to lightning or switching impulses, breakdown can occur [1].
Due to a smaller potential difference near the enclosure, protrusions fixed to the enclosure have less influence compared to protrusions fixed to the high-voltage conductor.
Fixed particles or protrusions at live parts, which are of critical size (1-2 mm), mainly reduce the required Lightning Impulse Withstand Level (LIWL). During the commissioning tests of GIS, 80% of the rated LIWL has to be verified. According to a CIGRE recommendation [4] this can be achieved for example by an AC voltage test with 36% of the rated LIWL. Additionally the 5 pC PD inception voltage shall not exceed 29% of the rated LIWL. For GIS ranging from 123 kV up to 550 kV the phase to ground service voltage is between 14% and 20% of the rated LIWL [5]. Therefore the service stress will not exceed 48% to 68% of the 5 pC PD inception voltage. For permissible uncritical protrusions, which have not been excluded due to the test requirements or service experience [5], either very low or no PD activity at all will exist in service. The size and shape of these protrusions and their insignificant influence on the dielectric strength will not change with time. Also according to experience, if there are undetected critical protrusions with stronger PD activity they will usually be reduced in size with time and the dielectric strength will be increased.

For this type of defects, over-voltages typically cause breakdown. The associated failure rate depends on the statistical occurrence of these over-voltages. However, there is no critical ageing since the dielectric strength is roughly constant with time.

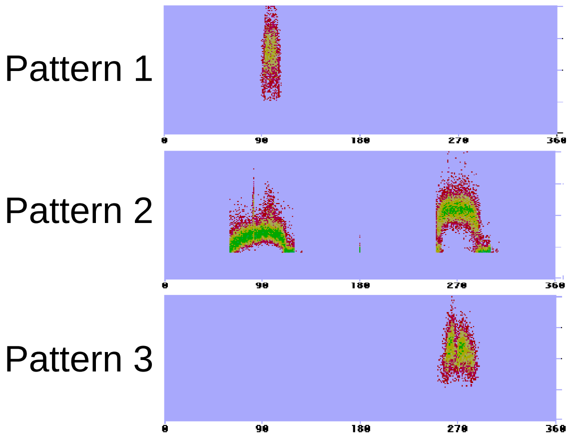

Figure 4.2: *Different types of patterns measured for protrusions fixed to the high-voltage conductor or to the enclosure.*

This category of defects also includes particles, which adhere to the surfaces of solid insulating materials. All of the related phenomena and consequences are the same as for protrusions at live parts, but in addition, chemical degradation of the insulation material may occur due to long-term PD activity. Therefore, it is of additional interest to consider whether such defects may cause progressive tracking and flashover. This and other tracking problems are considered in section 4.2.2.

The type of PD pattern for fixed protrusions depends on the PD process: inception, transition region (pattern type 2) or close to breakdown. The figure 4.2 shows typical types of PD patterns, which have been obtained. Table 4.1 shows the type of pattern measured for each stage in the PD process for fixed protrusions.

Table 4.1: *Three stages for protrusions fixed to the high-voltage conductor (HV-side) or fixed to the enclosure (LV-side), defined from inception (stage 1) to close to breakdown (stage 3).*

Defect	Stage 1	Stage 2	Stage 3
HV-side	Pattern 3	Pattern 2	Pattern 1
LV-side	Pattern 1	Pattern 2	Pattern 3

4.2.2. Particle Fixed to an Insulator Surface

Tracking is the formation of a visible path across the surface of solid insulating components like spacers. It is typically caused by test flashover. In severe cases it is a permanent conducting path usually of carbon, resulting from the interaction between surface discharges and spacer material. The tracking performance of the spacers depends on the spacer material, number of flashovers and their arc energy.

The arc energy is mainly emitted as thermal radiation and causes a partially conducting carbonaceous path on the surface of the insulator. In an SF_6 atmosphere however, the formation of free graphitic carbon is restricted. In the presence of free fluorine, the formation of a C-F compound is more likely than the formation of free carbon on the surface [6]. In most cases the carbon consists of isolated carbon particles. Experience has shown that such carbonised tracks either have high conductivity or they have an insignificant effect on the insulation properties.

A high-energy test flashover (500-2000 J/cm) can cause epoxy spacer damage with the result that both the surface resistance and the electrical strength are reduced. Independent of the materials, the specific erosion depth (erosion depth/flashover) is on average 10 μm with a tendency to a lower erosion pattern in the case of Al_2O_3 filled materials [7]. However, for modern insulating materials no reduction of the electrical strength occurs in the case of low-energy flashovers (<200 J/cm).

Particles adhering to spacers have not been found to cause tracks on spacers under long-term

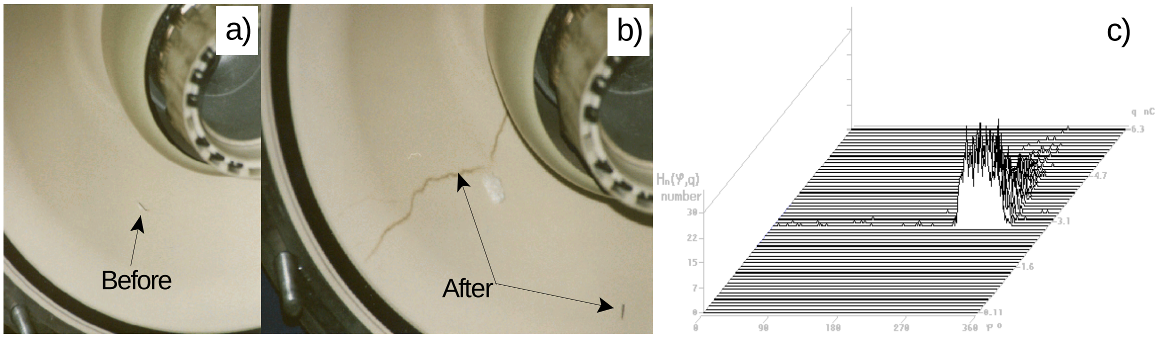

Figure 4.3: *a) Particle fixed to an insulator surface, b) the tracking on the insulator surface after flashover and c) the measured phase-resolved PD pattern.*

AC stress, unless the particles initiated flashover. For example, a small conducting particle is stuck to the surface of an insulator (spacer) as shown in figure 4.3a. Locally the electric field is distorted by producing a local field concentration. Consequently, the breakdown voltage along the surface is diminished and in some cases, discharges may occur before the breakdown occurs, see figure 4.3b. In figure 4.3c, the phase-resolved plot is shown.

In general it can be concluded that tracking phenomena remaining on surfaces of solid insulating components following successful high voltage testing are of no influence on the long-term performance of GIS.

4.2.3 Free Moving Particle

The defect that occurs most often in GIS and is most dangerous is the free moving particle [1]. A free conducting particle resting in contact with an electrode of an energized system is a localized perturbation of the conductor, which acquires charge and distorts the electric field. The shape, location and orientation determine the induced charge distribution [2, 3]. Depending on the accumulated charge of the particle and the applied electric field, an electrostatic force acts on the particle. The charged particle will lift as soon as the electrostatic force exceeds the gravitational force.

AC fields stimulate the movement of particles and they can cause breakdown when they approach live parts during their motion. Consequently mobile particles of critical size can reduce the AC Withstand Level (ACWL). They are regarded as being the most frequent and deleterious type of defects within the gas [8].
Under the influence of the electric field the particles are moving inside the enclosure. Frequently they move to natural particle traps (low field regions) and are stored there. Stimulation of this motion is often promoted by conditioning procedures during testing without effecting live parts. However, some particles may migrate from these natural traps during temporary AC over-voltages or due to vibrations caused for example by circuit breaker operations.
Moreover, all of these are considered as random phenomena, which may result in random failures but not in ageing. Mobile particles may also be caused by abrasion within switching devices, but malfunctioning switching devices only cause particles of a critical size (2-5 mm).

Large particles may also be caused during heavy circuit breaker (CB) operation but they should not be of a critical nature due to the CB design. These particles will be removed during repair or the obligatory maintenance procedures for such switching devices. In addition free particles can easily be detected by electrical or acoustic diagnostic methods [8] during testing or in service operation due to their high signal emission. Therefore free particles do not contribute to critical aging.

Once discharge activity has been found inside the enclosure, the major question, which arises, is about the dangerousness of the defect. In particular, important in the case of bouncing particles is the information about the movement of the particle.
As soon the particle is jumping between the electrodes, the dangerousness of the defect is serious.

Information gathered from the PD activity such as the UHF frequency spectra and phase-resolved PD patterns as shown in figure 4.4 can help in determining the particle movement. Table 4.2 gives an overview.

Table 4.2: *PD quantities and their characteristics used to evaluate PD measurements on GIS*

	PD pattern magnitude	PD pattern intensity	PD spectrum magnitude	PD spectrum intensity
stage I: electrical field $E_{\text{stage I}}$; particle starts to discharge	*low*	*high*	*low*	*low selective*
stage II: $E_{\text{stage II}} > E_{\text{stage I}}$; particle starts to move	*high*	*less*	*high*	*high and full*
stage III: $E_{\text{stage III}} > E_{\text{stage II}}$; Particle is jumping	*high*	*less*	*high*	*high and selective*

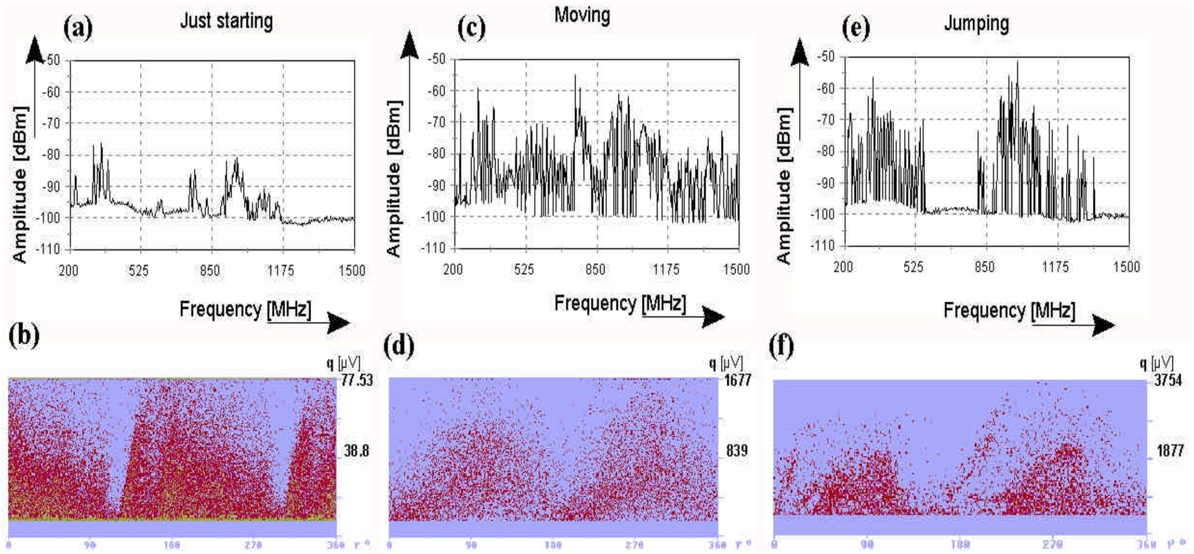

Figure 4.4: *Examples of PD based interpretation of different stage of a defect in GIS. PD spectrums, PD pattern of different stages of a bouncing particle are compared here.*

a.	*PD spectrum of stage I;*	*low amplitude,*	*low selective intensity*
b.	*PD pattern of stage I;*	*low amplitude,*	*high intensity*
c.	*PD spectrum of stage II;*	*high amplitude,*	*high and full intensity*
d.	*PD pattern of stage II;*	*high amplitude,*	*less intensity*
e.	*PD spectrum of stage III;*	*high amplitude,*	*high and selective intensity*
f.	*PD pattern of stage III;*	*high amplitude,*	*less intensity*

4.2.5 Electrically Floating Electrode

Deformed or incorrectly installed stress shields and floating components with poor electrical connections belong to a further category of defects. For this type of defect there is either no PD at all or very severe PD activity in case of floating components when they are periodically discharged.

If these discharges do not occur in highly stressed areas the dielectric strength is not affected, as long as the amount of the resultant dissociation products can be absorbed. In very rare instances incorrectly installed parts may move due to vibrations or mechanical impacts for example circuit breaker operations. These severe defects have to be eliminated by repair. Other such like or similar mechanical defects -for examples loosening bolts etc -which may lead to failures are beyond the scope of the report.

Floating parts in the installation i.e. electrodes imperfectly connected to HV potential may cause regularly repeating discharge groups of the same amplitude, see in figure 4.5 two groups: 5-7pC and 27-30 pC of PD activity.

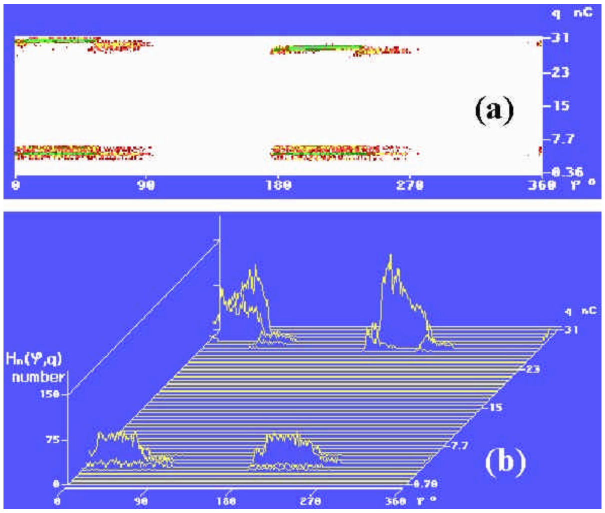

Figure 4.5: *Phase-resolved PD pattern of an electrically floating electrode in GIS; a), b) are different 3-D displays of the same PD pattern..*

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PART V GENERATOR STATOR INSULATION

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5.1. GENERAL

Both laboratory and field experience show that the PD activity of the stator insulation of a generator can be used as an indicator for breakdown, (figure 5.1). When investigating the correlation between PD measurements with the condition of the stator insulation system the following should be taken into account:

1. The main causes for breakdown of the insulation system of a stator are mechanical and thermal stresses. Furthermore, environmental / chemical effects can be important, especially for air-cooled generators and motors. Electrical aging of the insulation is of less importance for the lifetime of the stator insulation system. Since mechanical and thermal stresses are not uniformly distributed, the stator insulation system does not “age” everywhere at the same rate. The stator insulation system is as strong as its weakest link.
2. Generally, compared to other healthy high voltage components, such as power transformers and cables a healthy stator insulation system may produce internal discharges with measurable PD magnitudes while the repetition rates can be low. This is due to tolerance of mica-based insulation to PD. These internal PD’s in the stator-bars main insulation are not, generally, a cause for breakdown.

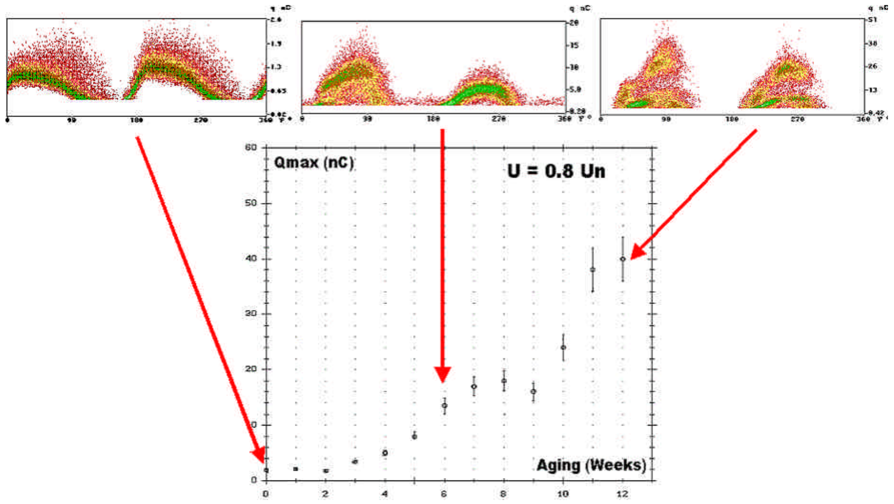


Figure 5.1 *Change in weekly measured off-line PD-level and PD pattern during an electrical aging test of a complete 15.7 kV stator coil. In week 12 one of its stator-bars suffered an electrical breakdown through the main insulation. The drop in PD-level in week 9 shows that the PD-level alone is not sufficient to track stator insulation degradation.*

3. It is currently not possible to accurately determine the size of a PD in a generator. The PD signal attenuates heavily during propagation. The amount of attenuation depends on the characteristics of the generator tested. This makes it difficult to correlate the measured size of the PDs with the aging of the insulation.

4. Currently, generator PD patterns are investigated for anomalies. The PD pattern of a healthy stator insulation system is known and is used as a reference. In many cases an initial measurement is performed on recent machines and is used as reference. On machines which may be several decades old initial measurements are made and a healthy PD characteristic is assumed. Any changes in the reference pattern could indicate a new active failure mechanism (for example: slot discharges, sparking between phases and delamination).
5. The PD behavior, and implications thereof, are also dependent on whether the insulation is an older thermoplastic system or a modern thermo-set insulation.

When PD phenomena can be successfully identified, we are capable of correlating the measured PD patterns with most active deterioration mechanisms in a stator insulation system. The next question is: “Now that we know what the problem is, how serious is it and what should we do about it?” To answer this question the correlation between the different degradation processes and occurrence of breakdown has to be charted. Generally, it is very difficult to investigate this relationship and in particular for complex components like generator stator windings. Adding to this complexity, very few machine operators run their machine until breakdown occurs. If a severe breakdown process is found using PD measurements, they tend to correct the problem rather than wait for machine failure.

5.2. CURRENT PRACTICE

Performing off-line PD measurements during stops is for most large generators operators common practice. Cigré WG 15.07 prepared and sent out a questionnaire asking operators what type of PD measurements they performed.

According to the responses obtained, the frequency response of the measurement equipment employed ranged from 10 kHz up to 350 MHz, although the most widely used frequencies were in the range 20 kHz to 30 MHz. Most of the systems were broadband. The question on sensitivity of the measuring equipment elicited a wide variety of responses from which no general conclusion could be reached. Organizations that provided a reply to this question quoted values in different units, i.e., pC, mV and dB, which renders direct comparisons between equipment invalid. The most common precaution observed, to ensure the reliability of the PD measurement, was to employ a PD-free high voltage power supply. Attention to calibration was also mentioned as being important by approximately half of the respondents, however only one organization specified that it was using a method based on IEC 60270. Consequently, one can assume that many organizations are using internal specifications. The lack of compliance with IEC 60270 is interesting considering the propensity of various apparatus-related standards to cite this document. One reason may be the caveat contained within IEC 60270 which cautions users about the problems introduced when testing objects with large inductive windings. The vast majority of off-line PD measurements are accomplished using high voltage capacitors ranging in value from 80 pF to 0.1 µF. Only in Canada was significant use of coupling devices, made from high voltage cables, observed.

According to the replies the majority of PD measurements are made without some form of protocol. Approximately 20% of respondents indicated that they employed a conditioning voltage to the test object prior to recording the PD parameters. This conditioning phase had a duration of one to five minutes or until “stabilization” had occurred. Unfortunately, what constituted stabilization is vague, although some responses indicated that the term refers to the PD, although without specifying a particular parameter, e.g., magnitude, repetition rate, etc.

Analog and digital techniques were used equally by the respondents to the survey. Regarding the use of the PD data to assess the condition of the insulation and make decisions thereof, while all respondents specified the parameters used and their use in decision support, very few replies provided any detail. That is, only two users of PD measurements defined levels of PD magnitudes or statistical quantities upon which pass/fail decisions are made. Regarding the exploitation of computer-based tools demonstrated that only limited use is made of these techniques. The vast majority of users, whether manufacturers or utilities, relying upon subjective knowledge.

All of the organizations polled in the survey believed that PD measurements were beneficial, although some stated that PD tools should remain the domain of the expert. One respondent indicated that although the experience of using PD measurements had been positive, the response from management of the company was mixed. Perhaps this response is a reflection of the expectations for PD measurements being set too high. These comments were based on experience amongst the organizations surveyed ranging from 3 to 45 years.

Approximately 45% of those organizations responding to the survey indicated that they followed IEC 60270 procedures when performing PD measurements. A further 35% were using the draft IEEE document, P1434, even though IEEE has only recently approved this guide. In some cases, both IEC and IEEE documents were being used. Several organizations relied upon internally developed procedures and guidelines. Clearly, decisions on the condition of the insulation of stator coils and bars are not made solely on the basis of PD parameters. Therefore, all of the respondents indicated that they employed other electrical diagnostic tools in addition to PD measurements. Principal among these techniques were dielectric loss (70% of respondents), insulation resistance and polarization index (70%) and visual examination (43%).

Finally, all respondents who expressed an opinion, answered that they would be in favor of developing a standard for PD testing of stator bars and coils.

The results of the survey demonstrate that PD testing is considered an important decision support tool by both utilities and manufacturers. Further, there is a strong academic interest in the field that will aid the development and understanding of PD measurements. There was also a consensus that there is a need to develop a standard, or at least, a set of guidelines for PD testing of stator bars and coils. However, the wide variety of methods currently employed which utilize different frequency responses, bandwidths and sensitivities render standardization difficult. Further, the survey provided little insight into the criteria used to assess insulation condition and make decisions thereof. However, all of the respondents indicated that they were using PD parameters to make some, unspecified judgments, on the integrity of the stator bars or coils.

Superficially, the lack of detail and the disparate equipment used appears to be at odds with the conclusion that some form of standardization is desirable. On one hand apparently increasing number of bodies do PD measurements on electrical machines for reasons of quality assurance and condition based maintenance as well as a tool for the evaluation of insulation systems improvement. These measurements are performed with quite different measurement systems and the evaluation employs various concepts. On the other hand there are no standards, regulations, or even guidelines how to do this. Thus leading to an increasing number of techniques and to the fact that there is practically no possibility to usefully compare measurement results. For these reasons a guide reflecting the techniques used and the experiences obtained on rotating machines which shows preconditions, possibilities and limits for specific types of measurements. Perhaps what is feasible, given the current state-of-the-art, is to use an approach similar to that adopted in IEEE 1434-2000 [25], in which the basic concepts and limitations of PD testing are discussed in such a way as to be permissive of all currently accepted PD measurement methods.

5.3. ON-LINE PD MEASUREMENTS

5.3.1 Difference Between On-line and Off-line PD Measurements

The first on-line PD measurements on generators were performed decades ago. Compared to off-line PD measurements there are two main reasons for performing PD measurements on-line:

1) On-line PD measurements can be performed while the generator is running. They can be performed any time, while off-line PD measurements can only be performed when the generator is removed from service. This makes on-line measurements much more cost effective. On-line measurements also provide the possibility to monitor the PD activity of a generator.

2) The operating conditions of the generator influence its PD behavior. Taking the generator off-line changes these conditions. Therefore, the PD activity during an off-line measurement is not the same as the generator in running conditions.

Compared to on-line PD measurements, off-line PD measurements have two major advantages:

1) It is possible to measure the PD activity at different voltage levels. This enables the operator to determine the inception and extinction voltage of PD activity and thereby helping him in the assessment of the stator insulation condition.

2) Generally off-line PD measurements have a higher signal to noise ratio and the influence of disturbance signals is lower. This results in a higher sensitivity, selectivity and resolution for off-line PD measurements.

Off-line PD measurements are performed on most large generators on a regular basis, once every 2-5 years. On-line PD measurements are a valuable addition to these measurements. A number of generator operators use on-line PD measurements to determine the need for off-line measurements.

5.3.2 Sensors for On-line PD Measurements on Generators

Presently, there are worldwide a number of widely accepted methods used to couple the signals associated with PD on operating generators. These include: couplers installed in the isolated phase bus (IPB), see below for a detailed discussion, capacitors applied on the circuit ring bus of hydraulic generators [24], inductive sensors on the neutral of the generator windings [26], and stripline antennae permanently installed in the stator winding [27].

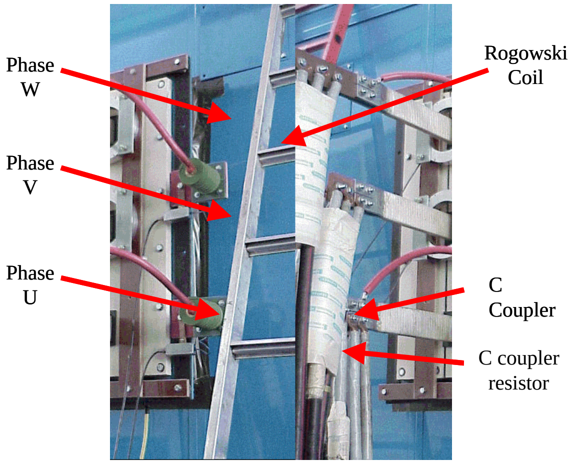


Figure 5.2 *Location of the different on-line VHF PD couplers on the generator tested. Phase U is equipped with a C coupler, consisting of a 80 pF capacitor in series with a 1500 W resistance. Phase V is equipped with a Rogowski coil and phase W is equipped with both a C coupler and a Rogowski coil.*

On-line VHF PD measurements can be performed using couplers which are installed in the IPB connecting the generator with the step-up transformer. There are three kinds of couplers: capacitive couplers, Rogowski coils and current transformers, of which capacitive couplers and *Rogowski* coils are the most used. For illustrative purposes, a series of tests employing such couplers are described.

To test the difference in behavior of a capacitive coupler and a *Rogowski* coil, a generator was equipped with both types of couplers. These sensors were installed on a 11 kV 55 MVA four pole generator on the outside of the generator casing, (figure 5.2). To test the performance of the sensors, the following set-up was chosen: phase U was equipped with a capacitive coupler, phase V with a *Rogowski* coil and phase W was equipped with both a *Rogowski* coil and a capacitive coupler. This set-up was chosen to investigate the influence of coupler type and electrical geometry on the sensitivity for PD measurements.
Detecting the PDs on phase U, which was equipped with the capacitive coupler, was not a problem. However, it was not possible to detect any PD's on phase V, which was equipped with the *Rogowski* coil. This made it interesting to see that both the capacitive coupler and the *Rogowski* coil on phase W were able to detect the PDs. Although the measured PD pattern was disturbed by corona from another phase, the PDs from phase W were clearly detectable, see figure 5.3 and figure 5.4.

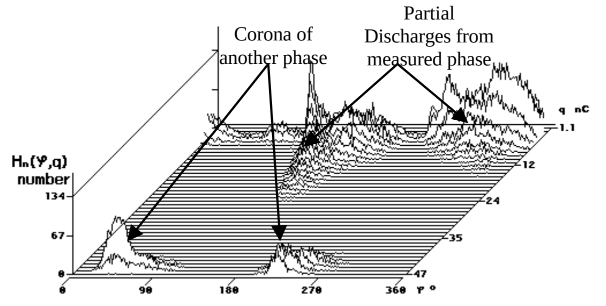


Figure 5.3 *PD pattern measured on capacitive coupler of Phase W.*

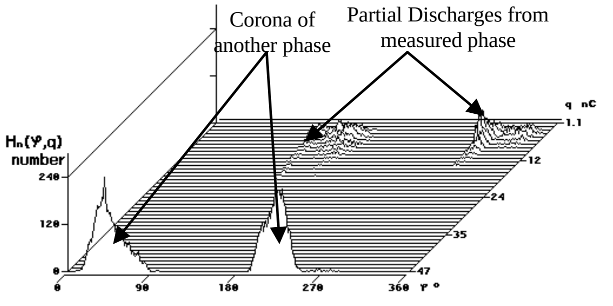


Figure 5.4 *PD Pattern measured on Rogowski coil of Phase W*

To understand why it is possible to detect the PDs on phase W and not on phase V using the *Rogowski* coil the propagation path of the PDs is investigated. The equivalent electrical circuit for the PD propagation path for phase V is shown in figure 5.5.

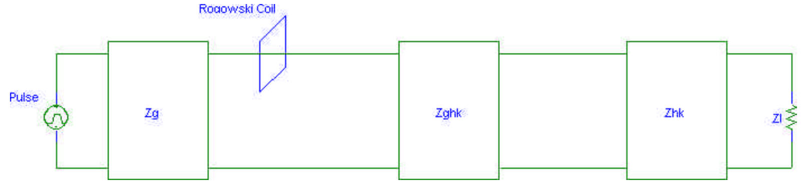


Figure 5.5 *Equivalent circuit for a partial discharge. Z_g is the transmission line represents the generator, Z_{ghk} is the far-field coupling between generator and high voltage cable, Z_{hk} is the transmissionline representing the high voltage cable and Z_l is the load.*

The shield of the cable connecting the generator with its load is not directly connected with the generator casing. Since the measurements are made at relative high frequencies, there is an air coupling between generator and the cable, represented by Z_{ghk}. This impedance Z_{ghk} is very large compared to Z_g and causes the current through the *Rogowski* coil to be very small compared to the original PD current inside the generator.

The capacitive coupler is placed between generator and cable and is connected to ground at the nearest points on the generator casing. The equivalent circuit changes into the one shown in figure 5.6.

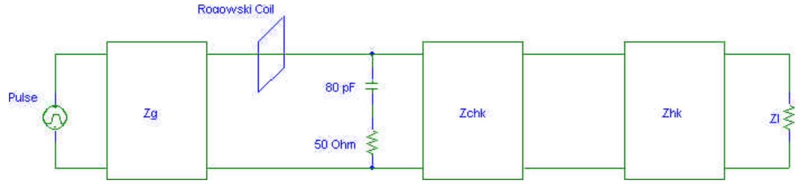


Figure 5.6 *Equivalent circuit for the propagation path of a partial discharge. Z_g is the transmission line representing the generator, Z_{chk} is the far-field coupling between C coupler and high voltage cable, Z_{hk} represents the high voltage cable and Z_l is the load.*

The impedance of the capacitive coupler is (a lot) smaller than the impedance Z_{ghk} of the far-field coupling between generator and cable. Consequently the PD current through the *Rogowski* coil increases significantly. The PD pulse is now detectable using the *Rogowski* coil.

This experiment shows that, when deciding which type of coupler to use, comparing C couplers and *Rogowski* coils can not be done without investigating the propagation path(s) of the PD signals. In some cases *Rogowski* coil couplers will have a higher sensitivity and in others situations C couplers will. This experiment shows that selection of the type of coupler should be done after a thorough investigation of the propagation properties of the PDs in that particular setup.

From a machine-users perspective, performing such an investigation is not very practical. The critical issue is cost and complexity of installation. As basic guidelines it is better to look at the admittance of the load of the generator. If the admittance of the load is high, for example a cable connection, a R*ogowski* coil could outperform a capacitive coupler and if this admittance is low, for example an air line, then it is likely that a capacitive coupler will be the sensor of choice. The use of striplien antennae does not require these considerations, however, careful attention should be paid to the consequences of the limited "view" of the winding such sensors afford. Many of these issues are discussed in IEEE 1434-2000 [25]. Although installing couplers without a thorough investigation could very well result in sub-optimal measuring results, there are several thousand coupler installations and successful implementations of PD monitoring systems that have been accomplished without such investigations.

5.3.3 Influence of Propagation on Interpretation

Propagation effects have a major influence on VHF PD measurements [16]. If the geometry of the three phases of a generator are not identical, the pulse propagation and accompanying oscillation frequencies in the three phases are not the same. I.e. if the propagation is not the same for each phase, than the measured PD pattern can not be compared in a direct manner. An example of this phenomenon was found on a 170 MVA generator.

Phase 3 of this particular 170 MVA generator has a significant different PD level than the other two phases. The cross talk was for some frequencies even higher than the phase's own PD-level. To check if propagation effects could be responsible for these results time-domain measurements were performed on sensors on different locations in the IPB.

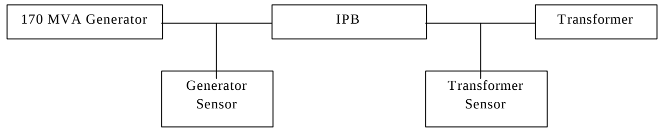


Figure 5.7 *Location of the capacitive sensors used to investigate the influence of propagation effects*

The IPB of this generator was equipped with two capacitive couplers per phase. On each phase a capacitive coupler was located at the generator side of the IPB and one was located at the transformer side of the IPB, see figure 5.7.

If the propagation path between the two sensors is identical for each phase, than the transfer function of a signal traveling from the generator to the transformer between the transformer and generator sensor should be identical as well. The transfer function between the two sensors is defined by equation 5.1.

$$H(f) = \frac{U_t(f)}{U_g(f)}$$

Equation 5.1 *Transfer function between the two sensors*

In this equation $U_t(f)$ is the fast Fourier transform (FFT) of the PD signal measured at the transformer sensor and $U_g(f)$ the FFT of the same signal measured at the generator sensor. The transfer function H(f) should be the same for each phase for comparing their PD level with each other.

Figure 5.8 contains the PD patterns measured on the three phases as well as the transfer functions of the sensors. The figure clearly shows that the transfer function of phase three differs significantly from the transfer functions of phase one and two. This confirms that propagation effects are the cause for the generator showing a different PD level in phase 3.

In the case of this particular 170 MVA generator setup the difference in propagation can be attributed to the physical shape of the IPB itself. The IPB of phase three is shorter and contains fewer corners than the IPB of phases one and two.

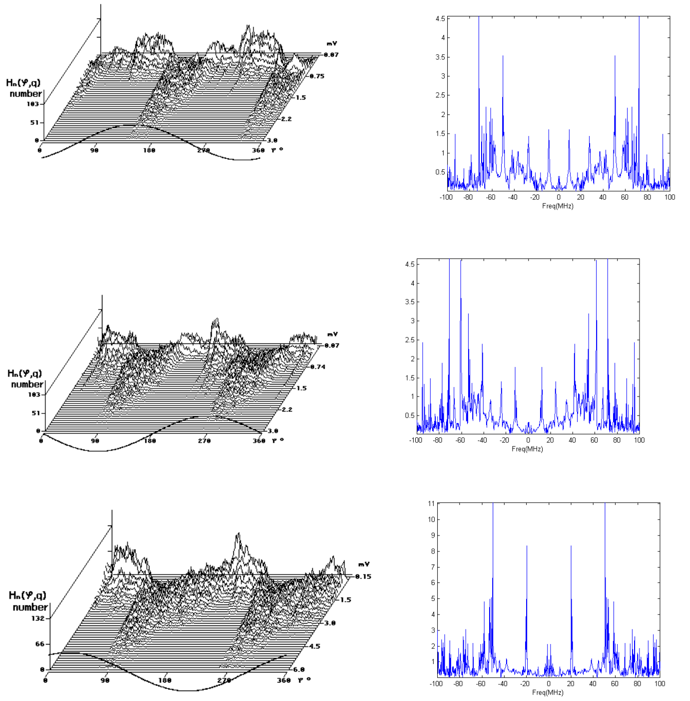


Figure 5.8 *Influence of propagation on the PD pattern. The PD patterns are shown on the left and the transfer function of the sensors is shown on the right. From top to bottom are shown phase 1, phase 2 and phase 3.*

5.4. ON-LINE PD IDENTIFICATION

Compared to off-line PD measurements identifying PDs from the pattern of an on-line PD measurement is relatively difficult. Next to the phases own PDs an on-line measured PD pattern can contain more severe disturbances. The main sources of electrical interference in generating stations are: the excitation system (sub-section 5.4.1), broadcast signals (sub-section 5.4.2), arcing and PD in the IPB, and arcing from sources such as welding operations, precipitators, etc. The latter two sources can have frequency content and other behaviour that are similar to PD originating in the stator winding.

As an example of the challenges represented by these noise sources, only three out of eleven generators, which are tested regularly, have an almost disturbance free PD pattern. The disturbances on the other nine can be divided into six groups: thyristor pulses, radio signals, corona, cross-talk, PDs from other HV equipment and random pulses of which the source is unknown. The interpreter of an on-line PD measurement should be able to distinguish the phase’s own PDs from these disturbances.

5.4.1 Thyristor Pulses

Figure 5.9 shows a thyristor distorted PD pattern, which was measured on a 300 MVA generator.

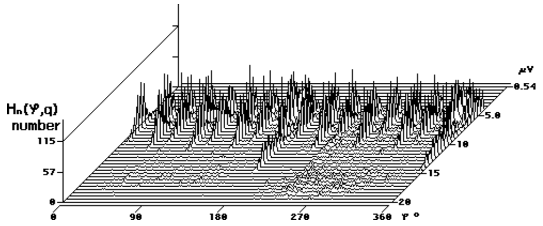


Figure 5.9 *Thyristor pulses distorted on-line VHF PD measurement of an 300 MVA Turbo Generator with centre frequency Fc=4 MHz and bandwith BW=300 kHz*

The thyristor pulses shown in figure 5.9 are caused by the AC / DC conversion of the rotor current. They can be identified as being from this particular AC / DC conversion unit, because the number of pulses is identical to the number of thyristors switched during a power cycle. In our experience thyristor pulses tend to have their largest influence on VHF PD measurements below 4 MHz. This value will vary depending upon the excitation system, the measurement technique and the length of the excitation leads.

5.4.2 Radio Signals

At three from the eleven power plants an AM-radio signal couples into the IPB and can be received at the VHF sensors. The resulting “PD Pattern” is very distinguishable from PDs, because it shows up as a band of PD’s in the PD pattern, see figure 5.10.

5.4.3 Corona

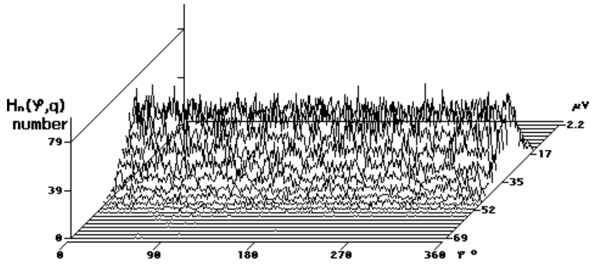


Figure 5.10 *Radio distorted on-line VHF PD measurement of an 300 MVA Turbo Generator with centre frequency Fc=16 MHz and bandwith BW=300 kHz.*

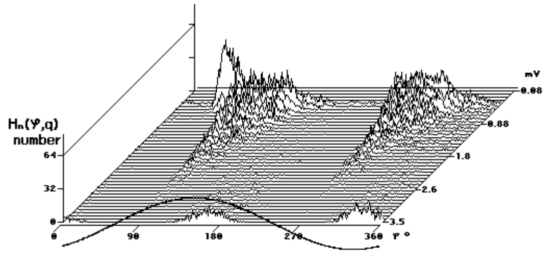


Figure 5.11 *Corona on a measured PD pattern of an 125 MVA generator with Fc=12 MHz and BW=300 kHz*

Corona has a unique PD pattern, which differs from that of generator produced PD’s. A corona pattern shows PD’s around the minimum and / or maximum of the power cycle and tends to have a fixed level. Corona can be identified and neglected prior to the interpretation of the generators own PDs. An example of corona disturbance is shown in figure 5.11.

5.4.4 Cross-talk

Cross talk from PDs of other phases on the PD pattern of the measured phase can be recognized using the power frequency phase-shift of the cross talk. Cross talk from phase U to phase V will have a phase shift of 120°. Normally the cross talk is smaller than the phase's own PDs. Is the cross talk larger than the phases own PD level, than the start of the search should be whether propagation effects could be the cause. An example of cross talk is given in figure 5.12

5.4.5 PDs from other Equipment

If PDs are detected with an on-line PD measurement does not necessarily mean that they originated in the generator. In one of the eleven regular measured locations, the measured PDs do not originate in the generator. It was found that the PDs occur in the generator circuit breaker, which resides in the IPB between generator and step-up transformer. The measured PD pattern is shown in figure 5.13. In this case it was possible to determine the cause of the PDs: a loose contact.

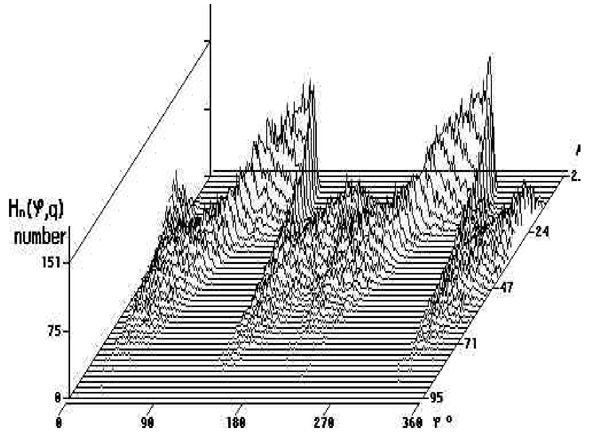


Figure 5.12 *Cross-talk of partial discharges of another phase on the PD pattern of the measured phase of an 750 MVA generator with Fc=20 MHz and BW=300 kHz.*

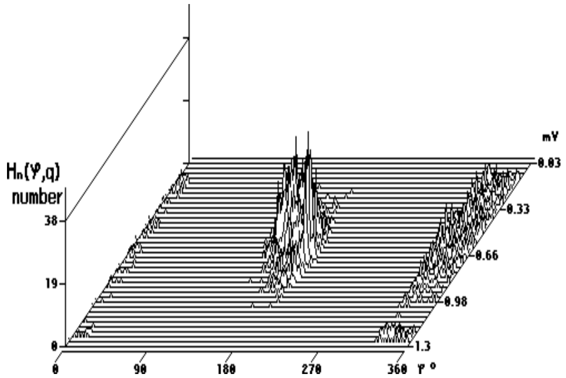


Figure 5.13 *Disturbed PD pattern, which was measured on a 625 MVA generator at Fc=75 MHz en BW=300 kHz*

5.4.6 Noise Rejection from the PD Pattern

Eliminating noise from the PD pattern can be done using a filter method. The most common methods to filter out the disturbance signals from the PD pattern are: a) an antenna measured the disturbance signals and b) two PD couplers are used to determine if the measured pulse originated in the generator or from the net. More information about these de-noising techniques may be found in [5],[6] and [7]. Under development are methods, which use the actual shape of the PD pulse. The shape is used to extract a number of features, which can be used to differentiate between disturbance pulses and actual PD's. An example of one such method is given on a actual measurement on a 650 MVA turbo generator. Figure 5.14 gives the phase resolved PD pattern of a 650 MVA turbo generator. In this PD pattern the actual PD's are just above the noise level. In addition to the PD's there are two types of disturbance pulses present, types A and B. Recording the PD pulses in time domain and extracting the typical time and typical frequency provides for the disturbance pulses and PD's for different phases of the generator, provides figure 5.15. This figure shows the clear clustering of the pulses originating from different signal sources. See [18, 20, 21] for more information on this method.

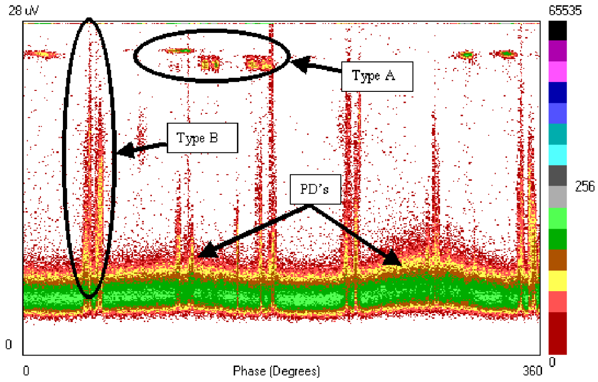


Figure 5.14 *PD pattern as measured on a 650 MVA generator using an on-line VHF PD measurement at Fc=55 MHz and a bandwith of BW=300 kHz.*

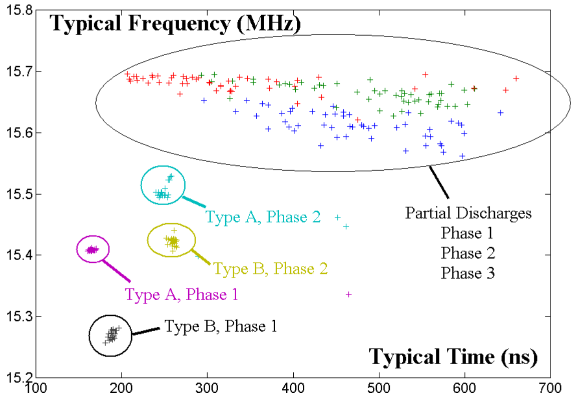


Figure 5.15 *Typical time and frequency of the disturbance and PD pulses on different phases on the same 650 MVA generator as in figure 5.14.*

Alternatively, the electrical interference signals can be eliminated, or minimized, by means of coupling schemes which reject the noise prior to being acquired by the recording device. One example of such a technique is the use of permanently installed capcitors in the circuit ring bus structure of hydraulic generators [24]. By relying on the very high frequency content of a PD pulse, and the fact that it takes a finite time for electrical pulses to travel along the generator circuit riung bus, common-mode electrical interference from the power system is eliminated. In another technique [27], stripline antennae, installed in the stator winding, are used to detect the high frequency content of the PD pulese which are analyzed in terms of pulse shape from which a noise rejection algorithm can be implemented.

5.5. INTERPRETATION OF ON-LINE MEASUREMENTS

After ensuring that the signals are the generator's own PDs they are interpreted. The interpretation method developed classifies a generator as being in one of the following four categories:

1. Insulation ok	No defects are detected
2. Insulation ok?	There might be a defect present in the stator insulation
3. Insulation not ok?	There is probable a defect present in the stator insulation
4. Insulation not ok	There is a defect present in the stator insulation

The interpretation method makes a statement about the possible presence of a defect or not. Detection of a defect implies any degradation process, which will lead to premature breakdown of the insulation system and is detectable using on-line VHF PD measurements.

If a defect is detected, further investigation has to be done to identify the defect. In some cases the type of defect can be determined using on-line PD measurement , E. Gulski et. al. [2]. For certain types of suspected deterioration mechanisms, e.g., loose windings, load variation of the generator can be performed to provide further evidence of the existence of the defect. Further, this diagnosis may be used so that, if necessary, the operating mode of the machine can be modified until a maintenance outage can be scheduled. Even if the defect can be identified using the on-line PD measurements it is advisable to perform different kind of tests (off-line PD, tan ä, polarization grade, visual inspection, etc. etc.) on the generator to confirm the result. This “second opinion” is needed to make sure the, normally very costly, preventive action is not done in vain.

To classify a stator insulation system into one of the four categories, an example of a decision tree is shown in figure 5.16. This decision tree is based on three tests: pattern shape, trend analysis and phase comparison. Each test gives a “pass” (ok) or “no pass” (fails) result, that will guide the user to a classification of the condition of the stator insulation.

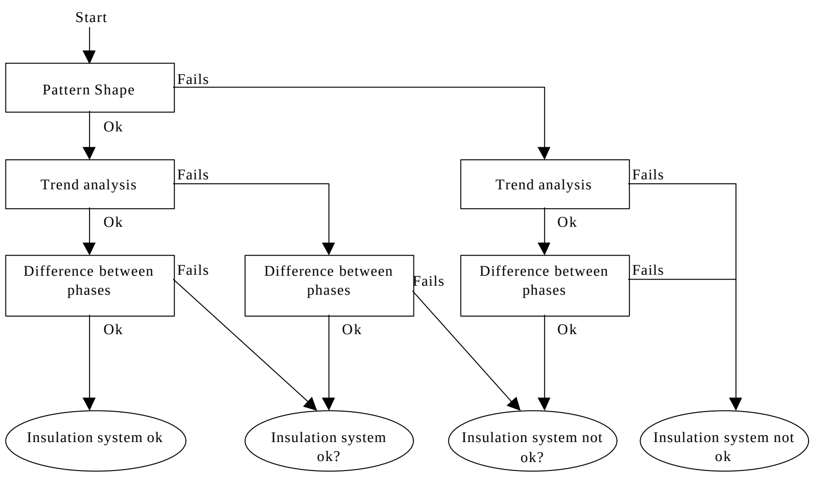
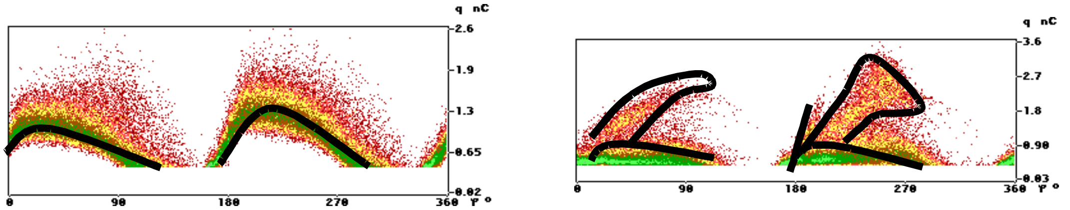


Figure 5.16 *Example of decision tree containing the three tests to categorize the generator into four possible classes.*

5.1 Pattern Shape

Figure 5.17 shows the PD pattern of a stator in a healthy condition and the same stator with a defect present. The shape of the PD pattern clearly changes due to this particular kind of defect. Different kinds of defects have different kinds of PD patterns shapes, G.C. Stone et.al. [4].



Discharge pattern of a generator in a healthy condition

Discharge pattern of a generator with a defect present

Figure 5.17 *Discharge pattern of a generator in a healthy condition and a discharge pattern of the same generator with a defect present after electrical aging.*

An overview of different kind of phase resolved PD patterns and their meaning is given in figure 5.18. When using figures like these one should always realize that these kinds of overviews do not really work well for on-line PD measurements. There are two reasons for this:

1) The applied voltage is static in on-line conditions
2) The PD pulse attenuates during propagation through the stator insulation

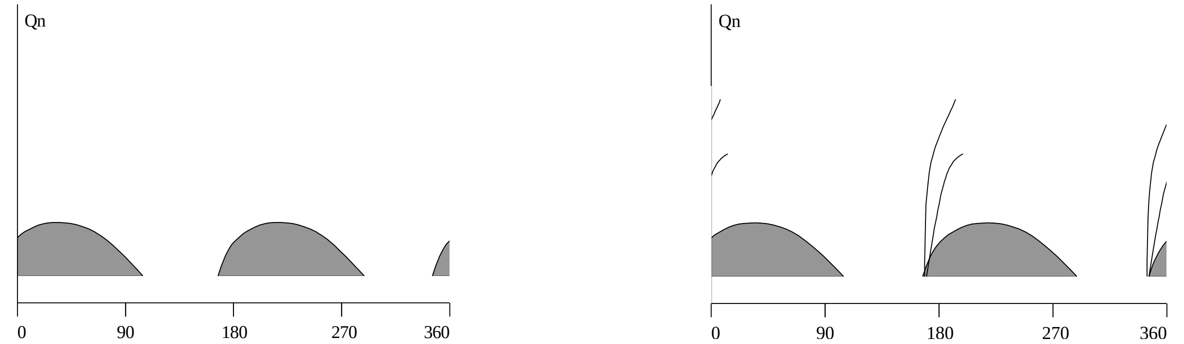
The PD pattern shape depends on the applied voltage. If the applied voltage increases, a void of normal size for low voltages will show the PD pattern shape of a large void. If the voltage is increased even further, the gap or severe degradation pattern might emerge.

The PD pulse attenuates during propagation through the winding. An example of this is severe degradation caused by slot discharges. If the location of the slot discharges is far away from the terminals of the generator, than the clouding pattern will hide in the pattern of the remaining healthy part of the stator insulation system.

The interpreter of the measurement has to decide if the PD pattern is that of a healthy insulation system or not. This test is the most important of the three tests and also the most subjective.

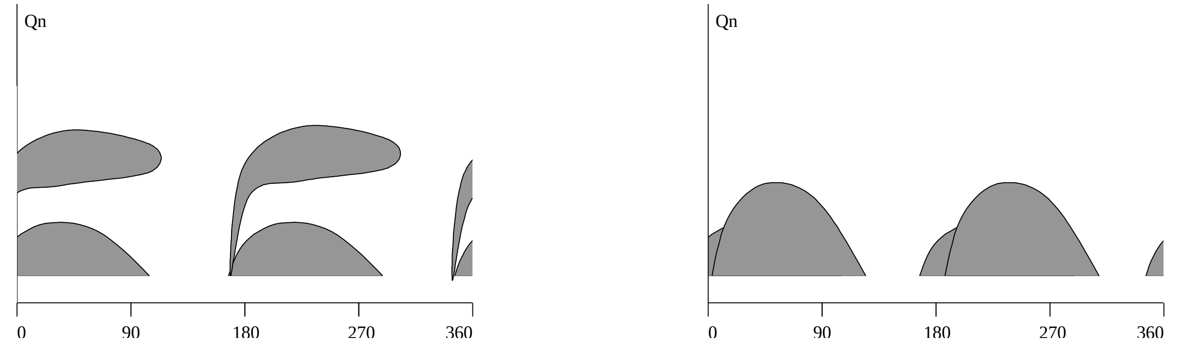
Different interpreters could interpret the PD pattern shape differently.

Several algorithms are available, which predict on the basis of PD pattern shape, what kind of defect is present. These algorithms may work well under controlled laboratory experiments, where no disturbances are present.
Using them on generator field measurements may be less successful, due to disturbances and the sometimes low signal to noise ratio, as well as the possible existence of several simultaneously occurring defect processes.



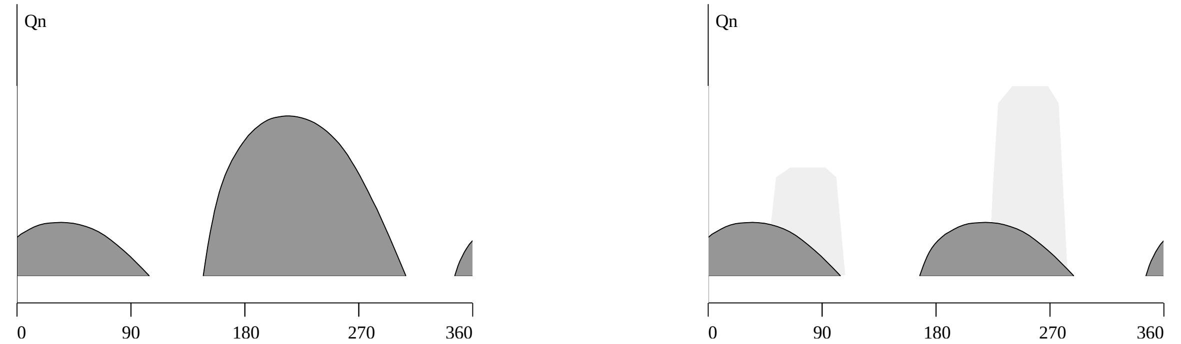
Two symmetrical low amplitude humps: small voids (healthy insulation system)

One or multiple lines of PD pulses at the start of the PD pattern: large voids (for example starting delamination or slot discharges)



Clouding, formation of a cloud above internal PD level: severe degradation or gap discharges (for example delamination, slot discharges or phase-core discharges)

Phase shift of PD pattern: PD activity between two phases of the generator



A-symmetry: Electrode bounded voids: PD activity typical for discharging defects in the stator bar main insulation

Low concentration PD near 90° and 270°: Surface discharges (for example end winding discharges)

Figure 5.18 *Example of a number of typical PD patterns and their cause.*

The interpretation method described uses the phase resolved PD pattern. It is also possible to use the Partial Discharge Height Distribution representation to do this. See figures 5.19-5.20 for a number of examples of PD height distributions of stator insulation systems. The PD-pulse height distribution detected on a single phase of healthy and damaged turbo-generators are reported in a linear plot, in semilog-plot and in Weibull graph. In particular, the inception of a new PD phenomenon turns the straight line of the Weibull graph, representing a good condition, into a more complex curve due to the combined pattern of simultaneous PD phenomena.

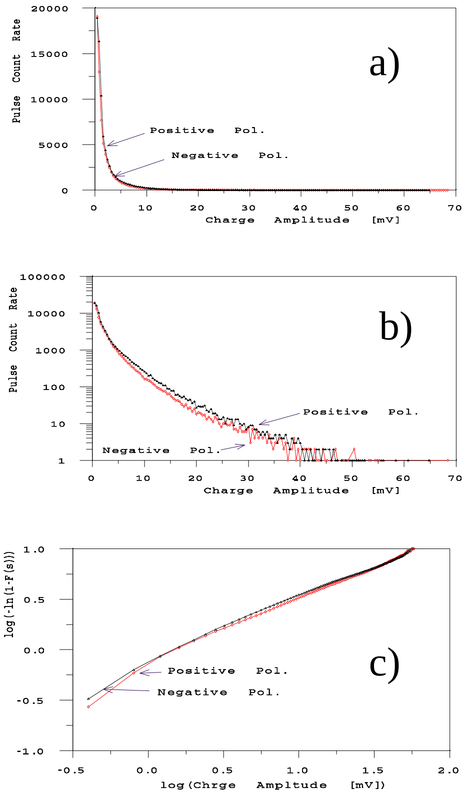


Figure 5.19 *Experimental Partial Discharge Height Distributions detected on a single phase of a 107 MW 12 kV thermosetting insulated turbo generator winding at rated voltage of 12 kV. PDHD reported on normal (a) and semi-log (b) plot and on the Weibull graph (c). Defects: internal micro defects. Diagnosis: good conditions.*

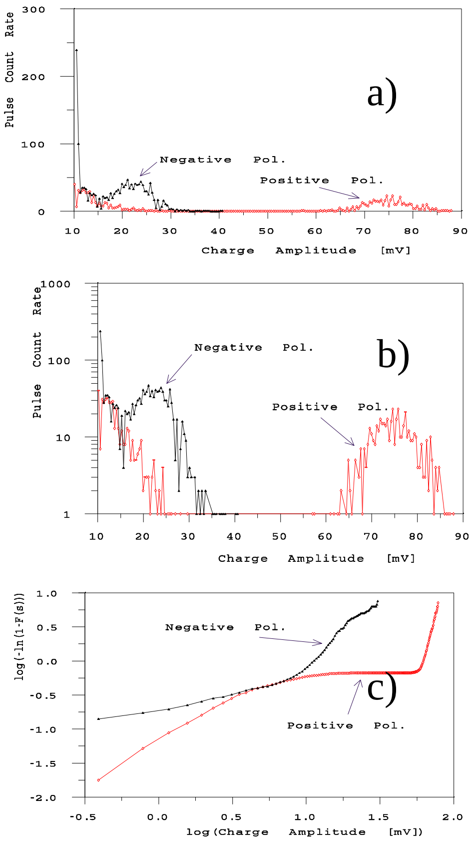


Figure 5.20 *Experimental Partial Discharge Height Distributions detected on a single phase of a 46.6 MW, 15 kV thermosetting insulated turbogenerator winding at rated voltage of 10 kV. PDHD reported on normal (a) and semi-log (b) plot and on the Weibull graph (c). Defects: macro-void inclusion due to defective impregnation. Diagnosis: maintenance.*

5.5.2 Trend Analysis

Performing on-line VHF PD measurements on a regular basis makes it possible to perform trend-analysis of the PD level. A sudden and permanent change in PD level could indicate a defect is present or a “sleeping” failure mechanism has become active. Trend analysis of the level of off-line measured PDs has been used successfully for the past decades.

The load and temperature of a generator influence the measured PD level. An example of the load influence on the PD activity is given by E.Binder et.al. [3]. For optimum results the on-line VHF PD measurement should be carried out under equal circumstances. In reality this could be hard to obtain, since it could be very costly to adjust the power generated. Please see IEEE 1434-2000 [25] with respect to the tolerances required to effect reliable on-line PD measurements. However, seasonal components to trend might be filtered by appropriate algorithms [22].

An example of a trend analysis is shown in figure 5.21. The figure shows the VHF PD-level at 30 MHz and 50 MHz on a 170 MVA generator from 1995 until 2000.
The figure shows the characteristic behavior of the VHF PD-level due to changes in operating conditions. To determine if a generator fails this test, the PD-level should be outside the standard deviation of the average PD-level. For this stator winding, these calculations are given in table 5.1.

	30 MHz	50 MHz
Average	-38 dBm	-44 dBm
Standard deviation	5 dBm	4 dBm
Relative “Error”	13 %	9 %

Table 5.1 *Average PD-level, the standard deviation and the relative measurement error of the VHF PD-Level of the generator*

If the PD-level is outside the standard deviation interval for more than 50% of the frequencies without a known cause, than the generator fails this test. A known cause could be that the generator is operating under very different operating conditions compared to earlier measurements, for example under zero load conditions.

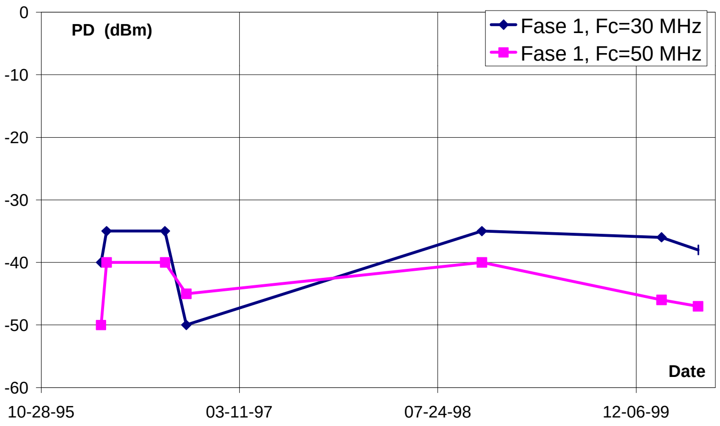


Figure 5.21 Trend-analysis of the VHF PD-level of an 125 MVA turbo generator. One phase as measured at two frequencies.

5.5.3 Phase Comparison

For off-line PD measurements the PD levels and patterns of the three phases are often compared. This is done based on the assumption that most defects occur on a single phase of the generator and not on all three at the same time or to the same extend. An example of this is given in [14].

How a phase comparison test is performed the measurement results of a measurement on a 125 MVA generator are used as an example. The PD-levels of the three phases of this generator are shown in table 5.2.

Freq	Phase U	Phase V	Phase W
12 MHz	1,2 mV	1,3 mV	1,8 mV
30 MHz	300 µV	250 µV	430 µV
50 MHz	130 µV	110 µV	90 µV

Table 5.2 *PD-Level as measured on different frequencies and phases of a 125 MVA generator*

For a generator in good condition an equal PD level for each phase could be expected. Normalizing the PD-Level of each phase per frequency will show a 33% contribution of each phase to the total amount of PD. By averaging the contribution of the phases for different frequencies the error in the measurements is considerably improved. For the measurement shown in table 5.2 this will result in table 5.3.

Freq	Phase U	Phase V	Phase W
12 MHz	28 %	30 %	42 %
30 MHz	30 %	26 %	44 %
50 MHz	39 %	33 %	28 %
Average	32 %	30 %	38 %
Deviation from 1/3	-1 %	-4 %	5 %

Table 5.3 *Phase comparison test of the example generator*

If the deviation of the average of one of the three phases is larger than 8 %, than the generator does not pass this test. Using the values from table 5.3, normalizing the PD-Levels and consequently calculate the averages over the three phases provides table 5.3. No phases have a larger difference than 8 %, the largest is 5 %, and thus this generator passes this test.

5.5.4 Operating Conditions

The operating conditions of the generator could have an influence on the PD activity of that particular generator. Some known operating conditions, which have an influence are:

- Power Output	If the PD level depends on the power output of the generator, then the probable cause is loose windings. Meaning that the statorbars have enough room to move in their slots due to the statorcurrent induced magnetic force.
- Temperature	The temperature could have an influence on the PD activity. The PD-level may increase, decrease or stay equal with a temperature change. Temperature can also ignite a PD source.
- Humidity	It has been shown that humidity sometimes has an influence on the PD activity in the end-winding region of a generator [23].

A detailed discussion of operating condition effects on PD behaviour is given in IEEE 1434-2000 [25]. An example of an activation of a PD source by temperature is given in figure 5.22.

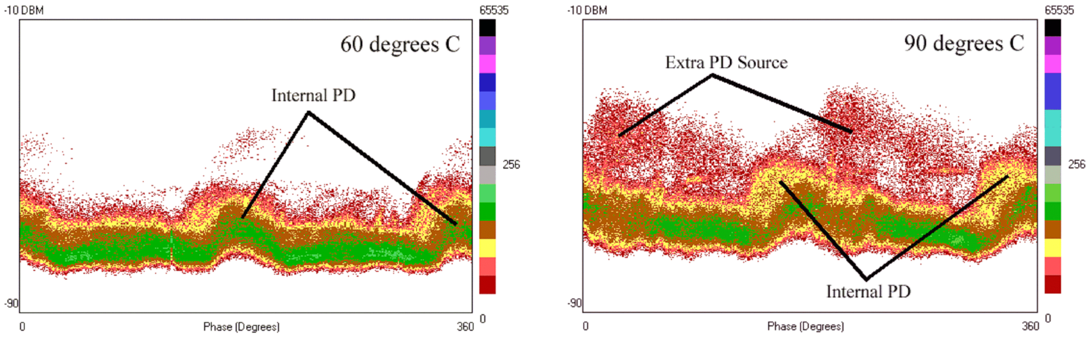


Figure 5.22 *On-line measured Phase Resolved PD Pattern with the generator at two different temperature. This measurement was performed on a 150 MVA closed air-cooled full VPI turbo-generator.*

The PD pattern measured on this generator already shows typical bunny pattern behavior, indicating relatively large voids in the insulation system. The extra PD source could be identified as initiating surface discharges on the end-windings of the generator.

5.5.5 Database

Worldwide there are a number of databases containing the results of thousands of on-line PD measurements. There is a move, especially in the US and Canada, to compare new, or single, on-line PD measurements with the contents of this database [28]. In this method, if the new, or single, measurement results in PD levels that are higher than those measured for generators of the same voltage class, age and operating mode in the database, then this might indicate a defect.

From a purely theoretically point of view this is not a sound method to determine if a generator is in a bad condition. This is because the measured PD-level is not the same as the PD-level of the insulation system of the stator. At present there are no methods to determine the relationship between the actual PD-level inside the stator insulation system and the measured PD-level. This is the case for off-line PD measurements, let alone for on-line PD measurements. From a practical point of view this approach does hold water. As with other methods used for interpretation of on-line PD measurements there is a margin of error, e.g. the method predicts a bad insulation system while the insulation system is in a good condition or the method predicts a good insulation while the insulation system is in a bad condition. If this “margin of error” is charted and quantified this interpretation method could be a valuable addition.

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