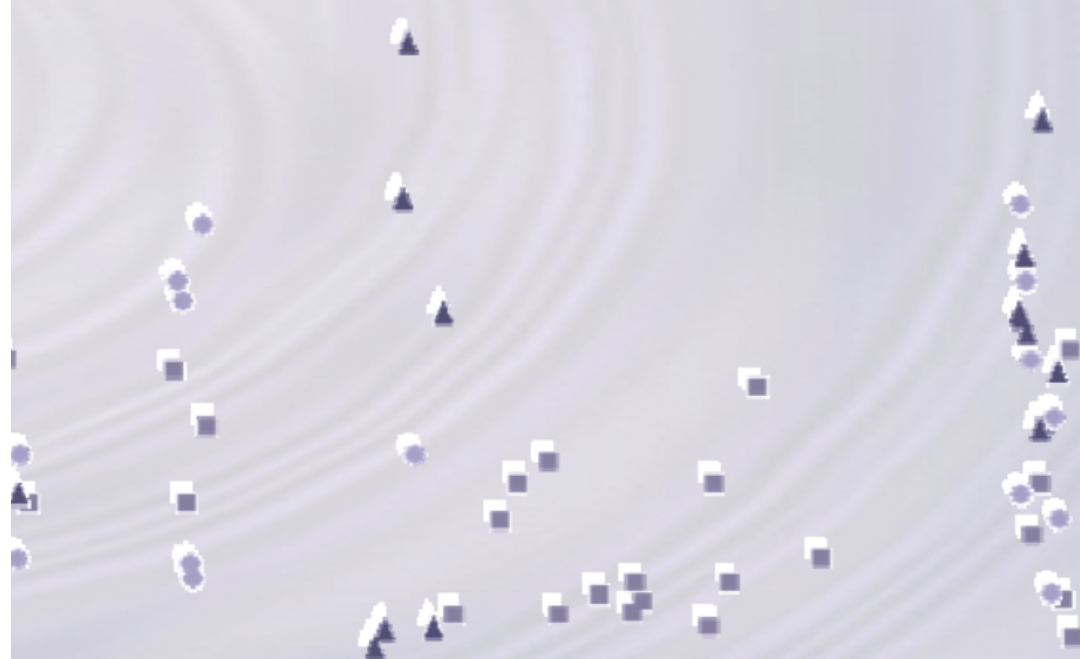


CONDITION ASSESSMENT OF POWER CABLES USING PARTIAL DISCHARGE DIAGNOSIS AT DAMPED AC VOLTAGES



FRANK WESTER

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SUMMARY

CONDITION ASSESSMENT OF POWER CABLES USING PD DIAGNOSIS AT DAMPED AC VOLTAGES

This thesis will focus on the condition assessment of one of the most distributed parts of the power supply system: the distribution power cable network. The distribution power cables have a very critical function in the distribution of electrical power over regional distances. The majority of the outages in the power system are related to the distribution cable network. The reasons for the failures in cable systems are for more than 60% related to internal defects, while the rest is related to external influences.

Analysing the frequently occurring defects types and the degradation modes of the different insulation materials, the material degradation in the cable network can be categorised into four local degradation processes, which are related to partial discharges. As a result it is shown that partial discharge characteristics provide sensitive parameters for degradation processes upon which values preventive measures can be based.

The distribution cable networks are directly buried, so the only direct physical access to the cable system possible is at the terminations and electrical detection is the main practical possibility for diagnostics, e.g. partial discharge detection. With this diagnostics, the insulation defects can be pinpointed to a specific component of the cable system. This location of the partial discharge sources along the cable length can be analysed by time domain reflectometry. Complicated signal interpretations can be required in this partial discharge localisation process.

For cable systems in service consisting of multiple insulation types, the standard location evaluation procedure may result in systematic deviations from the correct discharge source location. Due to the different propagation velocities in different

insulating materials, this deviation can be some percent of the cable system length and is strongly dependent on the ratios of the lengths and velocities of the different cable parts. This thesis offers a way to make the correct localisation analysis and to correct the false location analysis for these mixed insulated power cable systems.

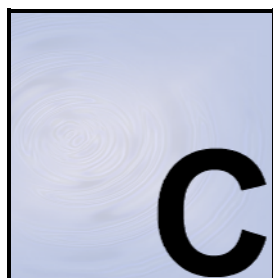
The feasibility of low energy partial discharge diagnostics at damped AC voltages (temporarily attenuating AC voltages as a result of an oscillation obtained by means of an LC resonant circuit) is investigated. Specific tools have been developed by which the PD detection is performed during damped AC voltages with frequencies in the range of 100 – 500Hz for 100-200ms. We have shown in this thesis that it is an effective energising method for partial discharge diagnostics. The compact and low weight measuring system results in a low noise level and high sensitivity in the field for discharging defects in impregnated paper as well as polymeric cable insulation.

The effects of the different test voltages on discharge activities are investigated. Different defect models are measured with 50Hz AC voltages, damped AC voltages at various frequencies and 0,1Hz voltages to study the partial discharge activities. The influence of test voltage shapes and frequencies are also verified on power cables in the field. In this thesis is shown that the values for the partial discharge parameters at damped AC energising are highly comparable to those obtained at conventional continuous AC energising conditions for different defect modes.

Furthermore, we have developed knowledge rules for condition assessment of the different insulation systems. As a result of statistical analysis of large amounts of measurement data, an effective and reliable method to determine experience norms (standard based on experience) for condition assessment has been derived. The various partial discharge properties relate to different aspects of the condition of a cable system and its components. The weighted combination of the various knowledge rules results in a methodology for decision making of maintaining cable systems. Different practical applications of the decision criteria model are evaluated based on quality control, risk reduction and reliability improvement.

Finally, as a spin-off of this research on damped AC voltages energising, we have participated the industrial development of a new damped AC voltage generator for partial discharge detection and localisation in high voltage transmission power cables.

F.J. WESTER



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1

INTRODUCTION

More and more distribution power grids are constructed from underground power cables, especially in the areas with a dense infrastructure. In the Netherlands, the distribution power grid¹ consists only of underground power cables, with nowadays a total length of over 100.000 km. The major part of the distribution cable network still consists of belted paper insulated lead cables, but during the last decade, XLPE insulated cable is more commonly applied².

The reliability and availability of the total power grid are relative high in the Netherlands [109]. In general, the distribution power cable grid is responsible for the major part of the outages in a power network [27]. On the one hand, this relative high failure rate is caused by external influences of non-electrical nature, e.g. digging activities. This is directly related to the distributed character of power cables. On the other hand, insulation deterioration in cable systems is causing the major part of the functional losses in the distribution network, caused by a variety of different defects [23]. Typical ageing stresses affecting cable insulation systems are thermal influences, mechanical influences, environmental influences and electrical influences.

Due to the relative high probability of functional losses in power cable systems as compared to other components, strategies are implemented to reduce the failure rate in the distribution cable network. In this way, the continuity of the energy supply can be improved. The failure rate due to external causes may be reduced by further optimisation of the communication between the companies with underground networks and the central network-laying registration.

¹ The commonly used nominal voltage for the distribution grid in the Netherlands is 10kV.

² This generation of XLPE type from the 1970s suffered from watertrees, but the installed cable length was limited in the Netherlands.

The dominant failure rate due to internal causes should be reduced by inspections of the insulation quality of the cable systems. In the Netherlands, the total distribution power cable grid is underground, direct buried. From remote terminations, internal inspections can be performed to detect defects possibly leading to functional loss of the cable system. Therefore, the applied diagnostic tool should be able to detect, pinpoint and distinguish the deterioration processes and stages for defects in the different insulation materials at different distances in a distribution power cable system.

In this thesis, the variety of different defects that may occur in power cable insulation systems is investigated. An innovative diagnostic tool, based on PD detection at damped AC voltages, is investigated for defect detection in practice including the application of knowledge rules for decision making about the insulation quality. In CIGRÉ working group D1.11, a process flow chart has been set up to find suitable diagnostics for specific degradation effect of HV assets [20], as shown in figure 1.1. Taking part in this working group, this process chart is used as a basis for investigations in this thesis.

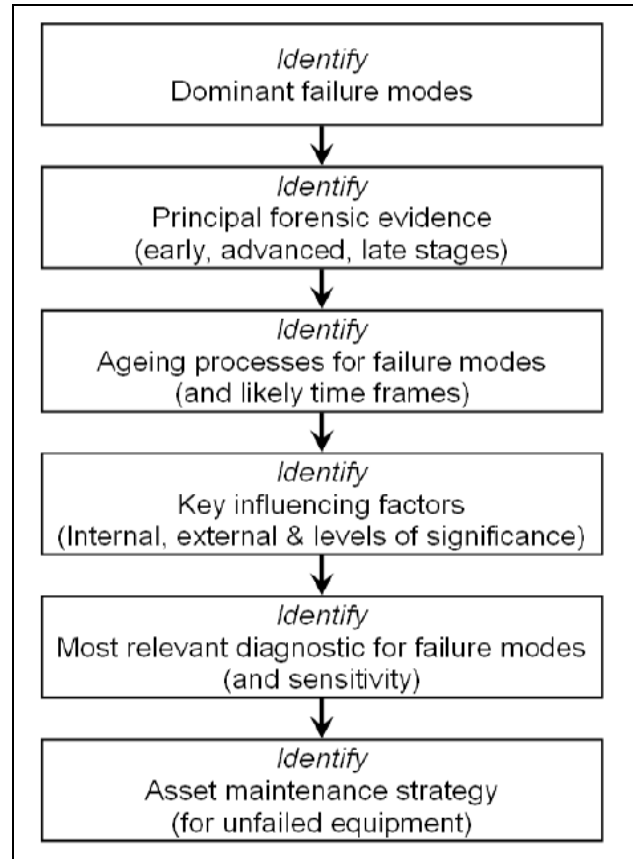


Figure 1.1: Methodology for analysing service aged insulation according to CIGRE WG D1.11 process flow chart.

1.1 DISTRIBUTION POWER CABLE NETWORK

A distribution power cable network consists of multiple strands of several cable systems connected to the feeding substations. A cable system is the connection between two (distribution) substations. Each of these cable systems can be seen as having an insulation system, consisting of multiple insulation subcomponents as cable parts, terminations and joints. A cable system is constructed with two terminations³, N cable parts and $N-1$ cable joints, as shown in figure 1.2a.

³ Also branched cable systems are applied in the cable networks around the world, which connect more than two substations and will therefore contain more than two cable terminations.

Power cables systems are distributed components. This means that at any failure site along the length of the cable, the resulting breakdown will only cause local damages in the cable insulation or in one of the accessories. Despite the fact that breakdowns in a cable system can be repaired by replacements of several meters of cable and two new joints (figure 1.2c), this is time-consuming and expensive labour. The average outage time per event for restoring the energy supply in the Netherlands for the distribution network is circa 1.25 hours [27]. Preventive maintenance actions on the defective cable components can be scheduled, without outage to the energy supply, and are in most cases are less time consuming and cost effective (less material).

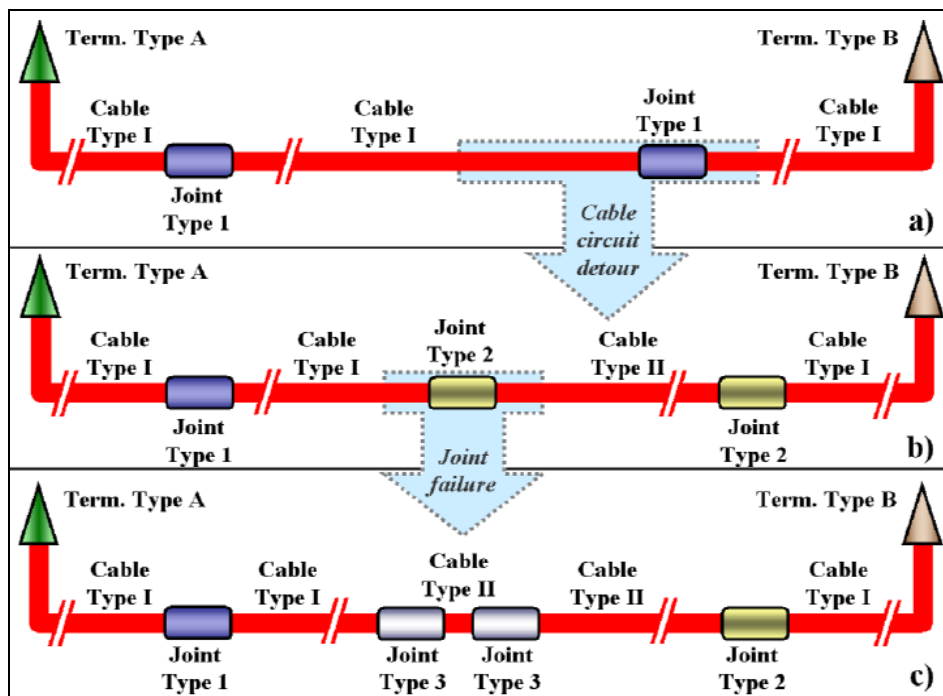


Figure 1.2: Representation of power cables divided in different components, each as an insulation system. Due to repairs or replacements over the service years, cable systems often contain components with different constructions and different insulation materials.

Due to the local changes in the topology, a cable system generally consists of various types of joints, terminations and cable parts. The age of the different components in one cable system may vary due to repairs during the lifetime. Over the years, the construction and the insulation materials of these cable components have changed. As a result of these design changes of components, different kinds of defects occur in the variety of cable components in the network. In addition, different deterioration mechanisms may be active for power cable systems and especially for the cable components.

The quality of a cable system is determined by the quality of its particular component(s). Different topological and operational conditions of a particular

cable system influence the service quality of a cable system enormously. Consequently, in the average service aged cable system, a mixture of old and young defect types occurs with different deterioration behaviour. Major defects in the components of new power cable systems may result in short term failures. Minor defects may deteriorate cable insulation, possibly resulting in failures in the long term, dependent on the defect type and the operational conditions.

1.2 RETROSPECTIVE OF DIAGNOSTICS FOR POWER CABLES

Cable diagnostics have to identify bad cable systems in the cable network. Diagnostics may be non-destructive or possibly destructive. In non-destructive diagnostics, the stress has no measurable effect on aging. The tests are based on detecting different dielectric properties, which are related to insulation ageing properties. Weak-destructive diagnostics are those with low influence on aging if used as short-time tests for periodic applications. The goal is to accelerate ageing of local weak spots in a cable system in order to localise them.

The only on-site cable insulation system for mounting and quality check for many years was the DC voltage withstand test. After-laying tests of new cable systems were performed at $4 \cdot U_0$ for 15 minutes, repeated test for insulation quality of in-service cable systems were performed at $3.2 \cdot U_0$ [93]. The cable system passed the test successfully if no breakdown occurred. Other kinds of testing methods, like dielectric loss measurements and partial discharge (PD) measurements were only applied in laboratories on smaller cable samples. During the mid 1980s, the first ideas for transportable diagnostic equipment for insulation property determination were brought up in international working groups. This was induced by the utilities' request for knowledge on the condition of cable insulation due to the increased number of failures. The knowledge that DC testing was not useful as a diagnostic feature for polymeric cable strongly increased the request for AC excitation stresses [30]. Also, DC voltages have shown to be a risk for older polymeric cables [28].

During the following years, several mobile diagnostic methods were being developed in two broad categories. The first category is diagnosing the overall insulation condition of a cable system, by analysing polarisation-relaxation phenomena [48,52,103,113], without pinpointing the weak spots. The second category concerns the measurements of partial discharges (PD) on-site. PDs are known as the intermediate or ultimate warning signal before breakdown occurrence in high voltage (HV) insulation materials. Discharging defects can be modelled by current pulse sources, which can be ignited after energising and which inject nanoseconds wide charge-flows into the cable insulation, resulting

in propagating EM waves. Using time domain reflectometry (TDR), the emitting sources can be located.

Cable systems are distributed components of several hundreds of meters up to several kilometres. For that reason, it is not important to know the condition of the complete cable system, but to know the local condition along the length of the cable. Therefore, detection, recognition and localisation of PD sources are a predictive method to qualify high-risk systems in the cable network. In this thesis, it is investigated whether PD diagnosis is a valuable tool for the condition assessment for the typical defects in the distribution cable network.

To obtain a realistic picture of discharging defects in power cables, the on-site PD diagnostics should be predictable and transferable to operating conditions. The on-site detection of partial discharges in power cables can be performed off-line as well as on-line. To perform off-line PD diagnostics, the power cable to be measured is taken out of service. An external power supply is used to energise the cable circuit and to ignite the discharging defects. In case of on-line PD detection, the power cable to be diagnosed stays in service during the measurement and the active PD sources under the service conditions may be detected [1,42]. However, there are still some hurdles regarding the sensitivity of the measurement in the field up till now [122,123], which are a bottleneck for the signal recognition for detection and localisation, as described in chapter 4. Therefore, in this thesis off-line PD detection and localisation are investigated.

For off-line PD diagnosis, external voltage sources are necessary for the ignition of PD sources and their detection and localisation. On-site PD measurements with continuous energising at power frequencies (50/60Hz) may be the best option from the physical point of view, however this is in most cases not economically interesting for on-site diagnosis. Due to the high capacitive loads of the power cables, the 50Hz energising circuits are large and heavy, trucks are needed for the transportation. The 50Hz energising systems are applied in practice for on-site off-line PD diagnostics of distribution power cables [83].

However, to manage the high capacitive load currents of power cables, different alternative energising methods are introduced in recent years [102]. On-site off-line PD diagnosis can be categorized in the following alternative voltage groups:

- Continuous power supply of very low frequencies (VLF) [34,88,119];
- Transient switching impulse voltage [32];
- Damped AC voltages (50-800Hz) [39,79].

Currently, the transportability of the alternative systems improved tremendously. Some of the different methods can even be transported in a passenger car.

Damped AC (DAC) voltage tests were introduced as a cost-effective voltage withstand test for polymeric insulated HV cables [29]. DAC voltage techniques reduce the power demand on-site by loading the cable with a DC supply after which the cable is discharged through an inductor. The test frequency in the initial DAC test systems was in the kHz range. PD detection was not possible with the initial energising systems, due to the high disturbances of the transients occurring during the gap-fired switching of the cable capacitor to the inductor.

For the investigations in this thesis, a new PD diagnostic method is introduced and applied for distribution power cables, which is based on DAC voltages. Innovative improvement of the HV switch in the circuit and large inductor resulted in a sensitive and compact test circuit, as shown in figure 1.3, where the test voltage frequency is 100 – 800Hz [39]. Sensitive PD detection and localisation are possible during the slow decaying voltages, as the application of a solid-state switch does not give transient problems.



Figure 1.3: Field application of the in this thesis applied PD diagnostic tool.

1.3 MAINTENANCE OF THE POWER NETWORK

Traditionally, power utilities have managed their assets mainly to obtain a high technical reliability of the power network, representing a significant portion of the utility's maintenance budget [5]. The on-going liberalisation processes in the electricity market enforce companies to change their maintenance approaches without negative effects on service to the customer.

Generally, three maintenance strategies can be applied to control the different assets of the power grid [97]:

- | | |
|---|--|
| 1 Corrective Maintenance:
(CM) | maintenance reaction only in case of failure occurrences |
| 2 Time Based Maintenance:
(TBM) | preventive maintenance actions depending on time- or usage-based intervals |
| 3 Condition Based Maintenance:
(CBM) | preventive maintenance actions depending on the momentary condition |

In case of corrective (reactive) maintenance (CM), repair or replacement actions are only undertaken in case of equipment failures. This means that the maintenance activities consist of fixing what has broken. Equipment failures may result in substantial damages with high repair costs. Apart from the directly involved equipment, the neighbouring assets may incur serious damages.

Preventive maintenance is always directed by the status of the network components, either assumed or measured. Time based maintenance is mostly carried out in regular time-intervals. Condition based maintenance (CBM) is preventive maintenance dependent on the actual momentary condition, determined by visual inspection or diagnostic measurements. By knowing the actual condition of components, the maintenance, replacement and expansion activities can be planned and performed when necessary.

One of the main goals of network operators is to strive for a higher degree of efficiency. On the one hand, they have to reduce the maintenance and reinvestment costs and maximise the service life of the existing components and substantially increase the operation loads for the network. On the other hand, service reliability, power quality and safety have to be kept at a high level [127]. Due to these demands, knowledge about the condition of the power network assets is of growing importance. The condition of the power cable network is for the major part dependent on the insulation condition of the different cable components used. By diagnosing the insulation of cable systems, repair and/or replacement of components with bad insulation quality can be planned. In this way, the overall quality of the power cable network is increased and the amount of functional losses of cable systems will decrease. By the determination of the condition of the assets, planned investments for renewal and updating of (parts of) the network may be postponed [117,128].

In general, asset management (AM) decisions are balancing deliberations from three points of view, as shown figure 1.4. The failure probability depends besides condition assessment on the component deteriorations, related to the service age, the type, the history and the laying conditions. Failure acceptability can be reflected as the degree in which a failure is acceptable from the societal point of view. The failure costs related to (future) failure are affected by the outage related expenditure. The input of the technical, economical and sociological aspects will give the final maintenance decision, dependent on individual cases.

Primarily, asset management (AM) decisions will be firstly based on the technical aspects of the condition assessment. Next, the economical and societal aspects are taken into account. Therefore, this thesis focuses on the technical aspect of the maintenance management, in particular the condition assessment.



Figure 1.4: The three categories of information aspects to support maintenance management of HV networks [110].

1.4 OBJECTIVE OF THE PRESENT STUDY

This thesis will focus on the condition assessment of one of the mostly distributed part of the power supply system: the distribution power cable network. The objective of the present study is to obtain more knowledge about the feasibility of diagnostic methodologies at damped AC voltages for the early recognition of failure related defects in distribution power cable systems.

With respect to the practical applicability of the diagnostic tool in the distribution network, the aim is to transfer the insights of defect types and detection into knowledge rules for a decision support system. These knowledge rules are the core of the technical condition assessment to determine the deterioration stage, to classify, recognise and localise local defects. The research is divided in three steps which address to different parts of the objectives:

INSULATION DEGRADATION

Identify the dominant failure modes for the variety of defects in the different cable components with regard to insulation degradation mechanisms. Determine the diagnostic properties necessary for the on-site detection of these degradation mechanisms.

PD DETECTION AND LOCALISATION

Investigate the suitability of damped AC excitation voltages for PD detection and localisation. Identify diagnostic properties to evaluate the dominant degradation modes.

To assess effective diagnostics, determine the influencing factors of the diagnostic for the detection and localisation of local defects; (i) the effect of signal propagation through power cables with a combination of different insulation materials and (ii) the effect of the test voltage shape and the frequency of the damped AC excitation voltages on the PD properties.

CONDITION ASSESSMENT

Based on the applied diagnostics and the operational point of view, formulate knowledge rules for the different obtained PD properties. Apply these knowledge rules in a decision-support model on the technical qualification of the cable system condition.

1.5 STRUCTURE OF THE THESIS

The research in this thesis is described in the following structure.

Chapter 2 describes the typical failures in the distribution power cable network, with their influencing factors. The resulting deterioration processes of the frequently occurring defects are investigated.

The propagation of PDs in power cables are discussed in chapter 3. Especially influence of combining different insulation materials in one cable system on the PD localisation is investigated, in order to analyse the correct defect sites in the complicated cable systems.

In chapter 4, the feasibility of a new diagnostic tool based on damped AC voltages is analysed. To assess effective diagnostics at damped AC excitation voltages, the diagnostic properties for the PD diagnostic are defined to obtain the required information to detect, locate and recognise the major part of the insulation deterioration defects.

Chapter 5 discusses the effects of the excitation voltage shape and frequency on the PD properties, based on the typical defects in laboratory models as well as field samples. In particular the PD detection at damped AC voltage energising results is compared to the conventional PD detection methods at 50Hz AC energising.

In chapter 6, the generation of knowledge rules for the systematic application of diagnostics is described. Especially from the point of view of reduction of the number of functional losses, these can be interpretation criteria or experience norms for the different diagnostic properties. In particular, statistical analyses on amounts of data are performed on the one dimensional PD properties for the different cable component types. Furthermore, a method for the estimation on the risk of failure is defined.

This decision support model is discussed in chapter 7, using the application of condition assessment for different cases of diagnostic purposes.

As a spin-off for the research on distribution power cables, chapter 8 describes the first PD diagnostics for transmission cables based on damped AC voltages, which is able to detect and localise discharges.

Finally, chapter 9 will contain the conclusions of the present research.

2

FAILURE RELATED DEFECTS AND INSULATION DEGRADATION

Failure statistics of the power network, as are described in appendix A, show that the medium voltage (MV) cable network is related to the major part of the outage time, 17 minutes per year per client. In the MV network, the cable joints are related to 37% of the total number of outages. Cable insulation is related to 13% of the outages and terminations to only less than 1%. The external causes in the MV network are related to 29% of the outages in the power network.

Cable systems can be seen as an individual insulation system, consisting of subcomponents as cable, termination and joint. Due to repairs or topological changes, cable systems often consist of components of various types and ages, as reflected in figure 2.1. Over the years, the constructions and the insulating materials of the cable components have changed. These design changes may result in different kinds of defects in the network. In addition, different deterioration mechanisms may be involved for power cable systems.

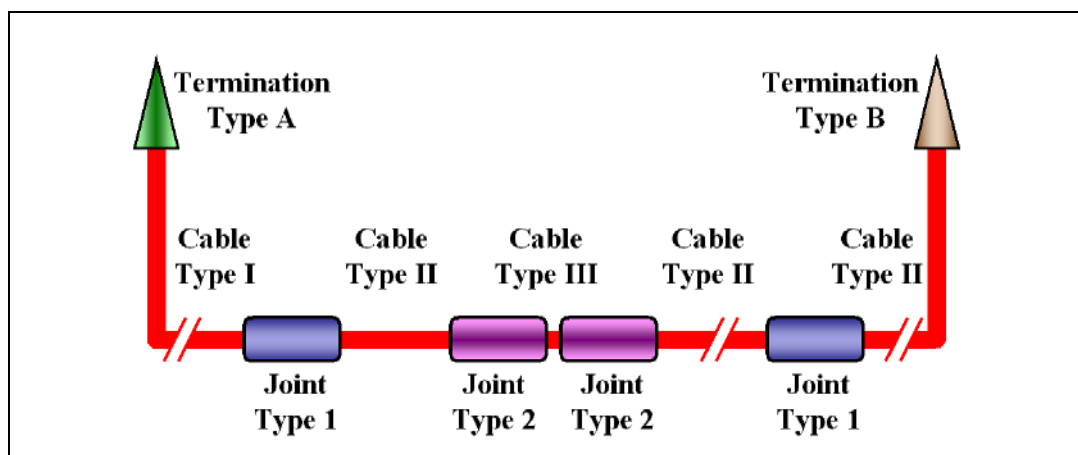


Figure 2.1: Power cable system existing of different components, with different constructions and insulating materials.

The complexity of its insulation systems indicates that there is a need for systematic investigations on distribution cable insulation degradation. By knowing the cable deterioration processes, diagnostic parameters necessary to support the condition assessment may be identified. To create a scientific basis for a diagnostic support system, we have systematically investigated the following topics in this chapter:

- identification of the defect introducing factors for distribution power cables;
- definition of the defect types for different components and their failure modes;
- definition of the insulation degradation mechanisms related to the various defects;
- identification of insulation deterioration symptoms of typical defects to find characteristic properties to detect and recognise the presence of those defects.

2.1 DEFECT INDUCING FACTORS

Several stresses can be pointed out due to which defects occur in cable insulation systems. These stresses can be divided into three categories; operational stresses, environmental stresses and human handlings. Table 2-1, table 2-2 and table 2-3 describe the different defect introducing stresses. Also combinations of these defect introducing stresses are possible.

Table 2-1: Operational stresses inducing defects in power cables.

Stresses	Inducing factors	Induced defects
Load cycles	Thermal expansion (radial and axial)	Increase of migration of materials
High temperatures	Chemical reactions	Drying out of paper insulation
		Depolymerisation of paper
		Increase of volume → voids
		Embrittlement of materials
		Gas formation

2.1.1 OPERATIONAL STRESSES

Dependent on the operational conditions of a cable system, different mechanisms may affect the insulating quality. Studies have shown that thermal stressing of paper/oil insulation [47,77], cause after decades of years embrittlement and decrease of mechanical strength of the paper, which is accompanied by an increase in the dielectric losses. As the cellulose structures are affected, reaction products will occur in the form of gases as CO, CO₂, and

others. Also, water will be formed as a reaction product of the embrittlement of the paper.

Power loads increase the temperature in a cable system and result in transversal strength (movement) on the cable systems. Axial forces on the cable connectors can lead to movement of the connectors inside the accessories. The distances between the conductors in an accessory decrease, causing increased electrical stresses to the insulating materials in between. Load cycles and short circuit currents can also cause mechanical stress on cable connectors in joints. Due to the pressure and tension stresses, the connectors may loose their connecting strength, leading to high resistive transitions, which will cause locally increased heat production into the insulation.

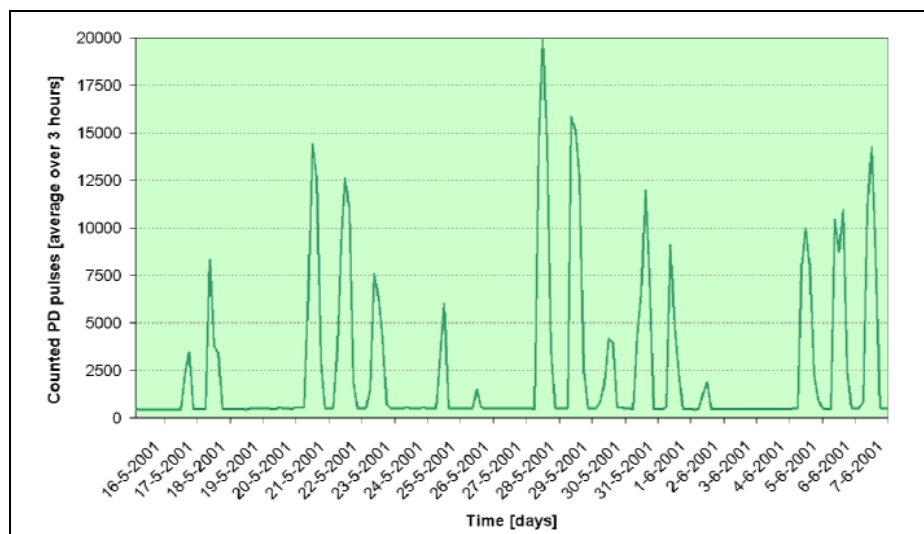


Figure 2.2: Effect of the load cycles on the PD activity in a power cable line. As the temperature rises, the volume of the PIL cable increases and multiple voids occur, resulting in increased PD intensity.

Furthermore, daily load cycles (figure 2.2) make the power cable expand and shrink thermo-mechanically, especially in paper insulated insulation. A fluid pressure is build up in the paper oil insulation, as a result of the expansion in the radial direction during high loads. As the loads are decreasing, the cable cools down starting at the conductors and an under-pressure occurs. Insulation fluid from the cable components will fill up voids in the paper insulation, and the oil levels in these components will decrease. In extreme cases, this may even lead to implosions of cable joints or terminations. This thermo-mechanical effect is also an undermining for watertightness of cable joints. The investigations on the operations on the inducement of defects are reflected in figure 2.3.

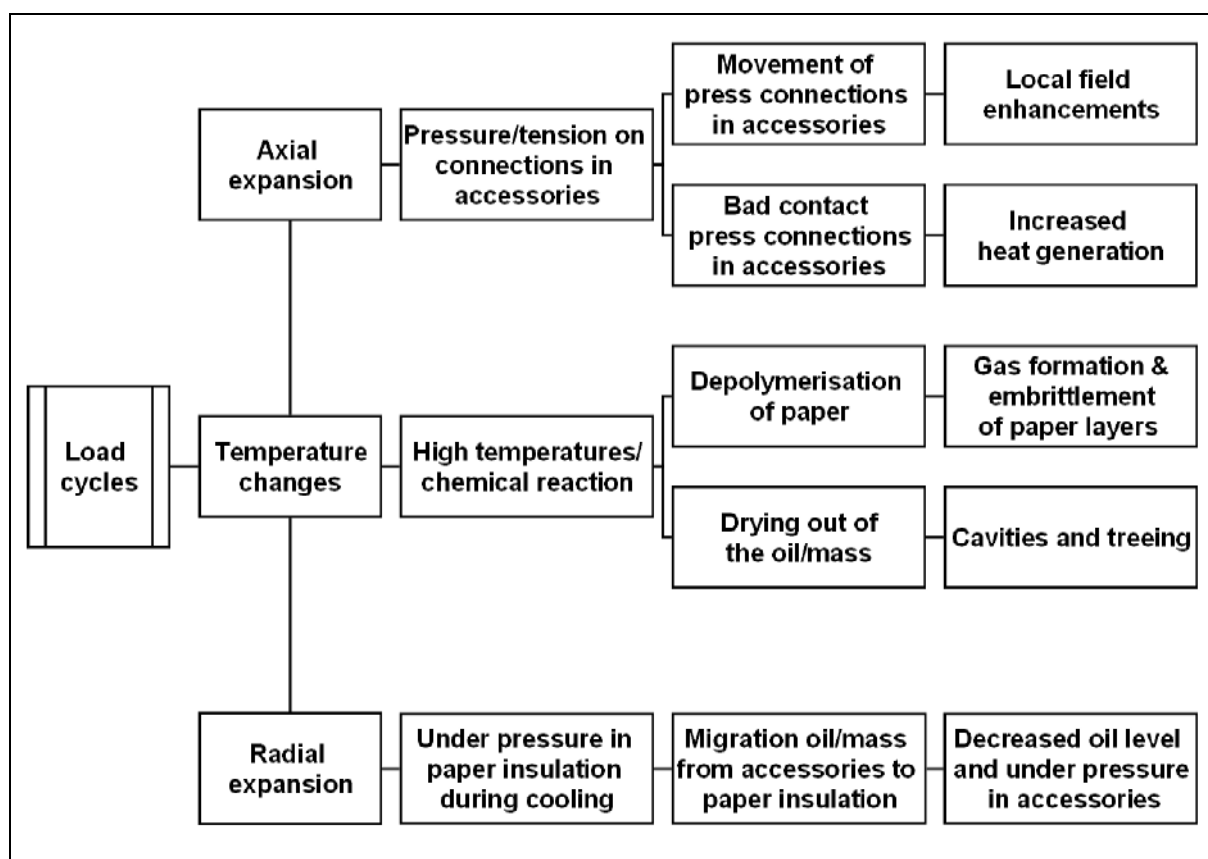


Figure 2.3: Investigation overview of the operational stresses for the inducement of defects.

The operational effects can not be prevented in most cases. Usually during the design of a new cable system, the effect of these stresses causes the life-time to remain unpredictable on the long run, unless appropriate diagnostics are applied. The development of the network loads and thus the cable system loads are not always known at the start of a cable system life-time.

Table 2-2: Defect introducing environmental stresses for power cables.

Stresses	Inducing factors	Induced defects
Water/humidity	Moisture penetration	Decrease of insulating qualities
Ground pollution	Corrosion	Lead sheath penetration, water penetration
Mechanical stress	Dielectric losses	Local overheating
	Tension	Forces on cable accessories
		Thermal ageing
		Loss of adhesion
		Cracking of materials

2.1.2 ENVIRONMENTAL STRESSES

The environment into which a cable system is situated has large influence on the introduction of defects in the insulation, as are shown in figure 2.4. Often, power cables are situated under the ground water level. This means that if the water blocking of a cable system is imperfect, water can penetrate into the insulation. In paragraph 2.2.3, the effect of water in typical cable insulating materials is described. Environmental burdens can result in perforations of the water blockings of power cables. Ground pollution may result in corrosion of the armament and the lead sheath. The corrosion of these cable layers will result in water penetration into the cable insulation.

Cable systems, which are situated next to DC-fed railways or tramways, may show perforations of the lead sheath. Swarming currents, due to DC return paths through the ground can locally cause corrosion of the lead sheath [129]. The resulting local perforations of the lead sheath often result in water penetration into the cable insulation, especially in cable without a PVC insulation sheath.

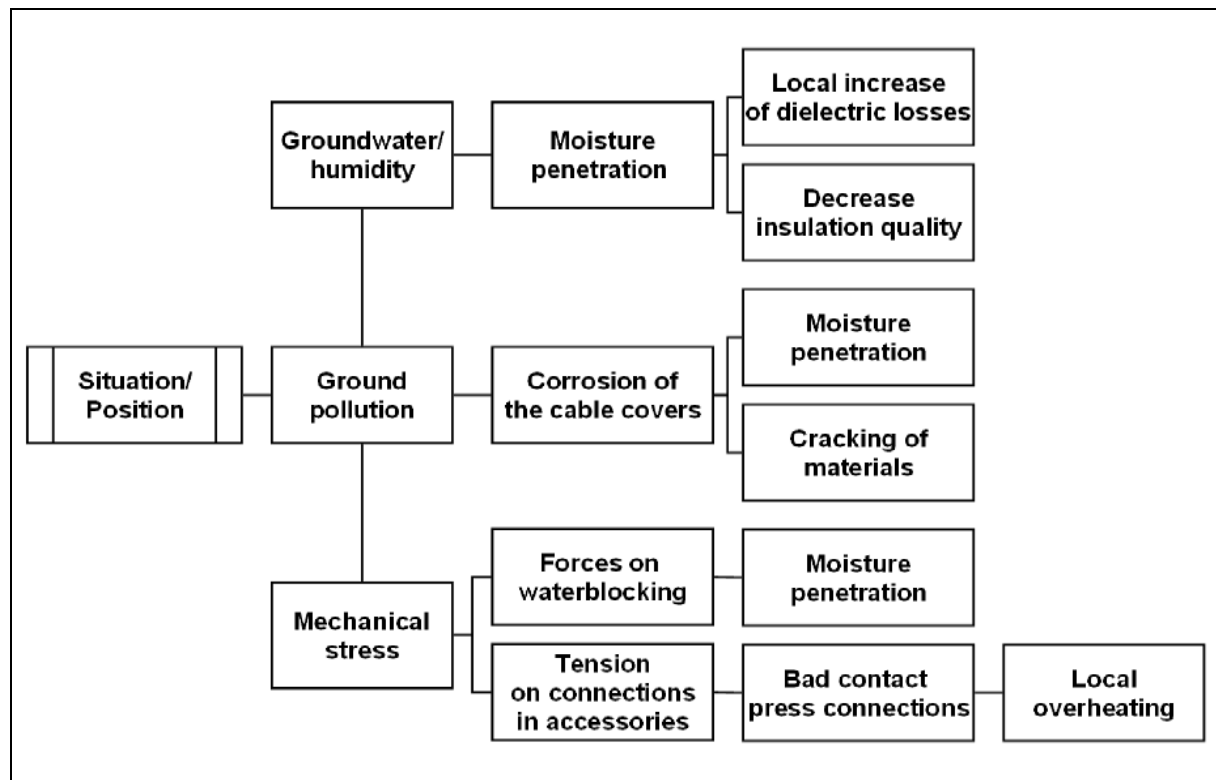


Figure 2.4: Overview of the environmental stresses on the inducement of defects.

Cable movement in soft (wet) grounds may impose mechanical stresses on a cable system, e.g. the cable accessories. The mechanical stresses may cause breakage of the water blocking in the accessories or lead to problems of the cable connectors in the accessories. Due to the current load, cable systems can extend in length, leading to forces on the cable connectors in the accessories.

Also for environmental stresses, we can conclude that they can not be prevented in many cases. For a new cable system, the future ground pollutions and the mechanical stresses cannot always been predicted for longer periods.

Table 2-3: Defect inducing human stresses for power cables.

Stresses	Inducing factors	Induced defects
Manuals/Instructions	Critical constructions	Cavities
Inaccuracy during mounting	Critical mixtures of insulating components	Bad hardened resin
Design	Imperfect water blocking of accessories	Moisture penetration → increase of temperature, decrease of insulation properties
	Introduction of PD related defects	Erosion of insulation
	Damaging of sheaths during laying	Lead sheath perforations, leakage of oil, water penetration
	Bad connections between conductors	Local overheating

2.1.3 HUMAN HANDLING

The on-site installation of new cable systems or replacement of failed components is an important defect introducing factors. Especially the cable accessories, which are assembled in the field, show an increased risk. Inaccurate assembly may result (later) in defects, but also hidden defects in the designs of cable components may result in defects. Fixing a cable accessory is an accurate job, where many external factors (weather, ground, time pressure) are of influence. Even if the work is performed accurately, small defects can lead to breakdown on the mid-long term.

Contrary to the previous stresses, the human influences can be prevented for the major part by improving instructions. The design, the production and the assembly of the cable components are human actions that can be adjusted. However, some human handlings can still bring new defects in the system. In this respect, it is referred to the share of ca 15% of maintenance induced failures for outages in HV networks [23].

2.2 TYPICAL INSULATION DEFECTS

By analysing the visual inspections, we have listed the typical defects in the different elements of cable network, as shown in table 2-4 and table 2-5, which are assigned to several defect introducing stresses involved. Visual inspection of the disturbed components has given insight in the different types of defects resulting in breakdown. From the forensic investigations during many years, we have found repetitive fault causes, which are described in this section. Some of the defect descriptions are hypotheses, obtained from the practical insight from forensic investigations.

Figure 2.5 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 switchgear. At the fault location, the two phases were not centred in the termination's housing, and therefore only insulated by the PVC housing. The resulting PD activity from the sharp edges of the connector degraded the polymeric insulation, leading to a phase to phase breakdown after several years. More detailed degradation processes are described in section 2.3.

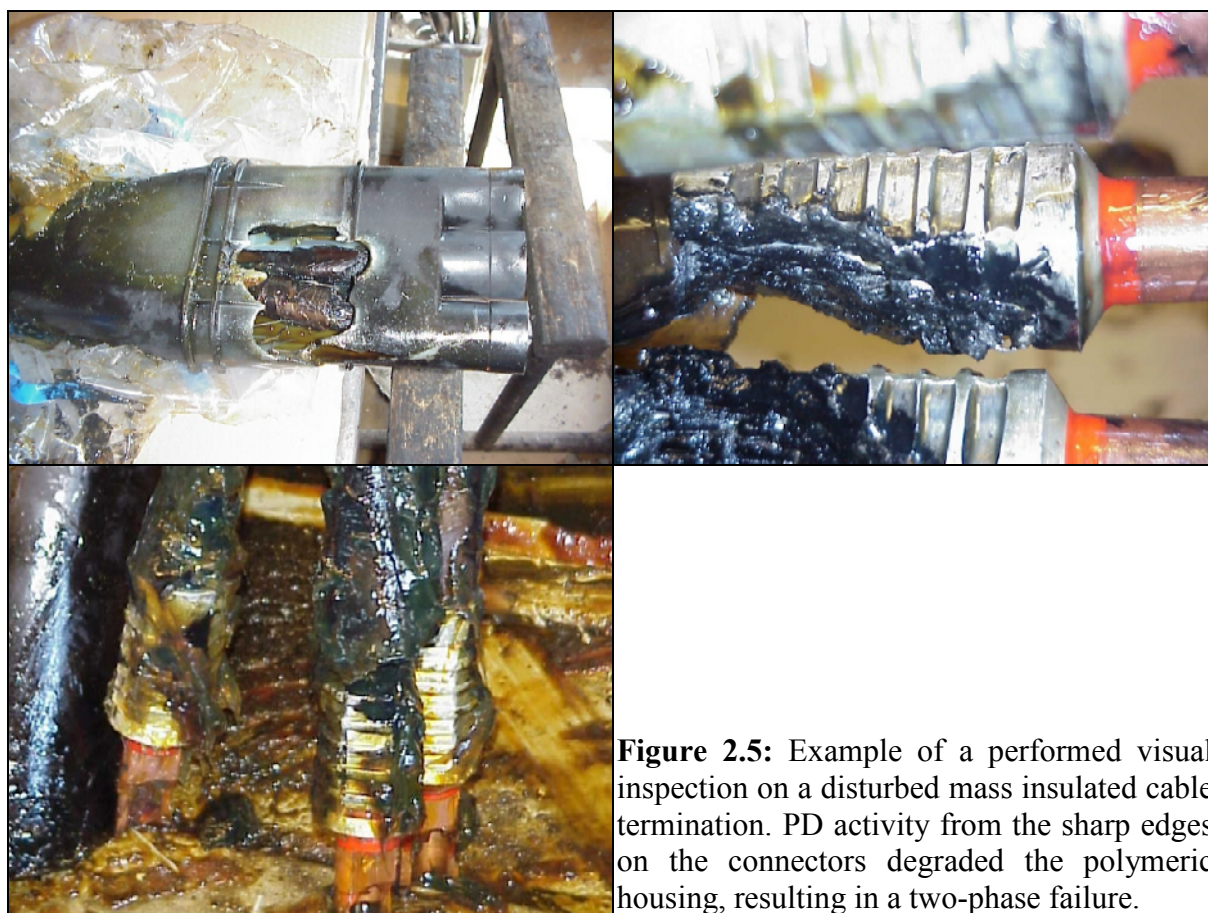


Figure 2.5: Example of a performed visual inspection on a disturbed mass insulated cable termination. PD activity from the sharp edges on the connectors degraded the polymeric housing, resulting in a two-phase failure.

Table 2-4: Typical insulation defects for PILC related components.

	Typical insulation defects	Defects inducing factor
Cable accessories	Decreased oil level	Operation
	Protrusions on connectors (sharp edges)	Human
	Moisture penetration	Operation, Environment & Human
	Cavities/Fissures	Operation & Human
	Contaminations	Operation & Human
	Bad hardened resin	Human
	Asymmetrical conductor positioning	Environment & Human
	Conductor problems	Operation, Environment & Human
Cable insulation	Drying out	Operation
	Cavities	Operation & Human (bending)
	Moisture penetration (perforations)	Environment & Human
	Moisture penetration (corrosion)	Environment

Table 2-5: Typical insulation defects for XLPE cable components.

	Typical insulation defects	Defects inducing factor
Cable accessories	Interface problems	Operation & Human
	Protrusions on connectors (sharp edges)	Human
	Moisture penetration	Operation & Human
	Cavities	Human
	Fissures	Operation & Human
	Remaining semi-conductive layer	Human
	Conductor problems	Operation, Environment & Human
	Field grading movement	Human
Cable insulation	Moisture penetration (perforations of the PVC/PE sheath)	Environment & Human
	Cavities (delamination at interfaces or inside insulation)	Operation & Human
	Water trees	Environment & Human

2.2.1 DECREASED INSULATION FLUID LEVEL

The continuous migration of insulation fluid from the joints (or terminations⁴) into the cable insulation due to load cycles decreases the fluid level in a joint and creates an gas under-pressure situation in the upper part of the joint, as reflected in figure 2.6. This gas pressure can be as low as 0.3 bar [101].

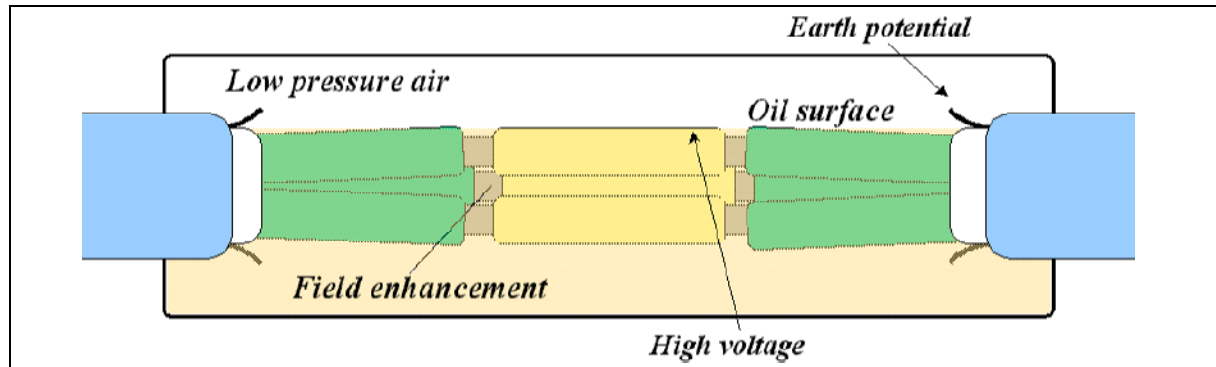


Figure 2.6: Example of the effects that may occur in oil insulated joints when the oil level decreases.

On a certain moment, one of the high voltage connectors will be located at the boundary between the low-pressure gas and the insulation fluid. This means that a low-pressure gas volume exists at the boundary of the fluid level and the housing wall. The PD inception voltage over the fluid surface decreases with the decreased gas pressure [68]. Due to field concentrations at the edge of the connector, discharges will occur over the fluid surface.

The discharges over the oil surface will result in floating carbonised oil parts. The high voltage electrode will effectively extend over the fluid surface, resulting in increased electric fields. A bridge of carbonised parts may be formed between the high voltage connector and the earthed lead screen, until the breakdown strength of the oil surface is reached. If the oil surface appears between two parallel-situated phases inside the joint, the surface discharges will occur under higher field strengths over a relative short distance.

2.2.2 PROTRUSIONS ON PRESS-CONNECTORS

Protrusions on the press connectors will give locally increased field strengths, giving PD activity. In a point to plane configuration (5cm) under oil, the inception voltage for PD is 32kV [36]. As shown by [36], this value decreases with a factor 10, if the sharp point is situated in air. So, in combination with the

⁴ Also due to the upright positioning of cable terminations, the fluid insulation in the terminations may empty in the cable insulation.

low-pressure gas due to the decreased oil level, sharp edges on the press connections in accessories may ignite PD activity. Furthermore, according to [75] the inception voltage of PD in oil decreases depending on the amount of dissolved gases, dissolved moisture and pollution.

OIL INSULATION

Due to PD under oil, particles of carbonised oil and gases are formed. The insulating quality of the oil will decrease by the dissolved gases and the carbonisation [73]. Carbonised particles in oil are polarised by the AC electric field. In inhomogeneous fields, the attracting force on a particle is stronger than the repellent force, as the field is higher on one side of the particle. The resulting force on a particle is equal to [68]:

$$F = \left(\frac{\varepsilon_0}{2} \right) \gamma \left(\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \right) \nabla E^2 \quad (2.1)$$

where γ = volume of particle
 ε_0 = permittivity of vacuum ($8.85 \times 10^{-12} \text{ F m}^{-1}$)
 ε_1 = permittivity of the oil
 ε_2 = permittivity of the particle ($\varepsilon_2 \gg \varepsilon_1$)

Due to the described force, carbonised oil-parts may form chains in the direction of the electric field between the electrodes. The bridges of conducting carbonised parts lower the breakdown stress appreciably.

SYNTHETIC INSULATION

Metallic protrusions in polymeric accessories may cause an intrinsic breakdown of a small part of the insulation, due to the locally increased field strength. At the tip of the sharp edge a gas-filled cavity will be formed. PD activity in the cavity will degrade the insulation further. If treeing initiates from the cavity, this may bridge the insulation between the electrodes [68].

2.2.3 MOISTURE PENETRATION

The probability of failure by moisture penetration in the cable insulation depends on the regional circumstances. Especially in the Netherlands, in large areas the ground water level can be relative high. In practice this means that if a cable system water barrier is leaking, e.g. due to external damages, water may penetrate easily, especially in mass-impregnated cables. Furthermore, defective water barriers in combination with the described under-pressure in accessories will result in easy moisture penetration in these accessories.

OIL INSULATION

Moisture absorption into cable components decreases their dielectric strength and increases their dielectric losses. If the maximum amount of dissolved water in the oil is reached, free water is present. In oil-insulated accessories, small droplets of free water can be seen as conducting impurities. Breakdown may occur as a result of increasing dielectric losses in the (slightly) conducting bridge, even at fairly low field strengths [68].

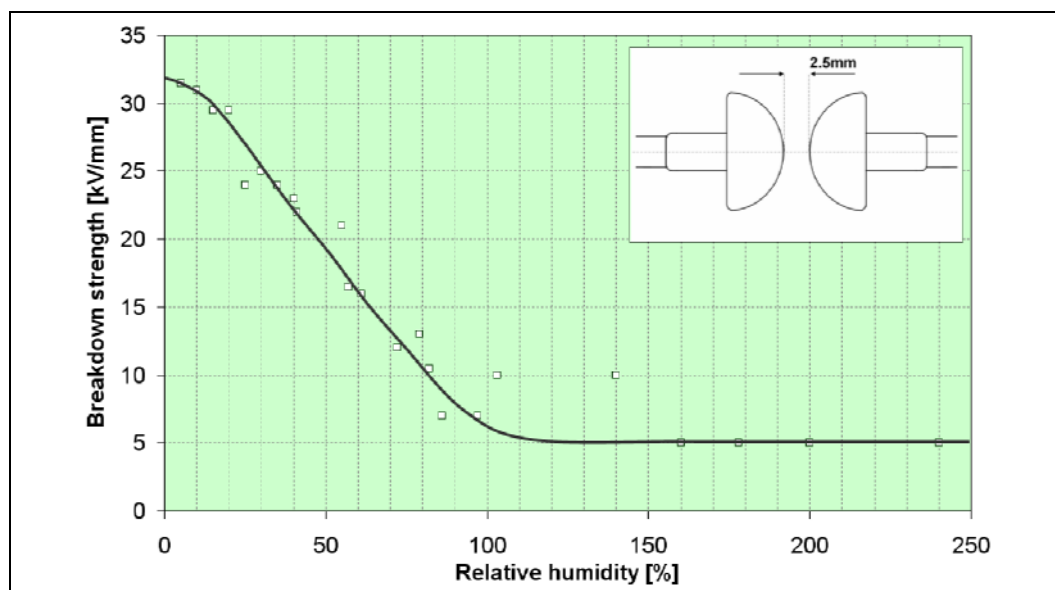


Figure 2.7: Graph of the breakdown strength of mineral oil in dependency of the humidity. Breakdown strength decreases up to ca 100% relative humidity after which it stabilises [50].

Figure 2.7 shows the dependability of the breakdown strength and the relative humidity of insulating oil. The relative humidity is used because the maximum amount of dissolved water in oil is temperature dependent. In this graph, it is shown that the breakdown strength decreases until the oil is saturated at 100% relative humidity. At this point, which is about 50ppm [54] at room temperature, the maximum level of dissolved water in oil is reached and free water occurs in the oil. From that point the breakdown strength stabilises to about 5kV/mm.

PAPER/OIL INSULATION

Moisture penetration in cable insulation occurs due to perforations by environmental or human causes or due to corrosive damaging of the outer screens. Moisture ingress in hygroscopic paper-oil insulation will cause changes in the dielectric strength and the level of dielectric losses, as reflected in the graph of figure 2.8. It is shown that the dielectric properties are adversely changing as the humidity of the paper is increasing [35].

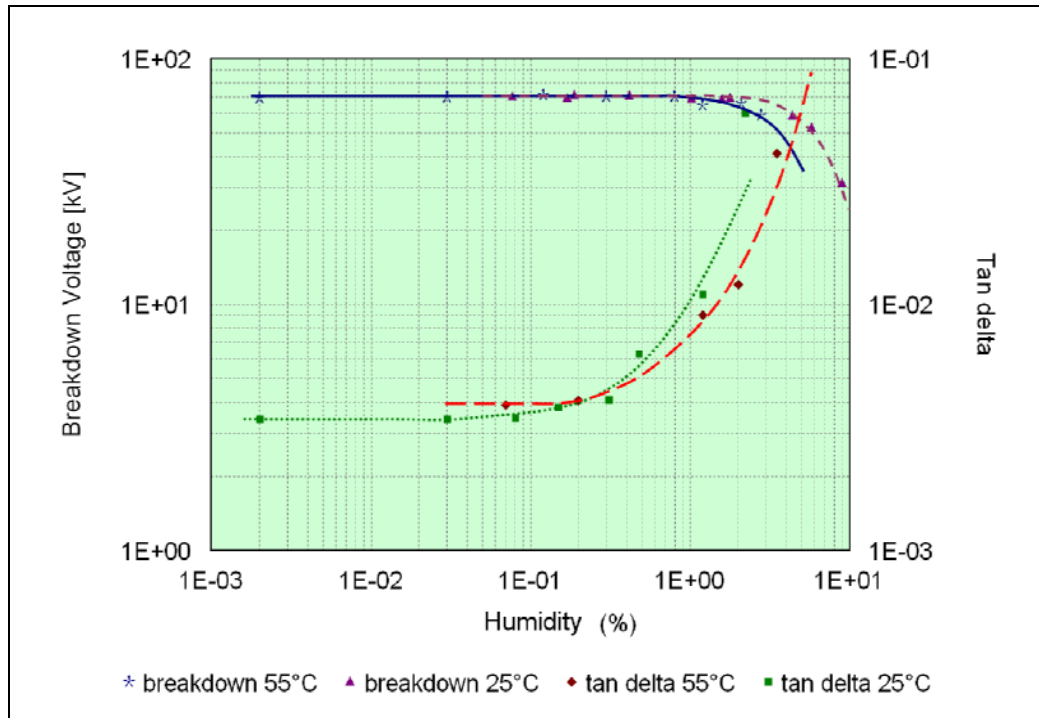


Figure 2.8: Changes in the dielectric properties of impregnated paper in relation to the humidity of the paper. For the breakdown voltage tests paper samples of 1mm thickness were used [35].

The breakdown voltage of impregnated paper is almost independent for the content of moisture up to a level of about 1%. If the water content is higher than 1%, the breakdown strength rapidly decreases. The dielectric losses of impregnated paper are almost stable up to humidity of about 0.1%. If the humidity is higher than this 0.1%, the dielectric losses increase. This rapid increase of the dielectric losses in relation to the humidity is caused by the extra charge carrier growth [6].

The paper layers will absorb penetrated water. The rate of degradation is increased roughly in proportion to the moisture content of the paper [112]. Due to this hygroscopic process, the insulation sooner or later will become more conducting. This will lead to a locally increase of the dielectric losses giving rise to temperature increment. Due to the local overheating, the cellulose structures of the paper will be affected on the long run. The paper will become brittle and the insulating quality decreases. Paper layers are therefore less resistant against PD activity and will be penetrated more easily.

RESIN INSULATION

In resin-insulated accessories, water ingress is for the major part a result of a diffusion process, which happens over a long period of time. The insulating material is penetrated from the outside towards the conductors. The outer part of the resin insulation will be more conducting than the inner insulation [63]. As a

result, the electric field distribution in the joint changes and increased electric fields near the conductor may occur, which may lead to total breakdown.

2.2.4 CAVITIES/FISSURES

RESIN INSULATION

Resin insulated cable joints may contain cavities due to the escape of gas from the shrink sleeve of the press connection. As the resin is hardening, the temperature increases, whereas the remaining gas in the shrink sleeve expands. The gas will escape at the end of the shrink sleeve where it will move upwards and is captured by the hardening resin, as shown in figure 2.9.



Figure 2.9: Examples of cavities in resin insulation, which may occur during the hardening process of the resin.

PRE-MOULDED AND SHRINK INSULATION

Internal cavities in (pre-moulded) solid insulating materials can occur during the assembly in the factory (usually inside the insulation) or due to the installation in the field. On-site assembly of cold⁵ and hot shrink accessories may result in long flat cavities on the boundary between the accessory and the cable insulation. The tangential field due to the field grading in these positions will result in easily occurring PDs. A gap between the press connector and the cable insulation may occur due to the removal of too much of polymeric insulation.

Hot shrink accessories can contain air-filled cavities if the shrinking process is not done properly or due to other mounting inaccuracies, as shown figure 2.10. In these cavities PD activity may occur, causing degradation of the polymeric shrink material. Insulation deterioration in cavities can take months or even years, but the resulting treeing can cause breakdown within minutes or hours.

⁵ Cold shrink joints are also named slipover accessories which have the characteristic to stretch.

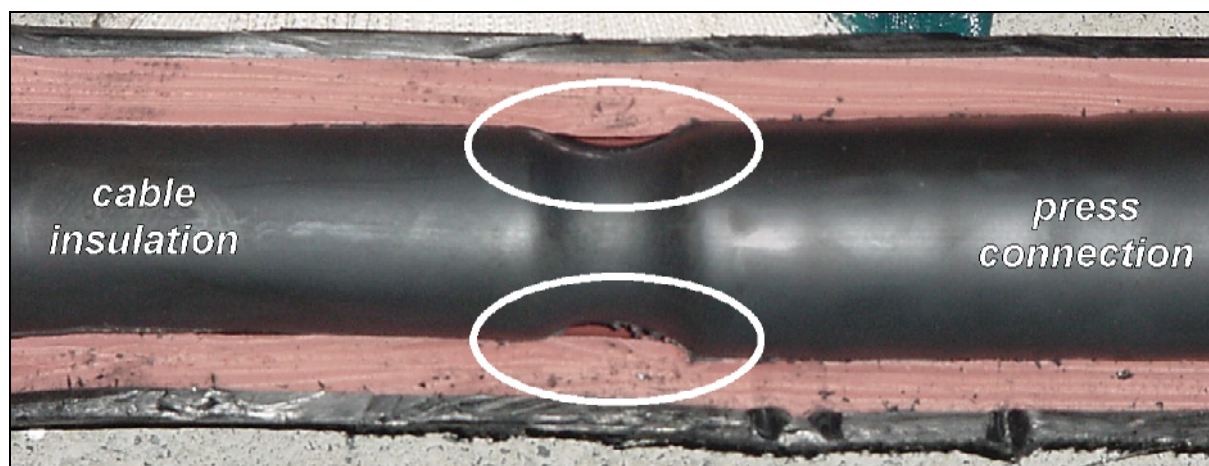


Figure 2.10: Example of the presence of cavities in the shrink type cable joints. A cavity occurs in the joint as the shrink-cover is unable to fill the too large gap between the insulation and the connector

2.2.5 CONTAMINATIONS

Contaminations in the insulation materials usually are conductive parts. In [17] is stated that free particles under AC conditions induce breakdown at field strength comparable to operational field strength for transformer oil. Especially the conductive scouring pasta inside the press connections is a typical example of conductive contaminations in the accessories insulation. The pasta is applied for improved contact between the cable conductor and the press connection. While inserting the cable conductor, the pasta will come out and should be removed accurately. If this pasta is not removed, increased field strengths occur and PD activity might occur.

2.2.6 BAD HARDENED RESIN

Resin insulation for cable accessories usually exists of different components, which are mixed on-site. If the components are not mixed correctly, either due to divergent mixture or due to a divergent mix-time, the resulting resin insulation is often not well hardened (and shows separation of the components). Cavities and fissures occur in the resin, giving rise to PD activity. Furthermore, as the resin has also the function of water blocking, water can penetrate into the accessory very easy. Both these effects of badly mixed resin components will degrade the insulating material.

2.2.7 ASYMMETRICAL CONDUCTOR POSITIONING

Asymmetrical conductor positioning inside cable accessories (figure 2.11) will create positions in the cable accessories with increased field strength. Generally, the cable accessories in the distribution network are over dimensioned, so that the effects of increased field are minimal. However, in combination with other defects, like cavities or moisture penetration, the increased field strengths may result in a decreased local insulation quality.



Figure 2.11: Asymmetrical positioning of the conductors inside a resin insulated joint.

2.2.8 DRYING OUT OF IMPREGNATED PAPER



Figure 2.12: Example of the treeing activity through the different layers of impregnated paper insulation.

High loads on power cables locally cause the mass in the impregnated paper insulation to dry out. Due to the increased temperatures, the mass will dry up, leading to an increase of the viscosity of the mass/oil, causing the formation of cavities between the paper layers. Especially the mass around the conductor will dry out, due to the highest temperatures in these locations. PD activity will occur in these cavities, leading to treeing in the paper insulation. The electrical tree will grow layer by layer [112], finally reaching the earthed outer conductor. An example of treeing activity in impregnated paper insulation is shown in figure 2.12.

2.2.9 CONDUCTOR PROBLEMS

Press-connections are used in cable accessories for linking of the conductors. These connections can be imperfect due to mechanical stress caused by the

operation or the environment. These bad connections may cause heating due to resistive losses. The insulating material around the press connections may be overheated. Overheating, especially of solid materials, cause local cracking. The cavities, which occur due to the cracking process, lead to PD activity and further degrading of the insulating materials.

2.2.10 REMAINING SEMI CONDUCTIVE LAYER

Synthetic power cables are constructed with semi conductive layers between the conductor, the polyethylene insulation and the earth screen. For the mounting of cable joint or terminations, the semi conductive screen between the insulation and the earth screen has to be peeled for connection to the field grading shield of the accessory. During the peeling process, small parts of this semi conductive layer might remain on the surface of the XLPE.

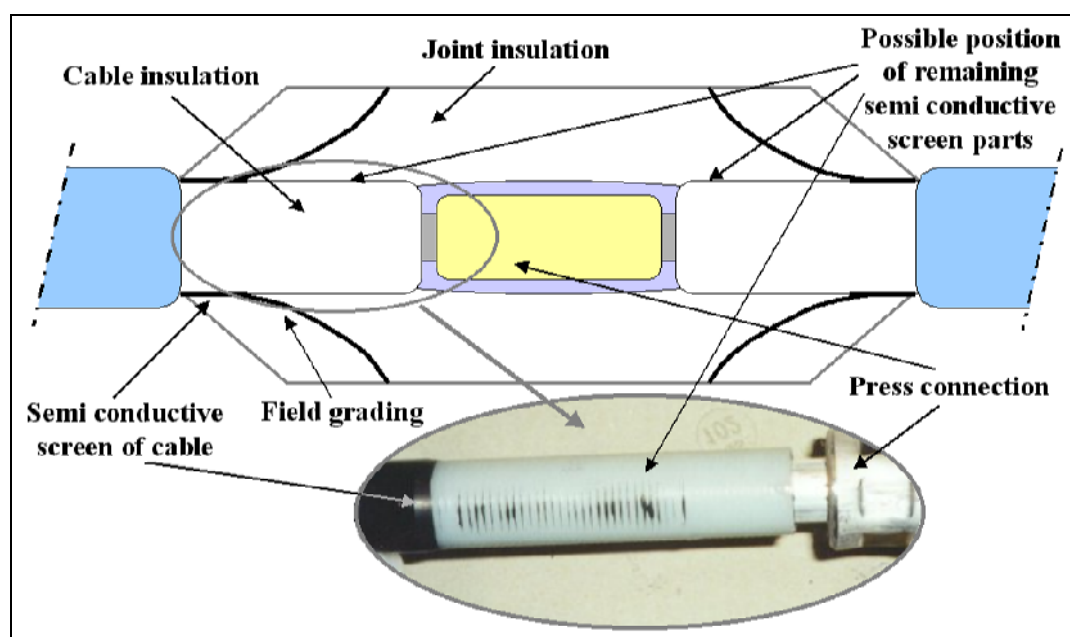


Figure 2.13: Reflection of the positioning of remaining semi conductive parts, as a result of inaccurate peeling the semi conductive screen from a polymeric insulated cable.

These semi conductive parts are situated on the boundary between the cable insulation and the accessory's insulation, see figure 2.13. The semi conductive parts in these position lead to electric field concentrations, resulting in PD activity in those positions of the accessories where the tangential field strength is high. As a result of the PD activity at the boundaries, deterioration of the accessory insulation and cable insulation will occur.

2.2.11 FIELD GRADING MOVEMENT

Due to the applied small dimensions, especially in polymeric insulated cable accessories, field grading is very important. The dimensions of cable accessories are larger than the cable, so the field distributions in the insulation differ. Capacitive or resistive field grading is used to gradually distribute the electric field. For optimal field grading, an accessory has to be accurately positioned for the connection between the stress cone and the semi conductive screen of the cable. Wrong positioning of the stress cone causes a locally increased field at the end of the cable's semi conductive screens.

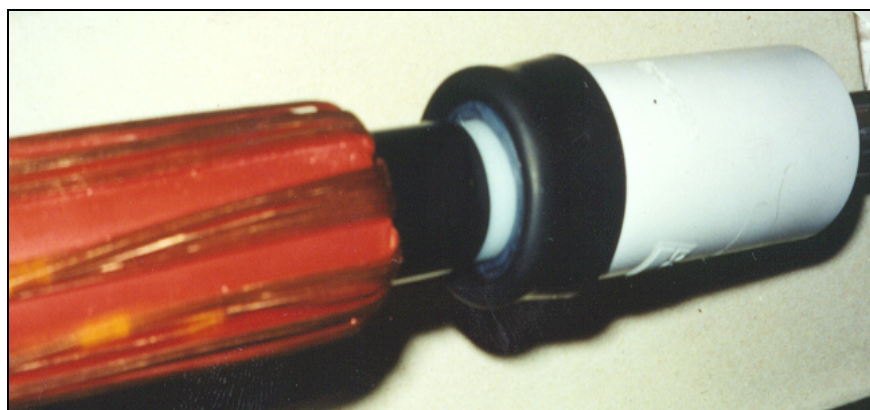


Figure 2.14: Reflection of bad positioning of field grading. Increased axial field occurs at the end of the outer conductive layer.

Two situations of bad positioning of field grading can occur. Defects can occur if the semi conducting screen is peeled away too far, which results in a gap between the stress cone and the insulation screen (figure 2.14). A field

concentration occurs at the end of the semi conductive screen, outside the field grading. PD activity will occur at this position where field occurs parallel to the cable insulation surface. As a result, surface discharges will occur at the end of semi conductive screen over the XLPE insulation.

If the accessory is moved over the cable insulation too far, the insulation screen will be disturbing the field grading. Again a disturbed field will occur at the end of the insulation screen, on the boundary between the cable and the accessory. Partial discharges will occur at the boundary, degrading the insulation. However, the electric field will not be as high as for the gap between the semicon and the stress cone. Therefore, the first situation is indicated as more critical than the second.

2.2.12 WATERTREES

As a result of the presence of water, an electric field and a temperature gradient in the cable insulation, chemical changes occur in the synthetic insulating materials, initiating water trees [6,75,118]. The water tree grows mainly in the direction of the electric field. Vented trees are fan-shaped and

grow in the radial plains. Bow-tie trees are originating from voids or contaminations [62] and grow in radial directions. As the tree progress over the cable insulation becomes critical, an electrical tree is initiated from the tip of a water tree, bridging the final part in the insulation. Such electrical trees are only present in the insulation during a couple of minutes, after which breakdown follows.

2.3 INSULATION DEGRADATION MECHANISMS

The described different defects are actually degrading according different mechanisms. In many cases the breakdown of the insulation will be preceded by discharge activity, as shown in table 2-6. In this chapter the four major degradation mechanisms are studied.

2.3.1 INTERNAL DISCHARGES

Internal discharges in power cable insulation can be caused by cavities or interfaces. The electrical stresses in the cavities are dependent on the shape and location [9] of the particular cavity. The breakdown strength of a cavity depends on its dimensions and the type and the pressure of gas. Gas-filled cavities may also be formed by local breakdown sites due to field concentrations around conducting inclusions. Due to PD activity from the inclusions a cavity is formed at the PD site. Furthermore, treeing can be initiated from an inclusion in solid materials or discharges in oil can occur from inclusions, as will be described in later sections.

The degradation process due to PD activity at the cavity surface is accompanied by chemical processes. Chemical reactions occur between the constituents of the ambient air in the cavity as well as reaction in which the polymer is involved [90]. During the first stage of the degradation, after just a short period of exposure to discharges, a layer of small droplets is formed on the surface of the polymer [89]. Most by-products are of an acidic nature.

In the second stage, after longer periods of discharge activity, local crystallisation of the droplets occurs at the points of impact of the discharges [31]. Solid by-products are present on the polymeric surface in the form of single crystals of oxalic acid [89]. The crystals with the presence of moisture are of conductive nature and have sharp edges [74]. In this way the field at the crystals is enhanced giving rise to increased discharge activity. The increasing discharge activity at the cavity surface leads to more and bigger crystals, increasing the PD activity.

In the final stage, clusters of the crystals are formed on the surface of the polymer. At the edges of these clusters field intensification occurs, giving rise to increased discharge activity, which result in the erosion of the dielectric surface. The edges of the crystals are eroded and craters are formed in dielectric surface below the crystals [89]. Figure 2.15 shows a drawing of the cluster formation of crystals, with the accompanied erosion of the cavity surface.

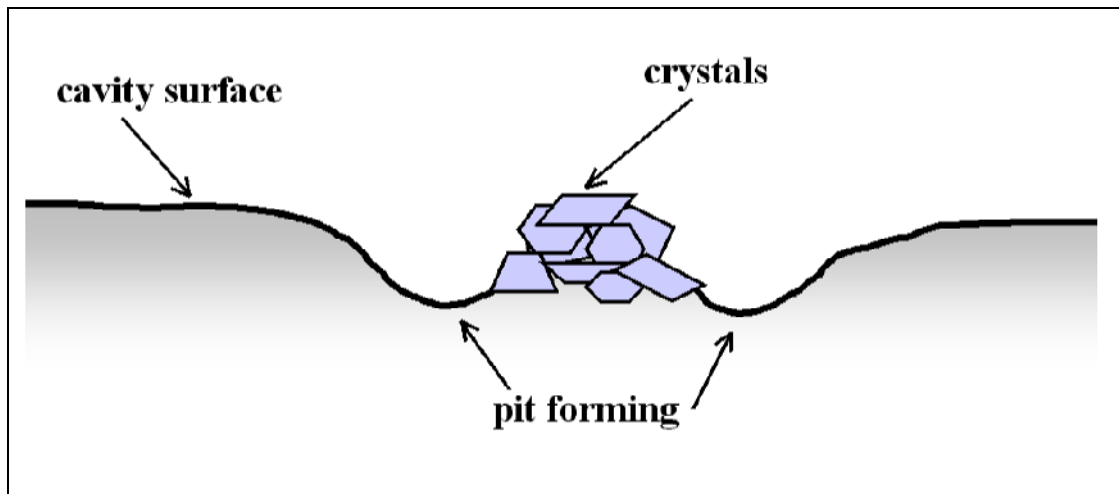


Figure 2.15: Schematic drawing of the degradation of cavity surfaces in polymeric insulating materials.

The pits around the crystal clusters grow deeper and deeper until a small channel is formed by the preferable discharge locations. The field strength at the end of the channel reaches the intrinsic breakdown of the insulating materials [68,74], leading to treeing (see § 2.3.3).

2.3.2 SURFACE DISCHARGES

Surface discharges occur at the boundary of different materials close to an electrode. For power cables, these can be boundaries between paper, oil (mass), air and polymers.

OIL/SOLID INTERFACE

Surface discharges on boundaries between oil and solid insulating materials have a different process of degradation. Due to the released energy of the continuous discharge activity, the oil insulation around the high voltage electrode will carbonise. Increased PD activity will occur caused by the field intensifications at these carbonised spots on the surface of the solid insulation. From the preferable locations of PD activity tracking activities will occur at the interface between the solid and the oil insulation [114].

OIL/AIR INTERFACE

Surface discharges on the surface of oil and air will also lead to carbonisation of the oil. These carbonised parts may float on the surface of the oil. The number of carbonised oil parts will increase due to the PD activity. Bridges of carbonised parts may be formed between the HV conductor and the earth screen over the surface of the oil, decreasing the electric strength and leading to a breakdown over the oil surface.

POLYMER/AIR INTERFACE

The degradation of polymer/air interfaces by discharges is accompanied by chemical changes of the polymeric surface. The chemical changes result in the formation of crystals on the surface [74]. Clusters of large crystals are formed with a high density close to the electrode (for cables the semi-conductive screen). Further away from the electrode, the density and the sizes of the crystals decreases. At the clusters of crystals, field intensification will occur, increasing the discharges activity. After sufficient long time of PD activity, tree-like erosion on the insulating material surface will occur [114]. The tree may originate at one of the cluster of crystals [51]. The track will grow over the surface of the polymeric material, bridging the electrodes (figure 2.16).



Figure 2.16: Treeing over the surface of polymeric insulation material in a cable joint.

2.3.3 ELECTRICAL TREEING

SOLID INSULATION

Electrical treeing in solids starts from defects like inclusions (conductive or insulating), cavities or protrusions on the conductor. After a relative long time compared to the actual tree process, the insulating material is eroded by discharge activities at the defects, in the same way as described for cavities. A channel is formed at the tip of the eroded insulation [75]. At the tip of the created breakdown channel field intensification occurs. Due to the increased

field strength at the tree tip, new breakdowns over short distances of the insulating materials occur. The tree grows very intermittently; it grows in those directions where the intrinsic breakdown of a small part of the insulation is crossed. At the stem of the tree, branches are formed in multiple directions, which will grow hollow. This pattern of tubules will grow until the tree transverses the electrodes [10].

PAPER INSULATION

Electrical trees in paper oil insulation are growing in a different way than those in synthetic materials. The discharges in the cavities adjacent to the HV conductor will damage the first paper-layer of the insulation [61]. After some time, this paper-layer will breakdown. Now, the PD activities will take place over the surfaces of the next layer, perpendicular to the electric field. The impregnated paper's surface will carbonise and a tracking path is formed between the paper layers [112]. At the butt gaps⁶ between the paper tapes, e.g. with cavities, the tree will grow to the next layers of paper due to the locally high tangential field concentration, see figure 2.17. The tracking path will grow in opposite directions as the direction of the field changes every half period of the voltage. As the next butt gap is reached, the process will repeat and the tracking path will grow layer by layer.

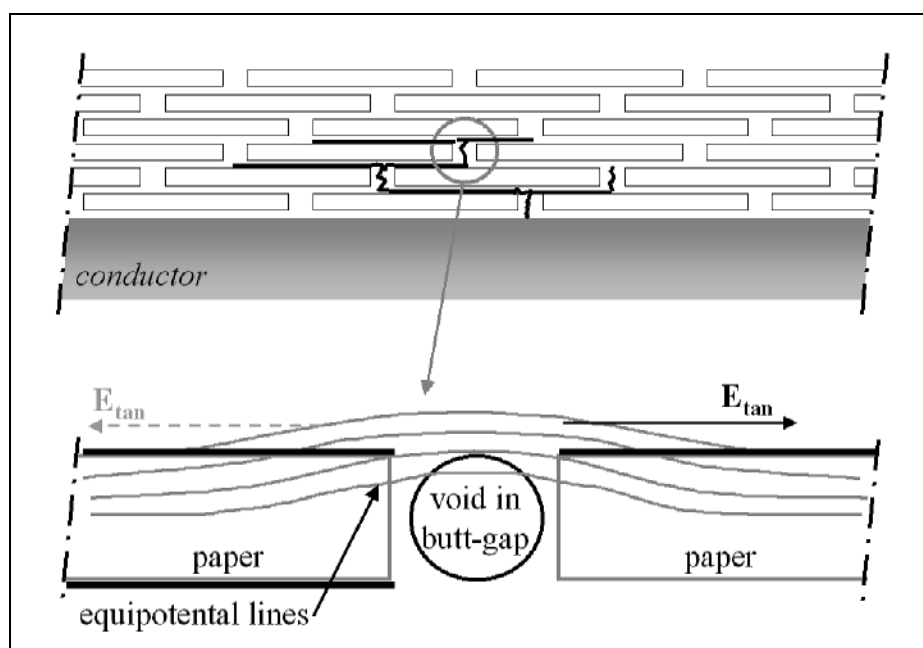


Figure 2.17: Representation of the degradation of paper insulation. The voids in the butt-gaps result in a tangential electric field. In this way PD will occur on the surface of the paper layers and will cross to the next level of paper as the next butt-gap is reached.

⁶ A butt gap referred to as the space between the different paper tapes at the same level of the total insulation thickness [112], as shown in figure 2.17. These butt gaps are generally filled with mass (or oil), but may also contain cavities.

The tree will eventually grow from the HV electrode in the direction of the earth screen crossing the paper layers in between. As the treeing process evolves, one of the branches will approach the earth screen and a full breakdown will occur.

2.3.4 DISCHARGES IN OIL

The electric strength of insulating oil is not dependent on the oil itself, but to a large extent on the impurities of the oil. Metallic dusts, cellulose fibres and dissolved gasses are of great significance for the insulating qualities of oil. A result of the contaminations in the oil is that the dielectric strength of the oil decreases [73].

Apart from these contaminations, sharp metallic edges from conductors may be starting points for PD in oil. Under the influences of PD, carbonisation through local overheating and the formation of acids can occur in the oil. Furthermore, higher moisture content in the oil increases the number of PDs at unchanging magnitudes [14]. Partial discharges under oil enhance the release of gases. The released property of different gas types is dependent on the released total PD energy, see figure 2.18. Typical gas types as may occur after discharge activity under oil [64] are nitrogen (N_2), oxygen (O_2), hydrogen (H_2), acetylene (C_2H_2), methane (CH_4), ethylene (C_2H_4) and ethane (C_2H_6).

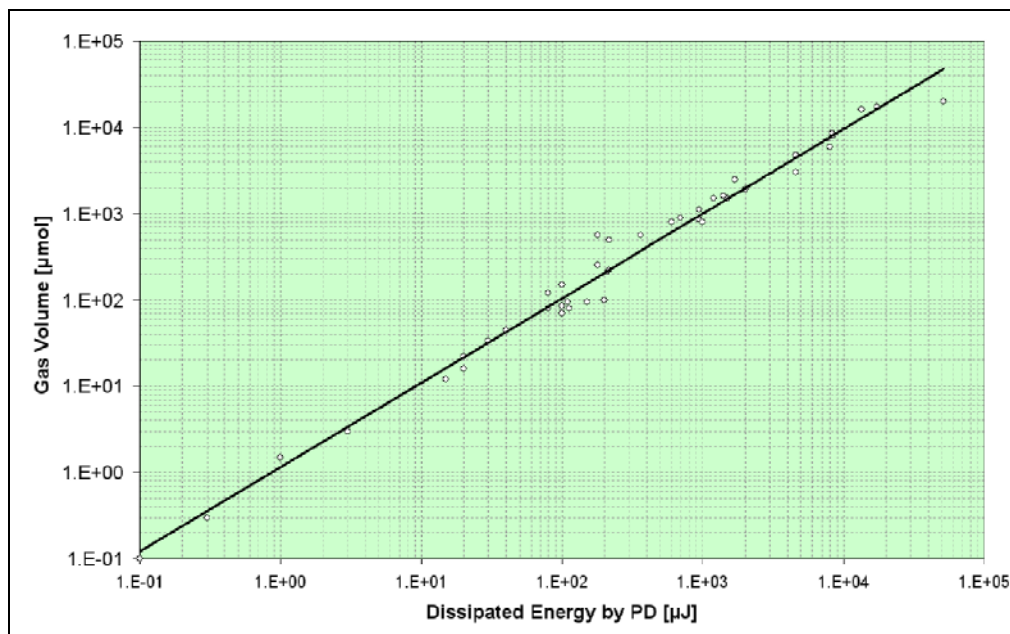


Figure 2.18: Relation between the generated gas volumes and the dissipated energy by PD activity [120].

Apart from the usual reduction of the insulation strength due to dissolved gases, gas bubbles can also form large voids in specific edges of the construction, initiating discharge activities.

2.4 INSULATION DETERIORATION SYMPTOMS

Evaluating the typical insulation defects and their introducing factors for the distribution power cables, it follows that PD activity may be involved in the degradation process. Table 2-6 shows an overview of the degradation processes for the different defects, which may occur in cable insulation. This overview shows that partial discharges are responsible for the intermediate or final stage of the deterioration processes (e.g. in the form of electrical treeing). From the described deterioration processes, partial discharges can be indicated as important symptoms to determine the presence of degradation processes in cable insulation.

Moreover, defects may be accompanied by PD activity, where the PDs are not responsible for the deterioration, but are just indicators for defects. E.g. cracking of insulating material (due to tension) may result in increasing fissure sizes, which will involve PD activity, as shown in figure 2.19. PD phenomena are for the described reasons a sensitive detection parameter to recognise and localise, the presence of the major part of the defects in the different cable components.



Figure 2.19: A slice of a cable joint, showing a large crack in the centre of the joint. The joint showed high PD activity during the diagnosis of the cable system.

Table 2-6: Overview of the degradation processes, which may occur in the different insulation systems of a power cable network.

Defect	Degradation process
Low oil level	Boundaries → surface discharges → tracking
Moisture penetration	Local increase of electric losses → overheating → PD
Protrusions on connectors	Local field concentrations → PD → electrical treeing
	Local field concentrations → PD → gas formation → decrease of dielectric strength
Cavities/fissures	PD → electrical treeing
Drying out of mass	Increase of viscosity → cavities → PD → treeing
Damaged outer screen	Local field concentration on outer screen → PD → electrical treeing
	Water penetration → local increase of electric losses → embrittlement of paper layers
Semi conductive parts	Local field concentration → PD → electrical treeing/tracking
Field grading movement	Local field concentration → surface discharges → electrical treeing/tracking
Conductor problems	Local overheating → cracking → cavities → PD → electrical treeing
Bad hardened resin	Cavities → PD → electrical treeing
	Moisture penetration → increase losses → cracking → PD → electrical treeing
Watertrees	Inferior insulation characteristics → electrical treeing

2.5 CONCLUSIONS

In this chapter, the typical defects that occur in the cable insulation and the resulting insulation deterioration are investigated.

- 1) The defect introducing factors for power cables are the operational stresses, the environmental stresses and the human influences. The latter stress is mainly involved at the start of the lifetime of a cable component during the on-site assembly. The operational and environmental stresses occur during the lifetime of the cable component during the operation. Some of the above-mentioned stresses cannot be prevented.
- 2) Investigations on disturbed components by visual inspections over the years have revealed the typical defects that occur in the power cable network. Table 2-7 shows an overview of the typical defects for the applied cable insulation and accessories.
- 3) The insulation degradation mechanisms related to the various defects can be reduced to four different types; degradation in cavities or fissures, degradation on surfaces, degradation by treeing and degradation by discharges in oil.
- 4) Insulation deterioration symptoms of the typical defects are identified by discharge activity, in the intermediate stages or final stages. As a result, partial discharges are characteristic diagnostic property to detect, which recognises the presence of these defects.

Table 2-7: Typical insulation defects for cable components.

Defect type	PILC accessories	PILC insulation	XLPE accessories	XLPE insulation
Asymmetrical conductor positioning	X			
Bad hardened resin	X			
Cavities/Fissures	X	X	X	X
Conductor problems	X		X	
Contaminations	X		X	
Decreased oil level	X			
Drying out of mass		X		
Embrittlement				X
Field grading movement			X	
Interface problems			X	
Moisture penetration	X	X	X	X
Protrusions on connectors	X		X	
Remaining semi-conductive layer			X	
Watertrees				X

3

PD OCCURRENCE AND LOCALISATION IN POWER CABLES

Power cables may contain various types of partial discharge (PD) sources. To detect and localise these PD sources inside a cable system, several techniques are possible on-site, such as acoustic detection and electrical detection [24,82]. Also other techniques, like optical detection, are available for PD detection in power cables [18], but these are not commonly applied in the field.

The major part of buried power cables in the world are characterised by:

- a. there is no or difficult physical access to the cable except for the two terminations, because the cables are buried in the ground;
- b. typical lengths are often longer than 500m, which means one or more cable joints are present in a cable system;
- c. mixed insulation types and different types of accessories may occur in one cable system;
- d. operational and maintenance history may have different influences on the insulation condition during the service life.

Considering these points, electrical detection of partial discharges at one of the cable ends is practically the most effective way to perform on-site PD diagnoses. At the termination, physical access to the cable conductors is possible. After disconnection from the network, the cable system can be energised by an external power supply for the ignition of the PD sources.

Surveying the literature, most theories and experiences in the field of PD detection and location in power cables are based on laboratory testing at cable factories. To provide analyses of PD occurrences in power cables in service, understanding of the presence and detection of PD is discussed in this chapter. General aspects as distortion attenuation during propagation affect the PD waves before the detection. The location of the PD sources along the cable length can

be analysed by PD pulse analyses in the time domain [66,67]. This technique can be applied on cable systems which consist of only one type of insulating material, e.g. XLPE. For cable systems in service consisting of multiple insulation types, the location evaluation procedure has to be corrected in order to reach accuracy in the location of defects in the field. This chapter discusses the corrected localisation method for these mixed insulated power cable systems. Cable systems consisting of one type of insulation are referred to as single type insulated power cables system. Cable systems consisting of more than one type of insulation are referred to as mixed insulated power cables system.

3.1 PD OCCURRENCE IN POWER CABLES

For better understanding of the discharge process and discharge measurement, different electrical models are developed to describe the combination of defect and dielectric. The capacitance model (*abc*-model) of the dielectric defect gives the most popular description of the recurrence of partial discharges at AC voltages. By means of this equivalent circuit, the magnitude of the discharge and energy transfer can be estimated, see figure 3.1. The amount of charge, which is displaced by the discharge current in the leads of the sample, is referred to as the apparent charge q_i , which is defined as:

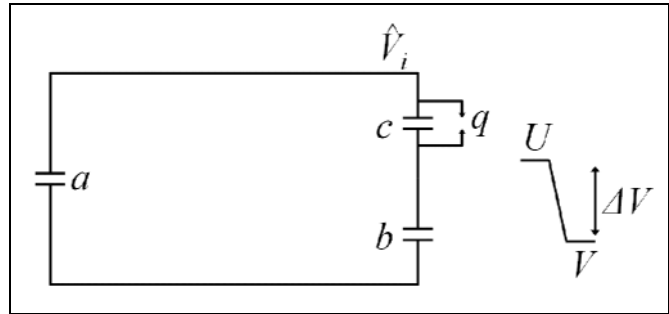


Figure 3.1: The equivalent circuit for PDs, where *a* represents the sound part of the insulation configuration, *b* represents the dielectric in series with the defect *c*. The discharge magnitude is defined as the charge displacement q in the sample, usually expressed in picocoulombs.

$$q_i = b \cdot \Delta V \quad (3.1)$$

where b is the capacitance in series with defect c and ΔV is the voltage drop across the defect.

Electrical discharges that do not completely bridge the distance between two electrodes produce patterns of current impulses in the leads of the sample. If the voltage V_c (figure 3.2) across the defect reaches the breakdown voltage U^+ , a discharge occurs in the defect. The voltage drops to V^+ where the discharge extinguishes. The voltage drop takes place in a time of just a few nanoseconds [11,90] (in some cases tens of ns). After the discharge has been extinguished, the voltage V_c over the defect increases again.

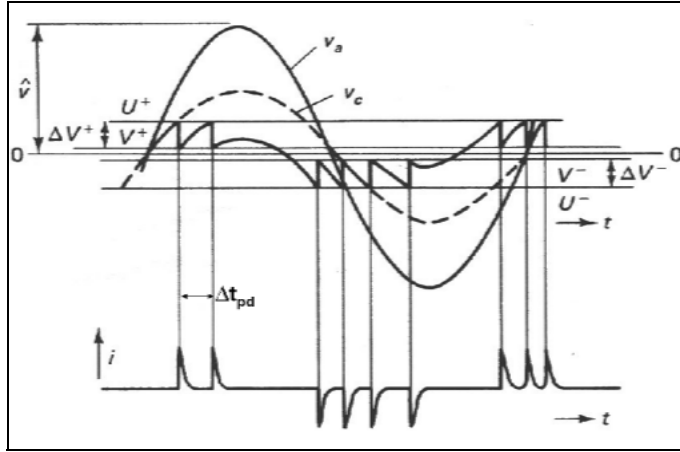


Figure 3.2: Principle of the recurrence of partial discharges in a defect during one AC power cycle.

When the voltage V_c reaches U^+ , a new discharge occurs. This happens several times, after which the voltage V_a over the sample decreases and the high voltage V_c drops to U^- where a new discharge occurs. In this way, groups of recurrent discharges, which occur during positive half, and the negative half of the voltage cycle will be found.

Long lengths of cable behave like a transmission line and can therefore not be treated as a lumped capacitor for PD analysis. If a partial discharge occurs in a cable system, the resulting current pulse will travel away from the original location. After multiple nanoseconds [67], the discharge ceases and a travelling wave of several metres is formed. At the measuring side of the cable ($Z_{detector} \gg Z_{cable}$), a (full) reflection of the PD wave will occur. Now, the PD wave will travel to the remote end of the cable system (open during measurements) where a full reflection occurs again. This process repeats until the PD wave is attenuated, partially due to reflections at impedance changes (like joints), but also due to attenuation and dispersion during propagation in the cable insulation.

In a normal lossy single-core power cable, the propagation constant γ of a cable can be expressed by the attenuation factor α [Np/m] and the phase constant β [rad/m]. The propagation constant γ can also be expressed by the wave frequency and the cable characteristic parameters R (conductor resistance), G (dielectric conductance), L (inductance) and C (capacitance) [65,115]:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L) \cdot (G + j\omega C)} \quad (3.2)$$

As a cable behaves like a transmission line, the capacitance a in figure 3.1 should therefore be replaced by the characteristic impedance of the cable. The characteristic impedance Z_0 of a cable is defined by:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{L}{C}} \left[1 + j \left(\frac{G}{2\omega C} - \frac{R}{2\omega L} \right) \right] \quad (3.3)$$

The characteristic impedance magnitude of a power cable varies strongly as a function of the frequency [4]. If a cable is supposed to be free of losses, Z_0 becomes pure resistive and dependent on the ratio between L and C .

The propagation velocity v of a travelling wave on a line is given by ω/β [65]. If the line is lossless ($R=0$ and $G=0$) or if R and G are negligible to ωL and ωC respectively, this propagation velocity can be determined as:

$$v = \frac{1}{\sqrt{LC}} \quad (3.4)$$

The propagation velocity of travelling waves in lossless or very low loss power cables is determined by the geometry and dimensions of the transmission line and the dielectric constant of the insulation (as the permeability of the insulation materials is approximately 1) [115]. For a coaxial lossless power cable (single-core cable), the propagation velocity can be estimated by equation 3.5, where r_{out} and r_{in} represent respectively the outer and inner radius of the power cable insulation:

$$\begin{cases} L = \frac{\mu_0 \mu_r}{2\pi} \ln\left(\frac{r_{out}}{r_{in}}\right) \\ C = \frac{2\pi \epsilon_0 \epsilon_r}{\ln\left(\frac{r_{out}}{r_{in}}\right)} \end{cases} \quad c_0 = \frac{1}{\sqrt{\mu_0 \cdot \epsilon_0}} \rightarrow v = \frac{c_0}{\sqrt{\mu_r \cdot \epsilon_r}} \quad (3.5)$$

As the permeability of the insulating materials is approximately 1, the propagation velocity of PD in PILC ($\epsilon_r \sim 3.5$) and XLPE cable ($\epsilon_r \sim 2.2$) can approximately be calculated with equation 3.5 as approximately 160m/ μ s and 200m/ μ s respectively. However, in practice lower velocities will be found in the applied power cable types. Especially due to the construction of a three-phase cable with a twist of the conductors, the velocities will be lower in practice.

Figure 3.3 shows the diagram for a cable with a discharge source. A discharging defect can be represented by a current source, which injects an amount of charge into the cable. The cable insulation impedance at both sides of a defect is determined by the characteristic impedance Z_0 . This means that a partial discharge of magnitude q_i , will be divided into two waves (each initiated by a charge of $q_i/2$), which

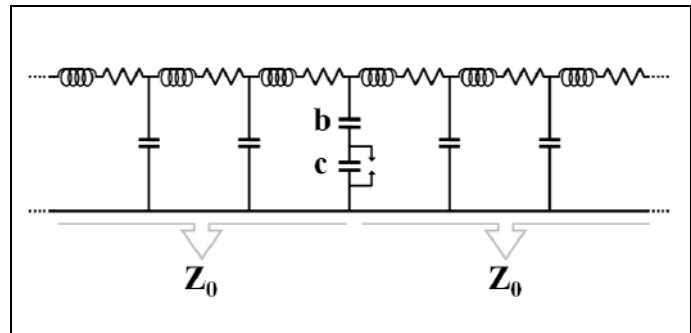


Figure 3.3: Equivalent circuit of a power cable with a discharging defect.

travel into opposite directions. The PD voltage wave magnitude across Z_0 , which is detected by the measuring equipment at the cable end, is proportional to the original magnitude of the discharge, supposed that the cable is free of losses [67]. Consequently:

$$\left| \int_0^{t_0} u_{pd} dt \right| = Z_0 \cdot \frac{q_i}{2} \quad (3.6)$$

where t_0 is the pulse width.

However, during propagation of a PD wave through a cable, the wave amplitude is attenuated and its width is enlarged, see figure 3.4. Injected pulse A is travelling through the cable. A' is the pulse after the first travel time to the opposite cable end and backwards. This means that the time Δt_c between A and A' is the propagation time of twice that cable length. A'' is the pulse after travelling through the cable twice etc. The distortion of a PD pulse is caused due to its varying of the characteristic impedance and the propagation velocity as a function of the frequency.

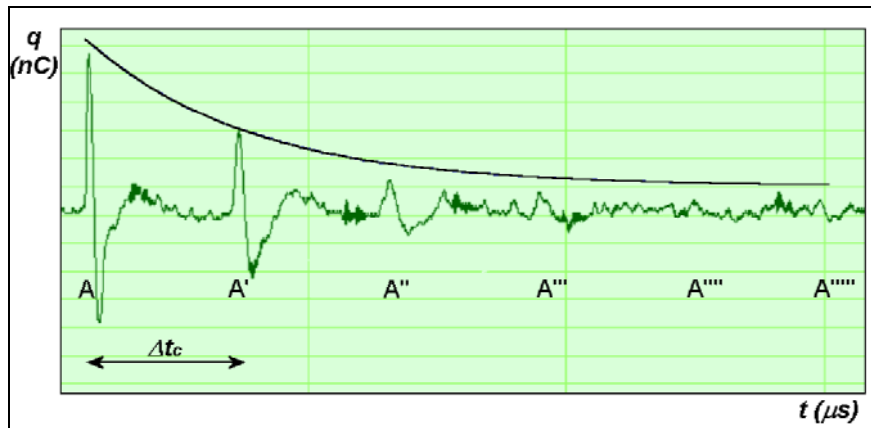


Figure 3.4: Pulses obtained from a 10kV single core XLPE cable after injection of artificial PDs, which are exponentially attenuated during the propagation through a cable sample.

A travelling wave decreases in first approximation exponentially over a distance x [64,67]. The voltage wave which propagates through the cable can be reflected as [115]:

$$u'_{pd} = u_{pd} e^{-0.5[(R/Z_0) + (Z_0 G)]x} = u_{pd} e^{(-x/\alpha)} \quad (3.7)$$

where u_{pd} is the original PD pulse, x is the travelled distance and α is the attenuation constant of the cable insulation (dependent on the insulation type).

This means that the original PD in the cable insulation related to the travelling wave arriving at the detector (u'_{pd}) can be determined by:

$$q_i = \left(\frac{2}{Z_0} \right) \int_0^{t_0} u'_{pd} dt \quad (3.8)$$

The shape and the widthness of the detected PD pulses are dependent on the insulation characteristics and the detection circuit, resulting in detected PD pulses of microseconds [8]. Due the low-pass filter characteristic of power cables, lower frequencies pass through the cable practically undistorted while the higher frequency modes are subjected to serious damping [12]. The attenuation factor in equation 3.7 is therefore strongly frequency dependent [4].

3.2 PD LOCALISATION

3.2.1 PRINCIPLES OF PD LOCATION ANALYSIS

If a PD source is active in a power cable system, the occurring PD waves will travel away from the source towards both cable ends. Pulse detection is carried out by connecting the detector to one of the cable ends, while the other cable end is left open. This means a full reflection of the PD waves at the open side of the cable system, see figure 3.5.

The location of the PD activity can be determined by calculating the distance x_i by measuring the time difference between the incident⁷ PD wave and the reflected⁸ PD wave [58,67], as expressed in equation 3.9:

$$\begin{cases} t_1 = \frac{x_i}{v} \\ t_2 = \frac{(l - x_i) + l}{v} \end{cases} \xrightarrow{\Delta t = t_2 - t_1} x_i = l - \frac{v \cdot \Delta t}{2} \quad (3.9)$$

where l is the length of the cable, Δt is the time difference between the incident and the reflected wave and v is the propagation velocity of PD waves through the cable.

⁷ The incident PD pulse is referred to as the first arriving pulse from a PD event in a cable system.

⁸ The reflected PD pulse is referred to as the second arriving PD pulse from a PD event.

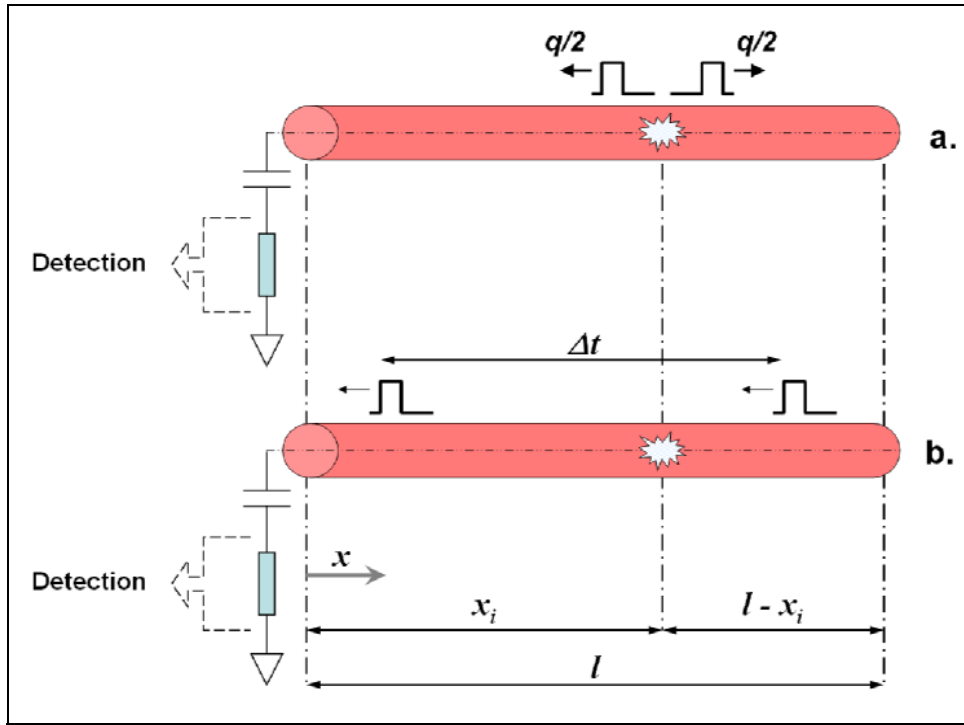


Figure 3.5: Principle of PD wave propagation and location in cables:

- a. just after ignition two PD waves travel in both directions;
- b. after reflection the PD waves travel in the same direction.

The detection can also be performed at both measuring sides at the same time, whereas both PD waves are detected at one of the cable ends. The distance x_i can then be determined by:

$$\begin{cases} t_1 = \frac{x_i}{v} \\ t_2 = \frac{(l - x_i)}{v} \end{cases} \xrightarrow{\Delta t = t_2 - t_1} x_i = \frac{l - v \cdot \Delta t}{2} \quad (3.10)$$

In practice, the velocity v is averaged for a particular cable system, and is usually determined by injecting standard calibration pulses into one end of the cable. The pulses travel through the length of the cable sample twice in a certain time interval. The propagation velocity can then be calculated by:

$$v = \frac{2 \cdot l}{\Delta t_{cal}} \quad (3.11)$$

Figure 3.6 shows a practical example of the calculation of the velocity in a three-core 10kV XLPE cable sample with a length of 1922 metres. The time difference between the injected pulse and the reflected pulse Δt_{cal} is $27.3\mu s$, which gives a propagation velocity of $140m/\mu s$.

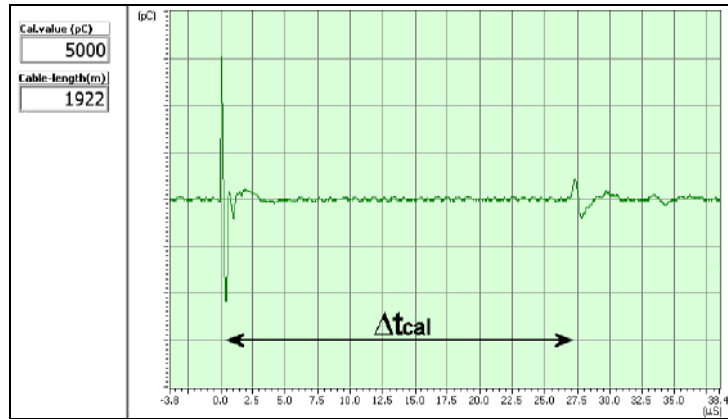


Figure 3.6: Example of the calibration of the propagation velocity in a XLPE cable system

A typical example of a PD location in a power cable is shown in figure 3.7. The first detected pulse is the incident wave of the PD event (*A*), after which the reflected wave (*B*) occurs. The incident wave is reflected at the detection side of the cable and if not attenuated to noise level, it will appear as *A'*. From the time difference between the incident and the reflected wave, together with the calibrated propagation velocity, the PD origin location can be calculated with equation 3.10.

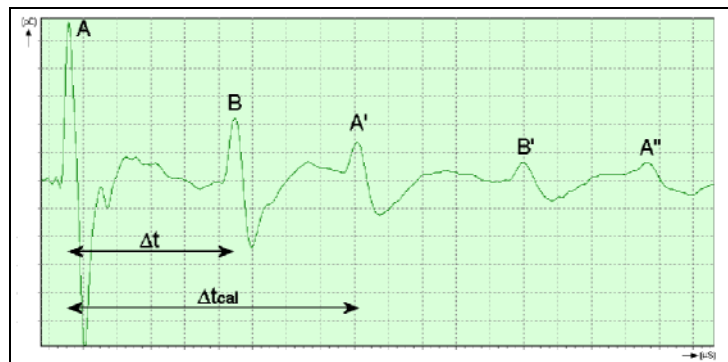


Figure 3.7: Example of the localisation of a PD source by analysing the PD wave time differences.

In the location analysis of PD, a systematic error occurs in the accuracy of the positioning of a PD source along the length of a power cable. This location inaccuracy is mainly caused by the pulse distortion during propagation and scatter due to noise. The PD location error for cable systems with known length⁹ is therefore less than 1% of the total length [72]. The location accuracy decreases for cable systems with unknown length.

If the time difference between the incident and the reflected wave is equal to the time difference between the injected artificial PD pulses at the calibration, this means that the PD occurs at one of the terminations. To determine in which of the terminations the PD site is located, the analysis of the pulse width is a useful tool. Figure 3.8 shows an example of two PD site locations in the same 10kV PILC cable with a length of 778 meters.

⁹ Cable system length can be accurately determined by applied build-in length indicators of the individual drums.

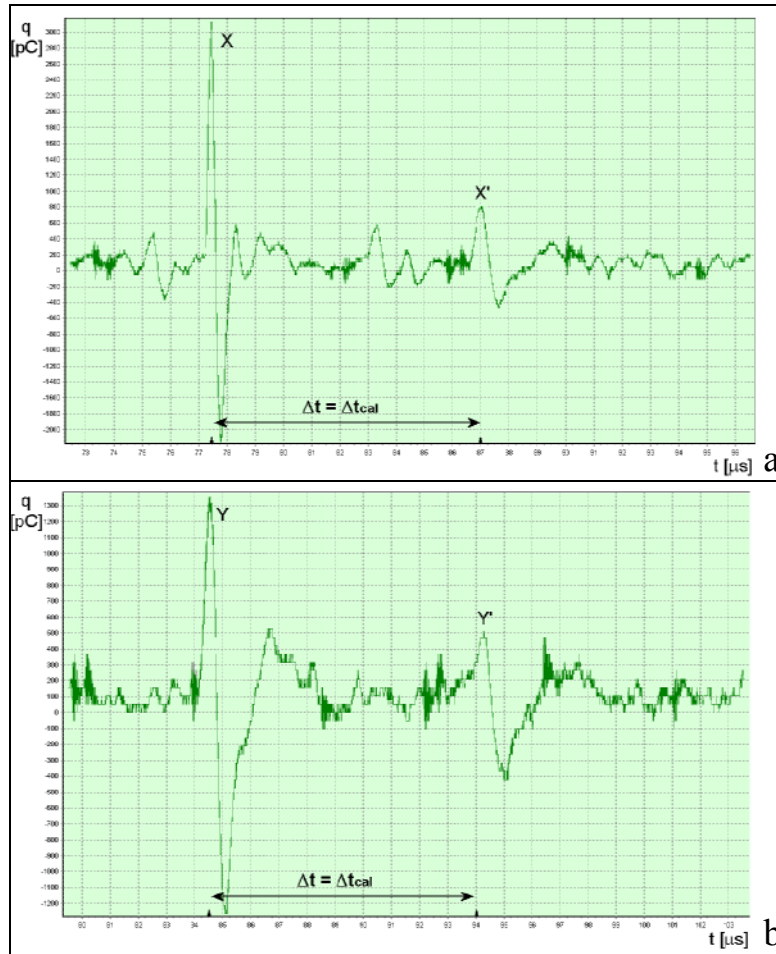


Figure 3.8: Measured PD pulses in the time domain obtained from cable terminations ($\Delta t = \Delta t_{cal}$).

- PD event originating from the near termination.
- PD event originating from the remote termination.

Recognition which termination is concerned can be performed by pulse width analysis. PD pulse Y is wider than PD pulse X .

frequencies will be filtered out by the cable insulation [12]. The PD pulse will become wider because of the distortion during the propagation through the cable insulation.

Another situation, that might occur, is superposition of the PD waves. If the time interval between the incident and the reflected PD wave is smaller than the duration of the incident PD wave, the detected PD pulses are superimposed, as shown in figure 3.9. In this example the localisation of a PD event in a 321 meters long 3-core PILC cable system is shown. The time Δt between the PD pulses A and B is shorter than the duration of pulse A . This PD event is localised at 277 meters. With an average pulse width of ~ 1 μs at the detection side of a power cable, this means for PILC ($v \sim 160$ m/μs) that for defects in the last 40 metres of a cable system, this superimposed PD pulse pattern may occur.

The PD event, as shown in figure 3.8a, originates from the near termination, while the PD event in figure 3.8b is originating from the remote termination. The time interval between the PD pulses is the same for both examples. However, the PD pulse X and Y clearly show different pulse widths, where PD pulse Y (remote termination) is wider than pulse X (near termination).

If the PD site is in the near termination, the propagation distance before detection is negligible. The detected PD pulse will contain higher frequency modes. On the other hand, PD occurring in the opposite termination is attenuated during the propagation of the cable length, before it is detected. The higher

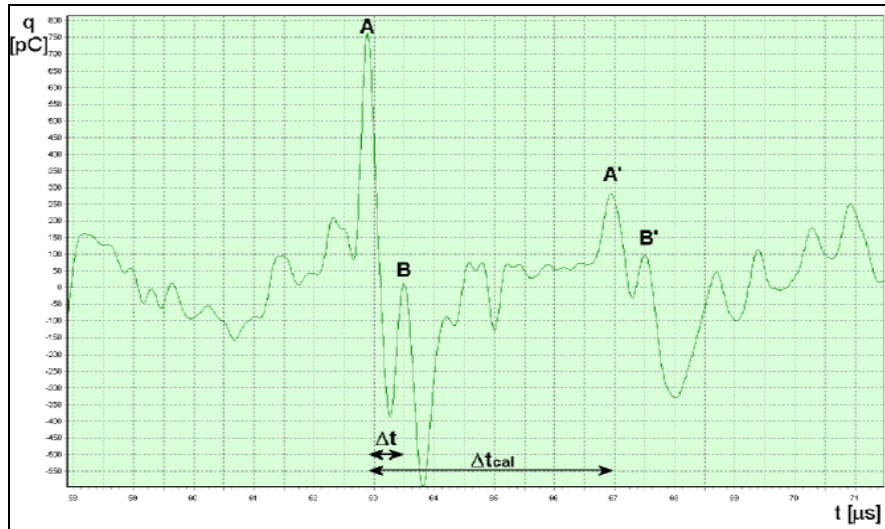


Figure 3.9: Example of the PD location of a PD event located closely (44m) to the remote end of a 3-core PILC cable of 321m. The resulting detected PD pulses are superimposed.

3.2.2 MULTIPLE DEFECTS PHENOMENA

During energising of a cable system in the field, multiple PD sources can be active at the same time. In that case, in a small time interval, multiple PD waves are detected from different locations along a cable length. Although the PD sources are ignited in a time interval Δt of several μs , they are still useful for localisation purposes, because they are distinguishable as a result of the high propagation velocity. This velocity, around $150m/\mu s$, results in a propagation time through the cable system of the incident and reflected wave for lengths up to 3 kilometres of several μs .

The data sampling and processing of the measuring equipment are also an influencing factor in the localisation sensitivity of PD events occurring in short time intervals. For functional localisation, the sampling rate of the measuring equipment should be at least 10MHz to recognise a PD wave of $1\mu s$. Furthermore, the processing time of the measuring equipment for one PD event should not exceed a few microsecond.

Figure 3.10 shows an example of different PD activities from two locations in a 270m long 3-phase PILC system. Three different PD events are shown as A , B and C . The incident PD pulses are indicated as respectively A_i , B_i and C_i , where the reflected pulses are indicated as A_r , B_r and C_r . The incident waves will travel back and forward through the cable, indicated by A_i' , B_i' and C_i' .

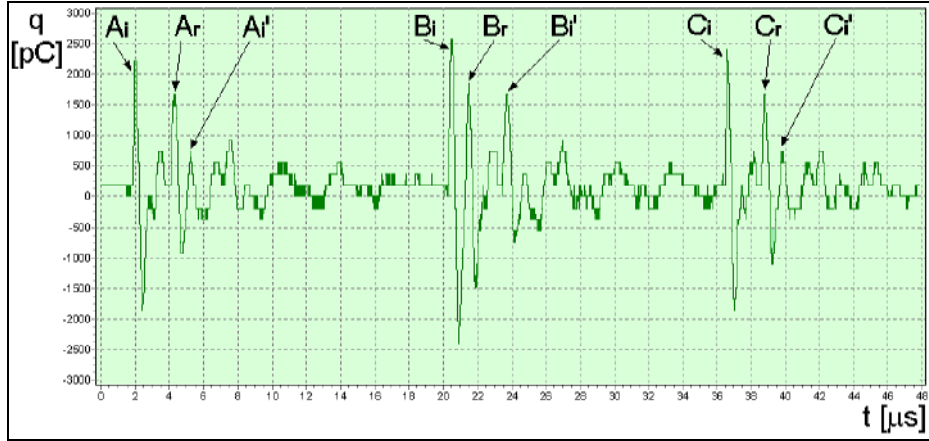


Figure 3.10: Multiple PD events occurring in a time span of $45\mu\text{s}$ only. Analysing the time difference between the incident pulses (A_i , B_i , C_i) and the reflected pulses (A_r , B_r , C_r) shows that successive PD events A and C are from the same location and event B from a second location.

From the time differences between the incident and the reflected PD waves, the origin location can be calculated according to equation 3.10. In this example, it is shown that in a time interval of $40\mu\text{s}$ three different PD events are distinguished. The time differences are equal for PD event A and C , about $2.4\mu\text{s}$, which means they both originate from the same location (could be different sources). For PD event B , the time difference is about $1\mu\text{s}$ and is therefore located in another position along the cable system. Although the time interval between the PD events A and C from the same location is only about $33\mu\text{s}$, the PD event at another location along the cable (B) is recognisable.

Analysing these PD locations needs an accurate selection of the matching incident and reflected waves. Partial discharges, which originate from different defects within a time-interval less than the propagation time of twice the cable system length (Δt_{cal}), may also occur during measurements, as shown in figure 3.11a. The two PD events, as obtained from a 664 meter 3-core PILC system, are indicated as S and T . In the location analysis, the incident and the reflected pulses of these PD events are overlapping. The incident pulse of PD event T (T_i) is detected before the reflected pulse of PD event S (S_r). The time differences between the incident and reflected pulses, Δt_S and Δt_T , are different, which means they originate from different locations.

The time interval between two successive PD events from the same defect can be less than a few microseconds [68]. If the propagation time of twice the cable system length (Δt_{cal}) is longer than the time between two PD events, the PD events from the same defects may result in overlapping pulse diagrams. Figure 3.11b shows an example of a measurement result obtained from a 610 meter 3-core PILC system. PD events Y and Z are originating from the same defect, as the time differences Δt_Y and Δt_Z between the incident and reflected waves are equal.

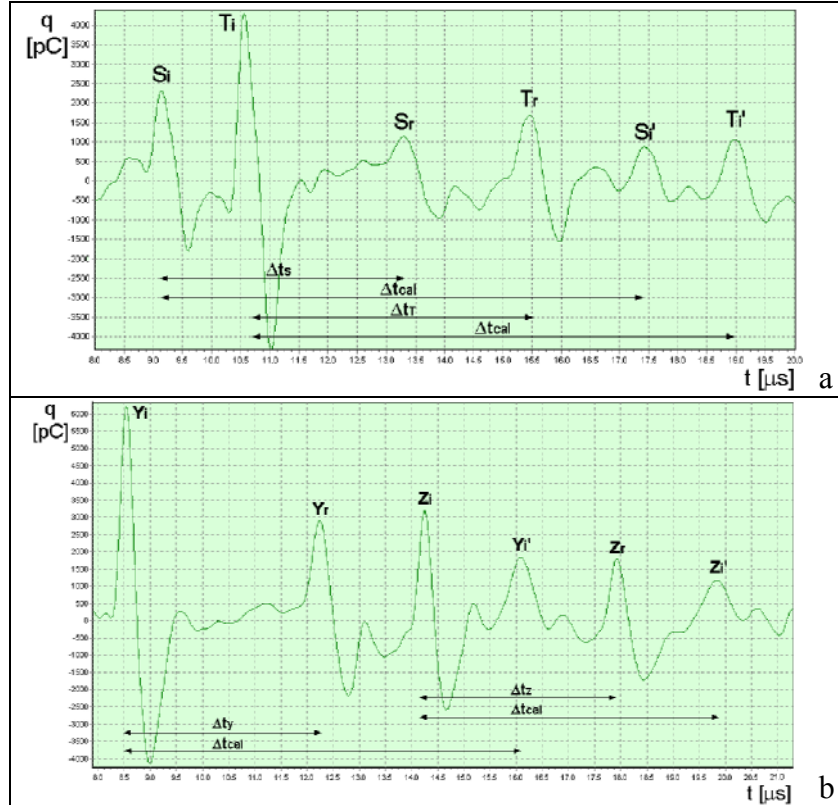


Figure 3.11: PD diagrams with disordered incident and reflected pulses from (a) different PD sources and (b) the same PD source. If the time-interval for two PD events is shorter than the travel time of the cable, the disordered pulses occur and accurate selection of matching incident and reflected PD pulses is required.

If the number of defects in a cable sample increases, the number of PD events will grow. This increases the probability of disordered PD pulses from different events. The time-interval where the reflected PD pulse of an incident pulse occurs, is proportional to the length of the cable sample. The probability of disordered PD events will increase with increasing cable lengths. Furthermore, the frequency of the test voltage is related to disordered PD events. An increased test frequency results in a steeper dU/dt . A steeper dU/dt of the test voltage means that the partial breakdown voltage of a defect is reached faster, according to figure 3.2. The time difference between the successive PD events of one defect will therefore be shortened. The disordered incident and reflected pulses from different PD events are thus dependent on:

- the number of defects, producing PD at particular voltage stresses;
- length of the cable sample;
- frequency of test voltage.

3.3 PD LOCATION ANALYSIS IN CABLE SYSTEM WITH MULTIPLE INSULATION TYPES

Due to the tendency to change from impregnated paper insulation to polymeric insulation for power cables, more and more situations occur where different insulation types are used in one cable system. These cable systems are called mixed insulated cable. Especially, cable extensions, cable repairs/replacements and cable detours are often done with polymeric insulated cable. The type of insulating material determines mainly the propagation velocity of PD waves inside power cables. As a result, applying PD diagnosis on these mixed insulated cable systems, errors do occur in the analysis of PD site locations.

Using the analysing method as described in equation 3.10 for mixed insulated cable systems, the calibrated velocity is the average propagation velocity of the applied insulating materials. The influence of cable joints is negligible due to their relative short lengths. Depending on the combination of practical lengths and materials, the location errors can be up to several percent of the total cable length. Therefore, another approach for the localisation of the PD source is required than the single cable type localisation as described by equation 3.10.

3.3.1 PD LOCATION ANALYSIS IN MIXED INSULATED CABLE SYSTEMS

The localisation method of PD in mixed insulated cable systems will be described for a cable system consisting of two cable parts and different insulating materials. Figure 3.12 shows a schematic view of a mixed insulated cable system, consisting of two cable parts of different insulation types with a length l_n and a propagation velocity v_n . If a PD occurs at location x_i , the incident and the reflected PD wave will travel different lengths of the cable parts.

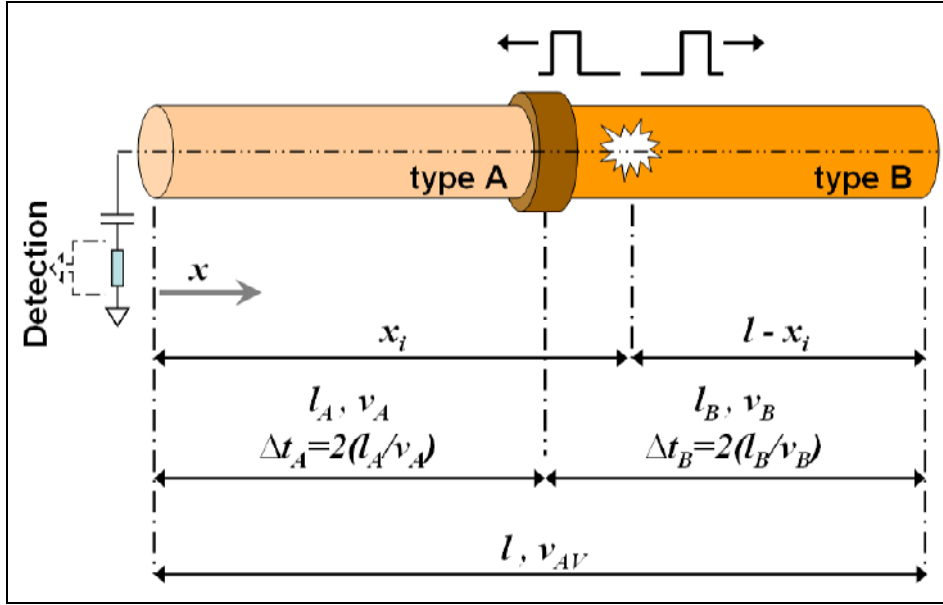


Figure 3.12: Schematic view of the propagation of PD waves in mixed (multiple insulation types) power cable systems. Each cable part is represented by a length l , a propagation velocity v and a travel time of twice its length of Δt . The influence of the joint is negligible for the localisation.

If the single cable type localisation technique is used for mixed cable systems, the analysis is performed using the calibrated propagation velocity, which is an average velocity. The propagation velocity for mixed insulated cable systems depends on the ratio between the lengths l_n of different types of cable parts and their characteristic propagation velocity v_n . The different lengths and velocities constitute the average propagation velocity v_{AV} that is obtained by calibration, as can be derived from (3.10):

$$v_{AV} = \frac{(l_A + l_B) \cdot v_A \cdot v_B}{l_A \cdot v_B + l_B \cdot v_A} \quad (3.12)$$

For the analysis of the PD origin locations in mixed cable systems, the time difference between the incident and the reflected PD wave is measured. The next step however is to find out from which cable part the PD wave is originating. Therefore, the detected time difference Δt_x of PD event x_i is compared to the (expected) travel time¹⁰ of the cable part most distant from the detection side (Δt_B). If Δt_x is smaller than Δt_B , the PD source is located in this cable part B. If $\Delta t_x > \Delta t_B$, the PD source is located in the nearer cable part A. If $\Delta t_x = \Delta t_B$, the defect is located exactly at the transition between the two cable

¹⁰ From the known length and the known propagation velocity, the expected travel time of a cable part can be calculated. Standard propagation velocities for different insulation types can be derived from other measurements on the same cable types: 3-phase PILC = 160m/μs; 3-phase XLPE = 138m/μs; 1-phase XLPE = 190m/μs.

insulation types. As a result, after the distinction from which cable part the PD event is originating, the locations of the discharge sources can be calculated by equations 3.13 and 3.14.

If the PD source is located in cable part B , which means that $\Delta t_x \leq \Delta t_B$, then

$$x_i = l - \frac{v_B \cdot \Delta t_x}{2} \quad (3.13)$$

If the PD source is located in cable part A , which means that $\Delta t_x \geq \Delta t_B$, then

$$x_i = l_A - \frac{v_A (\Delta t_x - \Delta t_B)}{2} \quad (3.14)$$

Figure 3.13 shows a practical example of a location error due to mixed insulated power cable. The cable sample consists of 465 m XLPE insulated and 561 m paper impregnated insulated power cable. The PD mappings show the individual PD locations along the power cable length for all phases (black dots represent the accessories). The upper PD mapping is analysed with the single cable location technique. The obtained result shows four PD concentrations (A at 0, B at 500, C at 645 and D at 955m).

If the measurements are analysed with equations 3.12-14 ($v_A \approx 140\text{m}/\mu\text{s}$, $v_B \approx 160\text{m}/\mu\text{s}$), a corrected PD mapping is obtained, as shown in figure 3.13b. The PD locations along the cable length have changed. The PD concentration A at 0m has not shifted of course, but the other three concentrations did:

- B shifted from 500m to 465m;
- C shifted from 645m to 620m, and
- D shifted from 955m to 949m.

The location correction is the highest close to the cable part transitions.

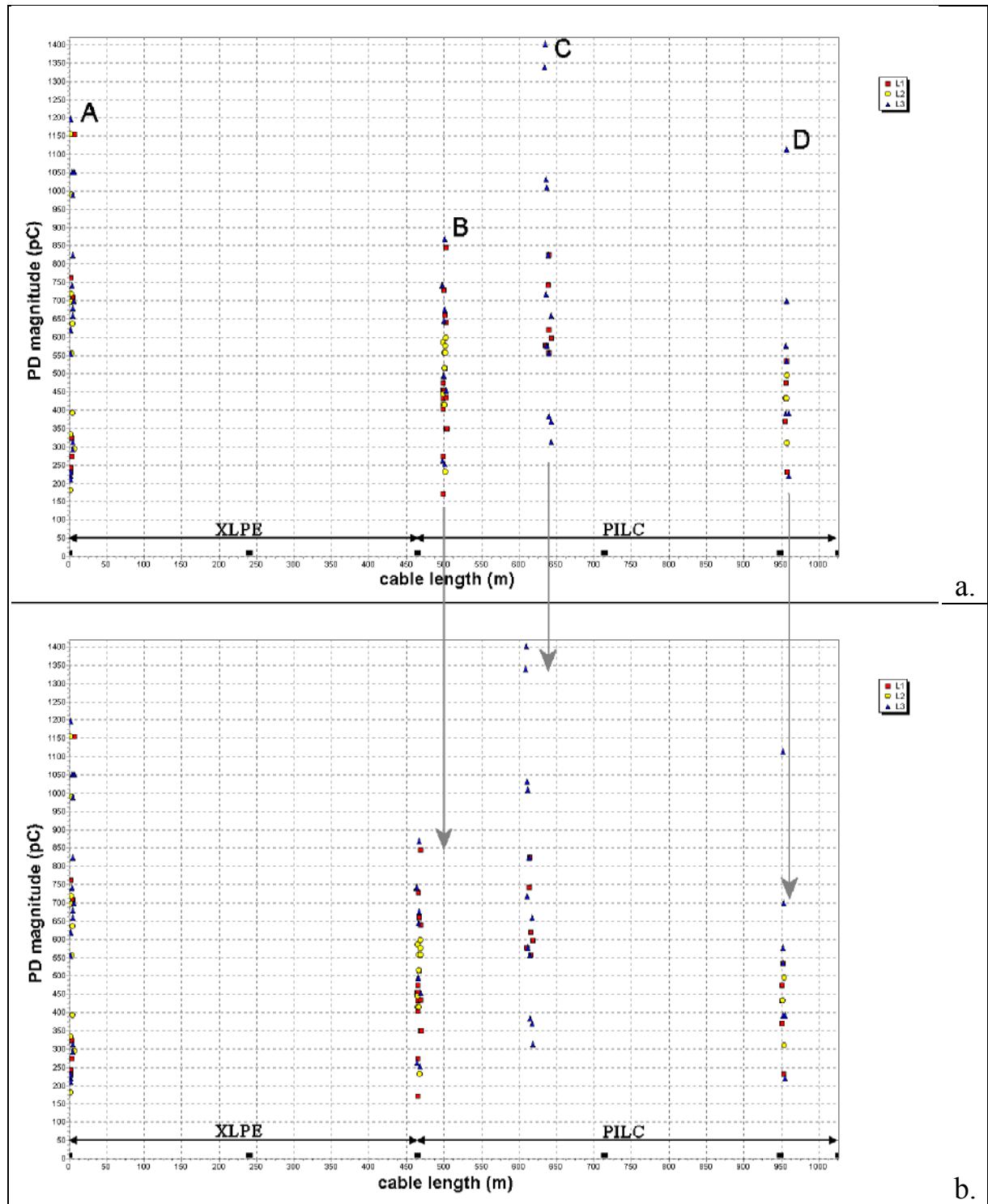


Figure 3.13: Practical comparison of the PD location in a mixed insulated cable system ($l_A=465\text{m}$, $v_A\approx 140\text{m}/\mu\text{s}$, $l_B=561\text{m}$, $v_B\approx 160\text{m}/\mu\text{s}$):

- PD mapping analysed with the average velocity ($\sim 150\text{m}/\mu\text{s}$);
- PD mapping analysed by equations 3.13 & 3.14 with the individual velocities.

The PD mappings, which are obtained using the single cable location method, can be corrected using equation 3.15. First, the position of the insulation type transition ($\Delta t_x = \Delta t_B$) should be located with equation 3.13. Next, the correct PD

locations have to be recalculated for the situations that the original location is before or behind the transition location.

$$\begin{cases} x_i \geq l - \frac{v_{AV} \cdot \Delta t_B}{2} & \rightarrow x_{ic} = l - \frac{v_B}{v_{AV}}(l - x_i) \\ x_i \leq l - \frac{v_{AV} \cdot \Delta t_B}{2} & \rightarrow x_{ic} = l_A + \frac{v_A}{v_B}l_B - \frac{v_A}{v_{AV}}(l - x_i) \end{cases} \quad (3.15)$$

where x_i is the location according to equation 3.10 and x_{ic} is the recalculated location according to equations 3.13 and 3.14.

Applying the correction to the example in figure 3.13a ($v_{AV} = 150\text{m}/\mu\text{s}$, $\Delta t_B = 7.01\mu\text{s}$), the calculated position of concentration B at 500m moves to 465m, according to equation 3.15. Even so, the concentrations C at 645m and D at 955m will shift respectively to 620m and 949m.

3.3.2 LOCALISATION DEVIATION

The systematic deviation of the location of PD sources, using the calibrated average velocity and equation 3.13, depends on the ratios of the applied lengths and the velocities of the different insulation types. Comparing the location results as obtained for the calibrated velocity in equation 3.10 (x_i) and the actual location (x_{ic}) from equation 3.13 and 3.14, gives the following location analysis deviation:

$$\begin{cases} \Delta t_{x_i} \leq \Delta t_B & \rightarrow x_{ic} - x_i = \frac{(v_{AV} - v_B) \cdot \Delta t_{x_i}}{2} \\ \Delta t_{x_i} \geq \Delta t_B & \rightarrow x_{ic} - x_i = \frac{(v_{AV} - v_A) \cdot \Delta t_{x_i}}{2} - l_B + \frac{v_A \cdot \Delta t_B}{2} \end{cases} \quad (3.16)$$

x_i is the location according to equation 3.10 and x_{ic} is the recalculated location.

The maximum deviation occurs where $\Delta t_x = \Delta t_B$, near the transition between the different insulation types. Figure 3.14 shows the results of the relative deviation in a mixed cable system with length l , assuming the two cable parts have the same length ($l_A = l_B$) and the propagation velocities are $v_A=160\text{m}/\mu\text{s}$ and $v_B=140\text{m}/\mu\text{s}$.

The maximum location deviation, as obtained in this situation, is more than 3% of the total cable length. The relative deviation is independent from the total cable length l and increases linearly from the remote end to the transition and decreases from the transition to the near cable end. The absolute location deviation will thus increase with an increasing cable system length, resulting in wrong locations for repair actions if the correct location analysis is not applied.

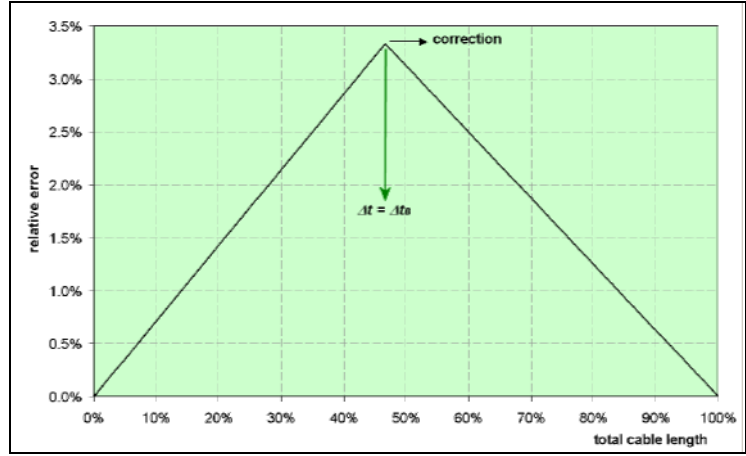


Figure 3.14: Relative location deviation in mixed insulated power cables systems using the calibrated v_{AV} instead of the separated velocities. The example shows a cable system with cable parts of equal lengths. In case $v_A > v_B$, the biggest deviation occurs close to the transition between the cable types, where $\Delta t_{xi} = \Delta t_B$.

As shown in figure 3.14, the location deviation can be determined for a full cable system, if the deviation at the transition is known. The relative deviation at the transition (for known velocities) can be determined from equation 3.16 with $\Delta t_x = \Delta t_B$, divided by l . The resulting equation for the maximum relative deviation (mrd) can now be expressed by:

$$mrd\left(\frac{l_A}{l_B}\right) = \frac{\left(1 - \frac{v_B}{v_A}\right)}{\left(\frac{v_B}{v_A} + \frac{l_B}{l_A}\right)\left(1 + \frac{l_A}{l_B}\right)} \quad (3.17)$$

As is shown in equation 3.17, the relative deviation in the single cable location method, depends on the ratios between the propagation velocities v_A and v_B and the cable lengths l_A and l_B .

Figure 3.15 shows an overview of the maximum location deviation, as calculated with equation 3.17, versus the ratios of l_A/l_B . The different curves show the results for different ratios of v_A/v_B . A positive deviation means that the location is further away from the measuring side. The single cable location calculation should be corrected by (a part) of the cable length. If $v_A > v_B$, the correction should be made away from the measuring side and if $v_A < v_B$ towards the measuring side of a cable system. The maximum values of the location deviation of the different curves can be derived differentiating equation 3.17:

$$\frac{l_A}{l_B} = \sqrt{\frac{v_A}{v_B}} \quad (3.18)$$

This means in practice, that if the different cable systems are of almost equal lengths, the location deviation is maximal.

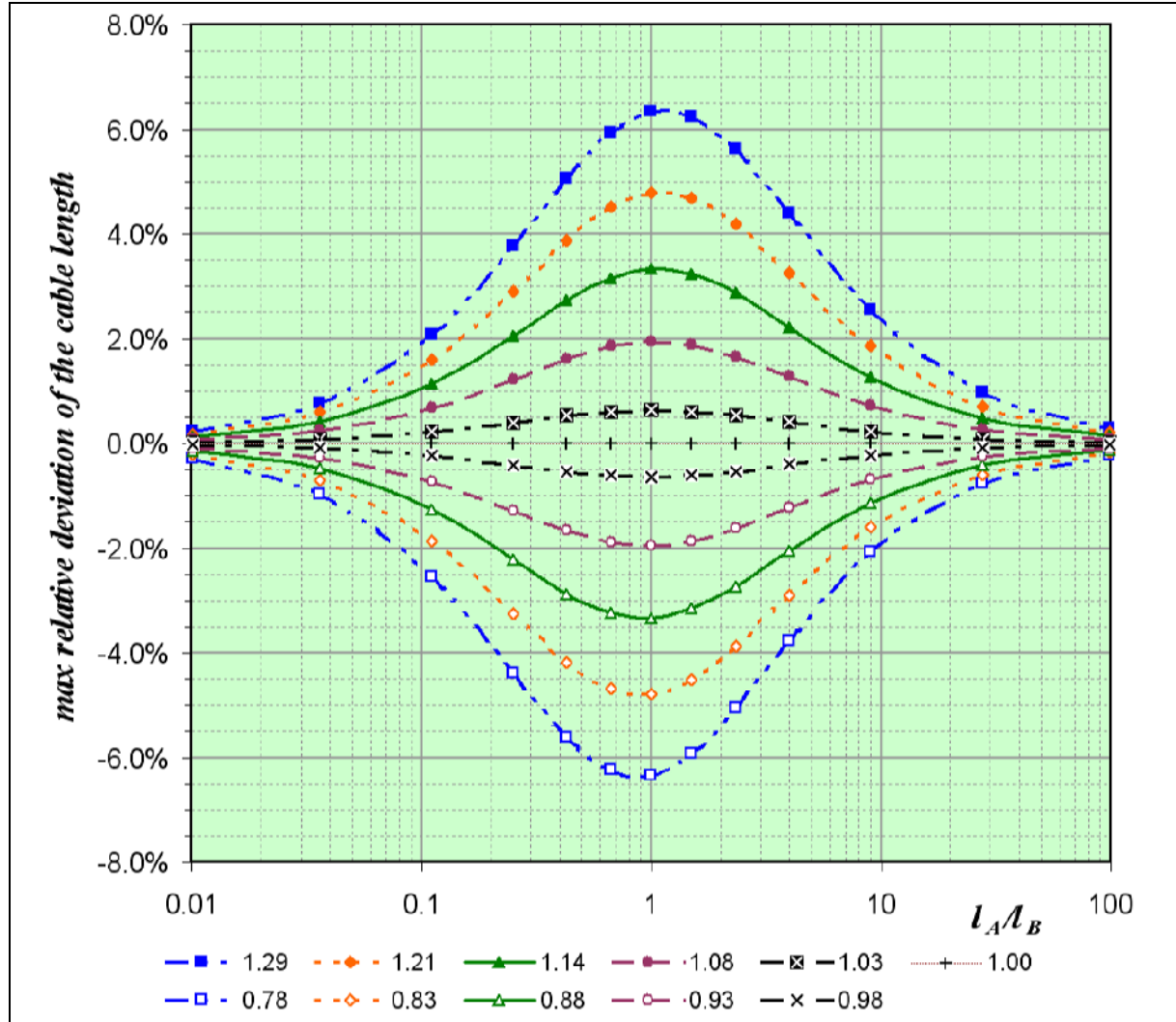


Figure 3.15: The relative deviation the cable system length in the PD location, made with single cable location techniques and average propagation velocities for mixed power cable systems with two types of insulation. The relative deviation becomes higher if the difference in the propagation velocities increases and shows a maximum.

Concerning the maximum location deviation using the single cable PD location method (§3.2), the following points can be concluded:

1. the localisation deviation increases as the difference in cable length at both sides of the transition decreases;
2. the localisation deviation increases as the difference in the velocities of the cable parts increases, independent on the cable part lengths;

3. the localisation deviation is maximal in that case where $l_A/l_B = \sqrt{(v_A/v_B)}$, independent on the combination of cable types (velocities);
4. if the velocity of a cable part is lower than the average velocity of the cable system, the correction is higher as compared to the cable part with a higher velocity than average velocity of the cable system.

In the example in figure 3.13a, the PD concentration B is located close to the transition. The ratios for l_A/l_B and v_A/v_B in this cable sample are respectively 465/561 and 140/160. According to figure 3.15, the maximum deviation is - 3.2% of the cable length (33m). The corrected location for PD concentration B becomes 467m.

3.3.3 PRACTICAL EXAMPLE

In practice, the correction of a PD mapping, analysed with the single insulation type location analysis can be performed using the graph in figure 3.15. If a cable system with different insulating materials is tested, the following steps can be used to determine the location deviation for each insulation transition:

1. calculate the ratio between the lengths of cable at both sides of the transition;
2. calculate the ratio between the average velocities of the cable at both sides of the transition;
3. use the combination as obtained in points 1. and 2. to find the correction factor in figure 3.15;
4. determine the position in the cable length for this correction by calculating the original position with equation 3.12, with the expected $\Delta t_x = \Delta t_{transition}$;
5. create the correction curves, which are the linearly connection between the correction maxim at the transition (and zero at the terminations).

An example of the above-described calculation procedure of the deviation curve is shown in figure 3.16. This example shows the obtained PD mapping (with single insulation type localisation) of a mixed insulated power cable of 1150m, with transitions located at 315m (from XLPE to PILC) and 890m (from PILC to XLPE). The different ratios and corrections are shown in table 3-1.

Table 3-1: PD parameters as obtained from the measurements on cable accessories with realistic mounted internal defects.

Transition between insulations	Length			Velocity			Correction to full length	Loc trans [m]
	l_{left} [m]	l_{right} [m]	ratio l	v_{left} [m/ μ s]	v_{right} [m/ μ s]	ratio v		
Transition 1	315	835	0.38	140	153.2	0.91	-1.9%	337
Transition 2	890	260	3.42	152.0	140	1.09	+1.6%	870

With the values as obtained in table 3-1, the correction curve can be made as shown in figure 3.16a. It shows that the PD up to ca 630m should be corrected towards the measuring side and the PD located right from 630m should be corrected away from the measuring side. The PD concentration in the joint at 605m should according to the correction curve, shift -0.25% of the cable length. This concentration shifts 3m to the left, which means it is actually just located at the joint, as a result of the general location deviation of $\pm 1\%$ of the cable length.

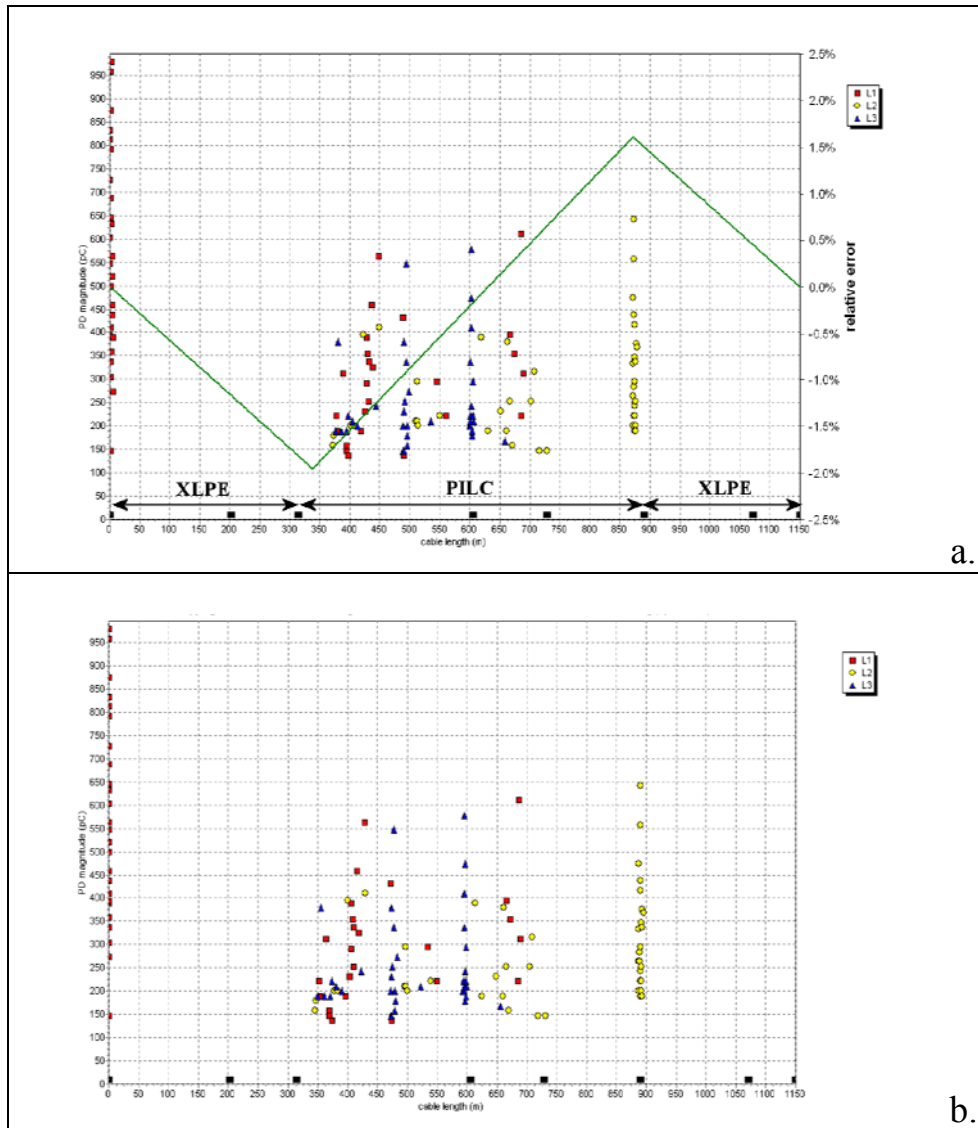


Figure 3.16: Practical example of the correction of PD in mixed insulated power cable circuits:

- PD mapping analysed according to single cable localisation method, together with the correction curve as obtained in table 3-1;
- Corrected PD mapping analysed by shifting PD according to the correction curve in the upper mapping.

Furthermore, the concentration at 870m is located exactly at the maximum of the correction curve, which means a shift of +1.6% of the cable length. The result of the shift is that the PD concentration moves 19m to the right and is actually located at the transition joint at 890m. Correction of all the PD in the upper mapping, will lead to a corrected PD mapping as shown in figure 3.16b.

3.4 GENERALISATION OF PD LOCALISATION

Figure 3.17 shows a schematic view of a mixed cable system, existing of N cable parts of different insulation types, each with a length l_n and a propagation velocity v_n . If a PD occurs at a specific location X , the incident and the reflected PD wave will travel different lengths of the various cable parts. The calibrated velocity for measurement is the average propagation velocity, which is expressed by:

$$v_{av} = \frac{2 \cdot l}{\Delta t} = \frac{2 \cdot (l_1 + l_2 + l_3 + \dots + l_N)}{\Delta t_1 + \Delta t_2 + \Delta t_3 + \dots + \Delta t_N} = \frac{\sum_{n=1}^N l_n}{\sum_{n=1}^N \left(\frac{l_n}{v_n} \right)} \quad (3.19)$$

where l is the total cable length, Δt is the propagation time of twice the cable length l and Δt_N is the propagation time of twice the cable length l_N .

For analysis of the origin of the PD locations in mixed insulated cable systems, the time difference between the incident and the reflected PD wave is measured. To find out from which cable part the PD wave is originating, the detected time difference Δt_X is compared with the sum of the (expected) travel times of the different cable parts, starting at the opposite cable part side (Δt_N). If $\Delta t_{Xc} < \Delta t_N$, the PD source is located in this cable part N . If $\Delta t_X = \Delta t_N$, the defect is located exactly at the transition joint between $N-1$ and N . If $\Delta t_X > \Delta t_N$, the PD source is located in the previous cable parts.

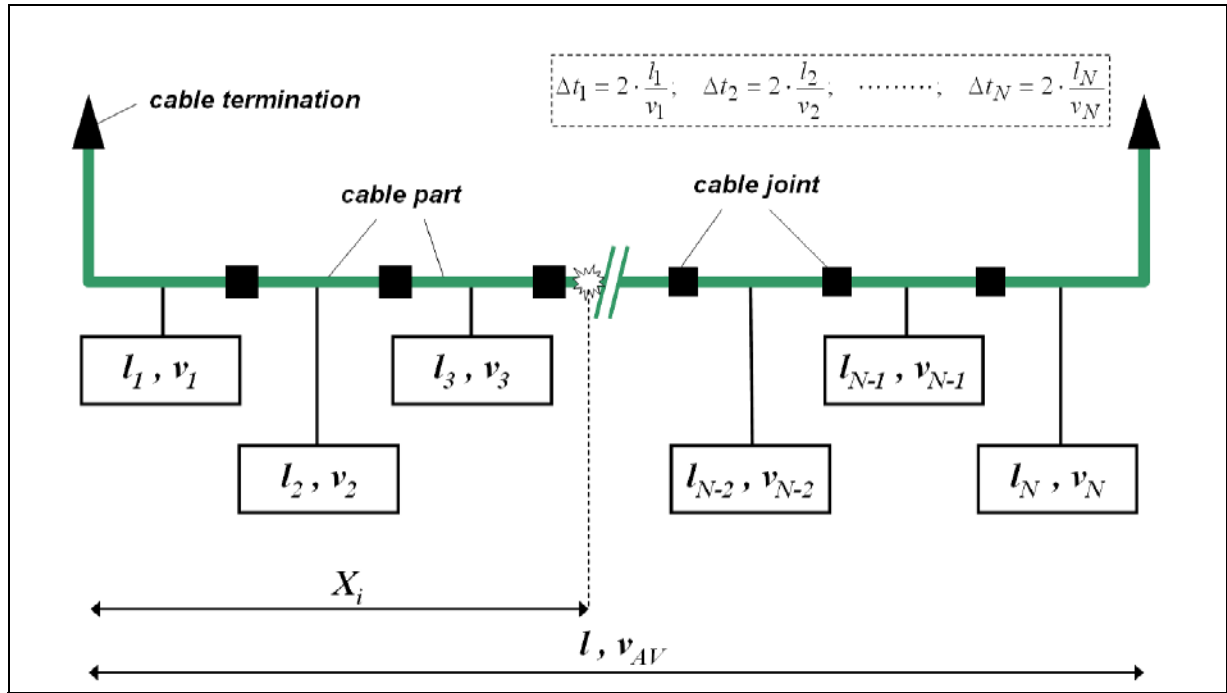


Figure 3.17: Schematic view of a cable system with N number of cable parts with different construction and insulating materials. For location analysis of mixed insulated cable systems, the cable part where the PD occurred at location X is determined from the time between the PD waves and the expected travel time of the different cable parts. The travel time of a cable part can be calculated by the known length and velocity (velocities for different insulation types can be derived from experience on the same cable types).

In the same way, the time difference Δt_X can be compared step by step for the pervious cable parts. If the travel time of the PD waves equals the travel time of (multiple) cable parts, the PD originates from one of the joints. As a result, after the distinction from which cable part the PD waves are originating from, the locations of the partial discharge sources can be calculated, according to the equations as shown in table 3-2.

So, after the distinction from which cable part the PD waves are originating, the locations of the PD sources can be calculated, according to the equation 3.20:

$$X_i = \left(\sum_{n=1}^Y l_n \right) - \frac{v_Y}{2} \cdot \left(\Delta t_X - \left(\left(\sum_{n=1}^Y \Delta t_n \right) - \Delta t_Y \right) \right) \quad (3.20)$$

where the PD is located in the Y^{th} cable part, determined by the time analysis, v_Y is the propagation velocity and Δt_Y the propagation time of that specific cable part.

Table 3-2: Overview of the calculation for the location of the PD events in power cables consisting of multiple insulation types. The time difference Δt_X is compared step by step with the sum of the (expected) travel times for the cable parts after which the location can be calculated.

Cable part	Detected time different of PD event compared to expected travel time	PD origin equation
N	$0 < \Delta t_X < \Delta t_N$	$X = (l_1 + l_2 + l_3 + \dots + l_N) - \frac{v_N \cdot \Delta t_X}{2}$
N-1	$\Delta t_N < \Delta t_X < \Delta t_N + \Delta t_{N-1}$	$X = (l_1 + l_2 + l_3 + \dots + l_{N-1}) - \frac{v_{N-1} \cdot (\Delta t_X - \Delta t_N)}{2}$
N-2	$\Delta t_N + \Delta t_{N-1} < \Delta t_X < \Delta t_N + \Delta t_{N-1} + \Delta t_{N-2}$	$X = (l_1 + l_2 + l_3 + \dots + l_{N-2}) - \frac{v_{N-2} \cdot (\Delta t_X - \Delta t_N - \Delta t_{N-1})}{2}$
$\vdots$	$\vdots$	$\vdots$
2	$\Delta t_N + \Delta t_{N-1} + \dots + \Delta t_3 < \Delta t_X < \Delta t_N + \Delta t_{N-1} + \dots + \Delta t_2$	$X = (l_1 + l_2) - \frac{v_2 \cdot (\Delta t_X - (\Delta t_N + \Delta t_{N-1} + \dots + \Delta t_3))}{2}$
1	$\Delta t_N + \Delta t_{N-1} + \dots + \Delta t_2 < \Delta t_X < \Delta t_N + \Delta t_{N-1} + \dots + \Delta t_1$	$X = (l_1) - \frac{v_1 \cdot (\Delta t_X - (\Delta t_N + \Delta t_{N-1} + \dots + \Delta t_2))}{2}$

3.5 CONCLUSIONS

In this chapter, several general and fundamental aspects of PD detection, localisation and recognition in service aged power cables have been investigated. From these investigations, the following conclusions can be drawn:

- 1) Location analysis of PD events in power cables requires interpretations of the resulted PD waves. Some PD location analysis cases need extra interpretation skills:
 - a) From the PD location calculation, no difference can be made between discharges occurring in the near or remote termination. Additional time-resolved analysis of the obtained pulse shape is required to distinguish from which of the terminations the PD originates;
 - b) PD originating close to the remote cable end will result in superposition of the incident and reflected PD pulses, in case that the time interval between the PD waves is smaller than the duration of the incident PD wave;
 - c) Multiple PD sources in a cable system can give overlapping PD processes in time. The disordering of the incident and reflected pulses from different PD events depends on the number of PD producing defects, the length of the cable system and the frequency of test voltage;
- 2) For mixed insulated power cables systems, a detailed localisation approach is required in stead of the single insulation power cables approach, due to the different propagation velocities in different insulating materials. Using the single insulation cable location analysis for mixed insulated power cable systems gives differences in the PD locations, which can be up to several percent of the total cable system length. The systematic deviation in the localisation depends on the ratios of the lengths and velocities of the differently insulated cable parts. A correction can be performed by separating the time interval into the individual propagation times of the cable parts. After determining the cable part from which the PD originates, the correct location can be determined by applying equation 3.22.

4

A DIAGNOSTIC TOOL FOR CABLE SYSTEM INSULATION

As described in chapter 2, most of the different types of insulation defects are related to PD activity. Therefore in principle, the high-risk cable systems in the power network in service can be identified by the detection, localisation and recognition of partial discharges (PD) at an early stage of possible cable insulation failure. The suspected parts or components of a cable system can be analysed over time by successive measurements, so that the need for replacements or repair actions can be noticed timely before a failure occurs.

The on-site detection of PD discharges in power cables can be performed off-line or on-line:

1. To perform off-line PD diagnostics, an external power supply is used to energise the cable system and to ignite the discharge related defects. As the cable is disconnected from the network, PD localisation can be performed as described in chapter 3.
2. In case of on-line PD detection, the power cable remains in service during the measurement. Active PD sources under the service conditions in all phases are detected, but the distinction between the phases is difficult.

As the power cable network under investigation is directly buried, the cable systems are only accessible at the cable terminations in the substations. For the further investigations in this thesis, only off-line PD detection is applied for the diagnoses of insulation condition. An on-line PD detection system is also investigated, which is based on the application of an external VHF PD sensor around the neutral (the cable earth connection to the substation earth) at the end of a cable system, as is described in appendix B.

This on-line PD diagnosis showed that it was in this form not effective enough as compared to off-line measurement for the following reasons [42,122,123]:

- Localisation of the PD in the cable length is not yet possible with the system. Extra pulse recognition is required to perform the location analysis, without the distinction between the phases.
- During on-line measurements, less in-depth analysis on the defects can be obtained as compared to off-line diagnosis, where tests are performed at various voltage levels instead of the operation voltage only. Hence, necessary information on PD levels at different voltages and PD inception voltage can be obtained from the PD related defects in the cable system.
- Calibration of the on-line VHF PD detection system according to IEC recommendations is not yet possible, so the PD levels cannot be quantified. Furthermore, comparisons of the PD properties between different cable systems are therefore not possible.
- The possibility to perform the on-line measurement strongly depends on the accessibility to the cable neutral of the switchgear type, the moment of measurement during the cable load cycle and the attenuation of the PD pulses (which is higher than with off-line measurements).

From these investigations, we concluded that the applied on-line PD detection is effective as a pre-selection tool for off-line diagnostics [123]. By measuring groups of power cables on-line, a pre-selection of those cables to be diagnosed in depth off-line measurement can be performed. Considering important utility aspects, e.g. operational and maintenance costs and the quality of information after the diagnosis, off-line PD diagnosis is still more sensitive and effective. In this chapter, the off-line on-site PD diagnostic tool based on damped AC voltages is described. Additionally, the obtained PD properties which are of importance for the condition determination are outlined together with the systematic field application of the system for on-site data collecting.

4.1 ON-SITE DIAGNOSTICS

For many years, DC withstand testing was the only testing method applied in the MV power cables network, but nowadays also AC testing is applied accompanied by PD testing. However, for some joints (especially the resin filled), the DC withstand test combined with PD test is the best option. Moisture penetration in the resin insulation, from the outside to the inside, generally does not result into PD activity. Because the moist part of the insulating material is more conducting, the rest (dry part) of the resin is stressed with almost 99% of the applied DC voltage and breaks down. Therefore, the DC test is effective for the moisture penetration and the PD measurements for other defects (cavities, protrusions) in these joint types. For the other types of joints and termination, PD testing at AC voltage stressing is the best diagnostic option. As shown in chapter 2, PDs provide sensitive symptoms of weak spots in the HV insulation.

For water-tree aged cables, other methods based on dielectric response e.g. return voltage, dissipation factor, dielectric spectroscopy or isothermal relaxation current are analysis methods recommended instead of PD detection.

In the last decades, a number of off-line energising methods have been introduced for the detection of PD related defects in power cables [79,80,83,108], as shown in table 4-1. External energising of the disconnected cable system is required for the ignition of PD sources. The detection equipment is therefore directly connected to the cable conductors (or through the switchgear). In this way, the different phases of the cable system can be energised and the high frequent PD pulses can be coupled out.

Table 4-1: Different energising methods for PD detection in power cables.

	Off-line energising voltage	On-line energising voltage
Continuous energising	20-200Hz AC voltages	50Hz line voltage
	Very Low Frequency (VLF) voltages	
Temporarily energising	<i>Damped AC (DAC) voltages</i>	-----
	Impulse excitation voltages	

The power P needed to stress the cable system is determined by the test frequency f , the cable capacitance C_{cable} and the test voltage U_{test} :

$$P = 2\pi \cdot f \cdot C_{cable} \cdot U_{test}^2 \quad (4.1)$$

The alternative voltages from table 4-1 are designed to decrease the required reactive power. The VLF method stresses the test object at 0.1 Hz frequency reducing the power by a factor 500. The DAC method makes use of linear DC charging current (see section 4.2) after which the cable oscillates with an air-core inductor, and no reactive power is necessary.

The required characteristics of excitation voltage sources for on-site PD measurements are:

1. The excitation voltage should ignite those PD sources in the cable, terminations and joints, which are also ignited under service conditions or under routine test conditions at the manufacturer and which will be harmful in the future;
2. The voltage source should cause no appreciable damage to the cable system during the time required to perform the measurements;
3. The amplitude of the excitation voltage should be adjustable;
4. The system must be resistant for on-site interferences and background noise of the system.

4.2 PD DIAGNOSTIC TOOL - OSCILLATING WAVE TEST SYSTEM

The off-line PD diagnostic tool as used for the conducted research in this thesis is based on the external energising of a cable system by damped AC (DAC) voltages. Originally, the DAC excitation is introduced as a withstand-voltage test for XLPE-insulated HV cables for commissioning purposes [2,3,29,78,106]. Nowadays, the DAC voltages are more and more used for non-destructive PD diagnosis of distribution power cables [125].

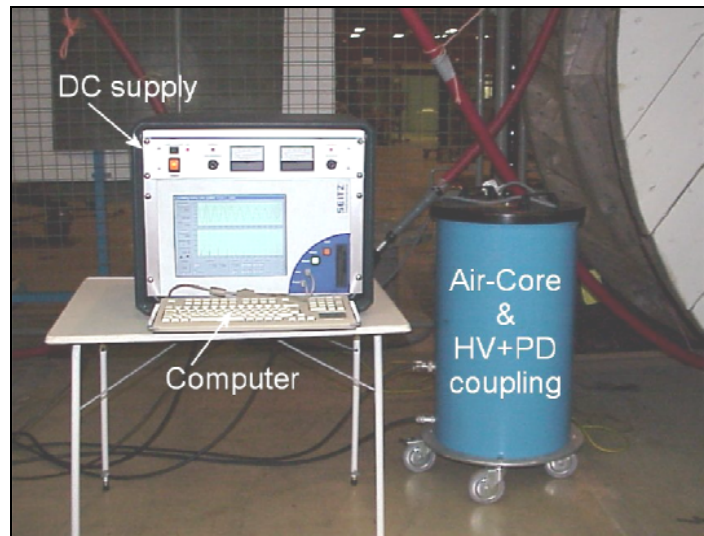


Figure 4.1: Application of the Oscillating Wave Test System (OWTS) on a cable sample in the laboratory.

The methods using DAC voltages for detection and localisation of PD in cables are known as Complex Discharge Analyses (CDA) [15] and Oscillating Wave Test System (OWTS) [39]. We have investigated the possibilities of OWTS in cooperation with Seitz Instruments. This tool, as shown in figure 4.1, is evaluated in the work of this thesis on its feasibility for preventive maintenance of power cables at distribution (next section) and transmission level (chapter 8).

4.2.1 TEST VOLTAGE EXCITATION SET-UP

For the generation of DAC voltages, the power demand remains low due to the cable charging with a DC power supply. After charging-up the cable is promptly switched in series with an external inductor. As a result, an oscillating voltage wave with a frequency as close as possible to power frequencies is used as an excitation voltage for PD detection. In figure 4.2 a schematic view of the DAC energising is shown.

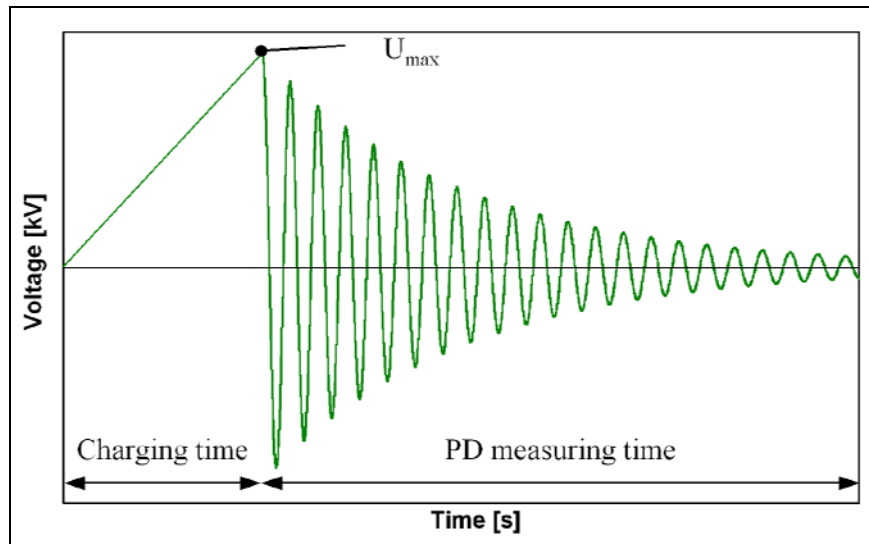


Figure 4.2: Schematic view of the damped AC energising as used for power cables.

Figure 4.3 shows the scheme of the energising method for DAC voltages for PD detection in power cables. The cable sample (represented as a capacitor) is charged linearly with a DC power supply (current) in a few seconds to the selected test voltage level. As soon as the cable is charged, the DC supply is disconnected and a solid-state switch connects the cable sample to an air-core inductor in less than $1\mu\text{s}$. In this way, an RLC loop is created and an oscillating voltage (damped AC voltage) wave is applied to test the sample for PD detection. Because of the fast closure time of the switch, almost no disturbances interfere with respect to the PD detection.

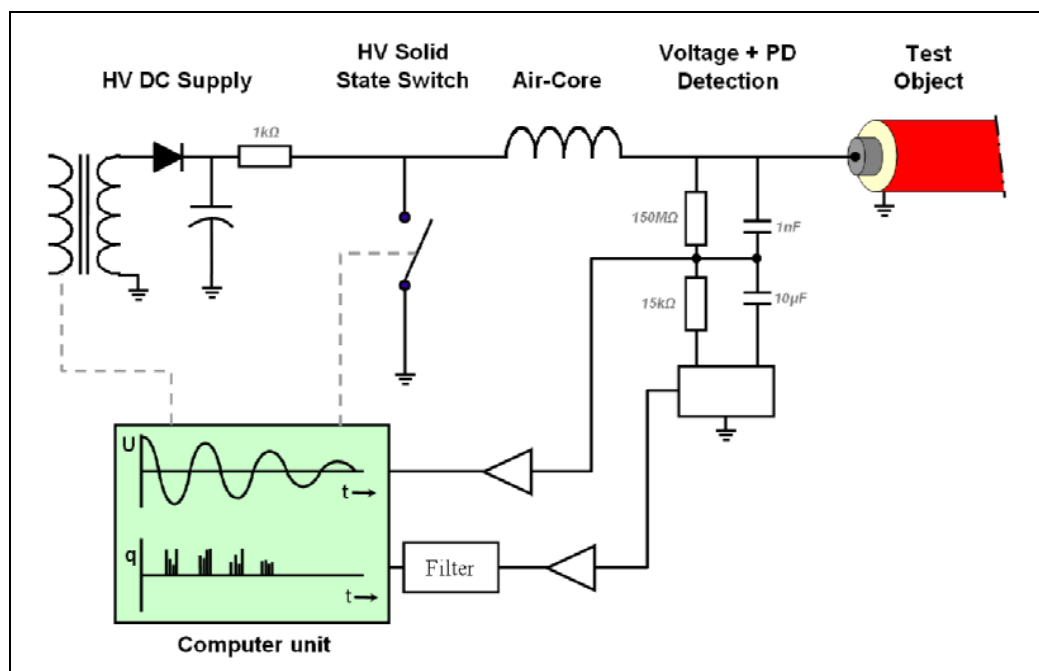


Figure 4.3: Schematic view of the OWTS diagnostic tool.

The resulting oscillating voltage is reflected as follows:

$$U(t) = U_0 \frac{\sqrt{\omega^2 + (\alpha_{DAC} - \beta_{DAC})^2}}{\omega} * e^{-\beta \cdot t} * \cos(\omega \cdot t + \theta) \quad (4.2)$$

with,

$$\theta = \tan^{-1} \left(\frac{\alpha_{DAC} - \beta_{DAC}}{\omega} \right) \quad (4.3)$$

$$\alpha_{DAC} = \frac{R_L}{L} = Q \quad (4.4)$$

$$\beta_{DAC} = \frac{1}{2} \left(\frac{L + R_L R_C C}{R_C L C} \right) \quad (4.5)$$

$$\omega = \sqrt{\frac{1}{LC} + \left(\frac{2R_L R_C L C - R_L^2 R_C^2 C^2 - L^2}{4R_C^2 L^2 C^2} \right)} \quad (4.6)$$

where L is the fixed inductance of the system (~ 0.8 H), R_L is its resistance (~ 20 Ω), C is the capacitance of the cable sample and R_C is its ohmic resistance. Furthermore, α_{DAC} reflects the quality factor of the system and β_{DAC} the damping factor of the oscillating voltage wave.

The linearly continuous DC charging of the cable sample up to a particular test voltage, directly followed by a switching and oscillation period, makes that no “steady state” DC condition occurs in the cable insulation [70]. The charging time of a cable, as can be calculated with equation 4.7, depends on the maximum load current of the DC supply (I_{load}), the test voltage (U_{test}) and the capacitance C . The charging time (t_{ch}) for various cable capacitances and test voltages are shown in figure 4.4, based on the maximal load current of 12mA of the applied DC supply.

$$t_{ch} = \frac{U_{test} \cdot C}{I_{load}} \quad (4.7)$$

As the charging of a test sample caused a linearly changing field in the insulation, it can be seen as a VLF stress to the cable insulation (a quarter period of a voltage cycle). As the charging time depends on the cable capacitance, also the AC stress frequency varies. As can be derived from figure 4.4, the effective frequency during the charging of a cable system is in the range of 0.03Hz (for a

large cable capacitances) to ca 2.5Hz for small cable capacitances. These are internationally used and accepted frequencies for voltage test on power cable systems [26,55,59,95].

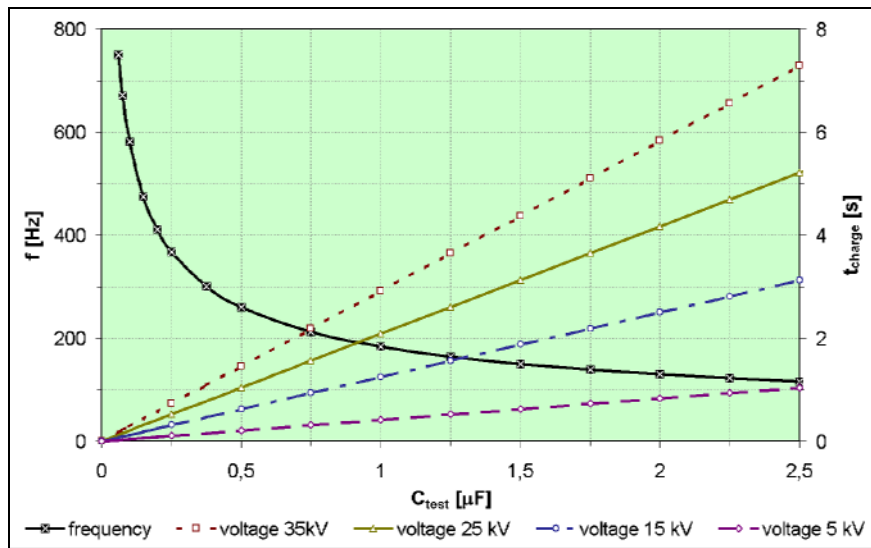


Figure 4.4: Dependency of the charging time (for a DC source of 12mA) and the test frequency on the cable capacitance.

The test frequency of the oscillating voltage wave is approximately the resonant frequency of a lossless circuit (derived from equation 4.5, where the 2nd term under the square-root sign is negligible compared to the 1st term):

$$f = \frac{1}{2\pi\sqrt{L \cdot C}} \quad (4.8)$$

This means that the test frequency of the applied DAC voltage depends on the capacitance size of the cable system, see figure 4.4. The cable capacitance varies because of its length and insulation type.

Table 4-2: Examples of the typical test frequencies for 3-core 10kV power cable systems for different insulation types.

Cable length [m]	Impregnated paper insulated (400pF/m)	XLPE insulated (350pF/m)
100	890 Hz	951 Hz
500	398 Hz	426 Hz
1500	230 Hz	246 Hz
5000	151 Hz	161 Hz
10000	103 Hz	110 Hz

The air-core has a low loss HV design, such that a resonance frequency can be obtained in the range of 100Hz to 800Hz, close to the service voltage frequency. Table 4-2 shows examples of typical capacitance values of 3-core 10kV power cables for different insulation types. For higher voltage class of power cables the test frequency will slightly increase as the capacitances decrease.

The quality factor Q of the resonant circuit remains high due to the relative low dissipation factor of power cables. Dependent on the cable Q can be 30 to more than 100. A slowly decaying oscillating waveform (damping time up to 0.3 seconds) is applied as test voltage to energise the cable sample and to ignite the present PD sources. Inherent to the applied technique, the PD activity can be measured on-site with undisturbed sinusoidal voltage cycles, see figure 4.5.

The PD detection circuit is not operational during the disturbing loading and switching time of the DC supply. The DC supply is not disturbing the PD detection as it is disconnected from the detection circuit during the measuring time (figure 4.3). The solid-state switch is of no influence on the detection sensitivity due to the short switching time ($<1\mu\text{s}$).

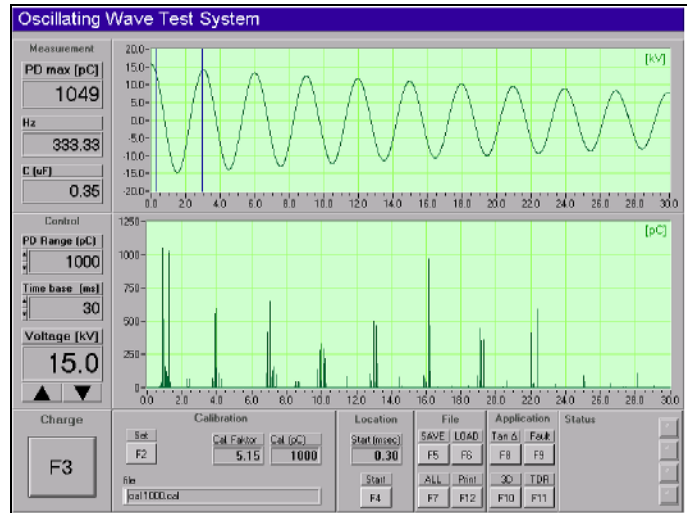


Figure 4.5: Screen dump of a measurement result obtained from a XLPE power cable after one DAC voltage shot at $13\text{kV}_{\text{peak}}$ using OWTS.

4.2.2 PD AND VOLTAGE DETECTION

As the DAC frequency represents the AC power line frequency, the measurement bandwidth of the PD detection circuit is chosen in accordance with IEC recommendations [53]. For the purpose of PD localisation by travelling waves, the bandwidth is increased up to 10 MHz combined with a 100 MHz digitiser.

The PD activity signals, ignited during one or more oscillating voltage waves, are detected by the system, which can process the signals for two purposes:

1. Single PD pulses can be analysed for original location by using travelling wave analysis. Statistical evaluation of the selected PD signals can be obtained after several DAC voltage shots to evaluate the location of discharge sites in the power cable. A PD mapping (figure 4.10) is created, which shows the distribution of the detected PD in a cable system length, as a function of the magnitude or the intensity.
2. A phase-resolved PD pattern can be resolved from multiple DAC sequences. In this way, patterns can be obtained which are similar to those recognised under 50(60) Hz conditions [19]. For recognition purposes, such PD phase-resolved patterns might additionally be processed using discrimination and classification tools.

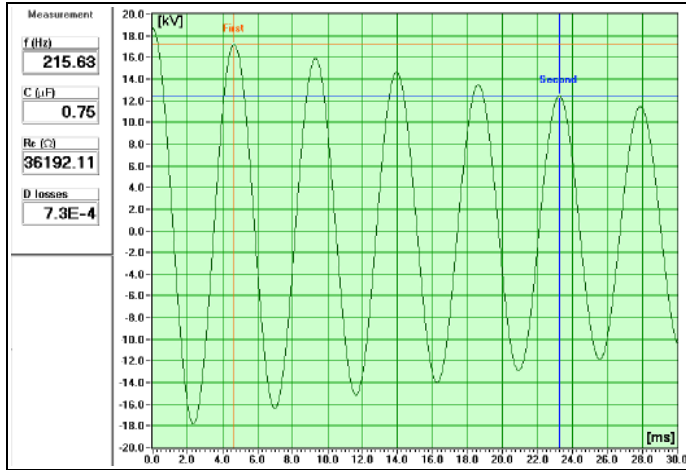


Figure 4.6: Example of the determination of the dielectric losses on a XLPE cable system, using the damping characteristics of the DAC voltage.

The unknown factor β_{DAC} can be calculated directly from the damping characteristics of the DAC voltage, using the voltage and time of the voltage peaks of different periods. E.g. if the peaks from the first and fifth period of the DAC voltage are used for calculation:

$$\frac{U_5}{U_1} = e^{-\beta(t_5-t_1)} \Rightarrow \beta_{DAC} = -\frac{\ln(U_5/U_1)}{(t_5-t_1)} \quad (4.10)$$

Now, the dielectric losses DL of the cable sample can be calculated with:

$$DL = \frac{1}{\omega \cdot R_C \cdot C} \quad (4.11)$$

4.2.3 PD PROPERTIES

For the determination of the insulation condition, several PD properties are found of importance and used in this thesis. For field application of the PD diagnostics, the PD properties as shown in table 4-3 turned out to be of relevance [124,126] from practical experiences. The properties are measured directly by the detection equipment for the cable system, or derived after analysing the measurement data for individual cable components from the PD mapping. The PD properties are collected in the so-called fingerprint of a cable system.

Based on the resulting resonant frequency, the cable capacitance C can be calculated (equation 4.8). The dielectric losses can be derived from the decay characteristics of the oscillating voltage wave, as shown in figure 4.6. These dielectric losses can be distracted from equation 4.5:

$$R_C = \frac{L}{2\beta_{DAC}LC - R_LC} \quad (4.9)$$

Table 4-3: PD properties as obtained from DAC measurements for the total cable system and derived after location analysis for the individual cable components in the PD mapping.

Cable system	Cable component
PD inception voltage	
PD extinction voltage	
PD magnitudes at $\sim V$	
PD pattern	
PD intensity	
PD mapping	PD inception voltage
	PD magnitude at $\sim V$
	PD occurrence frequency

PD INCEPTION VOLTAGE AND EXTINCTION VOLTAGE

The PD inception and extinction voltage are directly related to PD processes. These are one of the most important parameters for insulation quality assessment by PD detection, as is true for most high voltage components.

According to [53], the PDIV is the applied voltage at which repetitive PD are first observed in the test object, when the voltage is applied to the test object is gradually increased from a lower value at which no PD occurs.

For PD testing at DAC voltages this means that the PDIV of cable system is obtained by increasing the test voltage step by step. That test voltage at which the internal PDs occur for the first time is identified as the inception voltage of the specific sample. Figure 4.7 shows the measuring results at increasing test voltages obtained from a single-phase 6kV XLPE power cable, with a length of 644m. The defect in this cable sample is a locally damaged semi-conducting screen.

From the analysis of the increasing test voltages, it is shown that up to a test voltage of 8kV_{peak} , no PD activity occurs but only some background noise (small spikes) is detected. However, at a test voltage of 9kV_{peak} , the first internal PDs occur, with values of 150pC, which means for this specific example that 9kV_{peak} is the PDIV. Further increase of the test voltage shows that the PD activity is intensified at growing magnitudes.

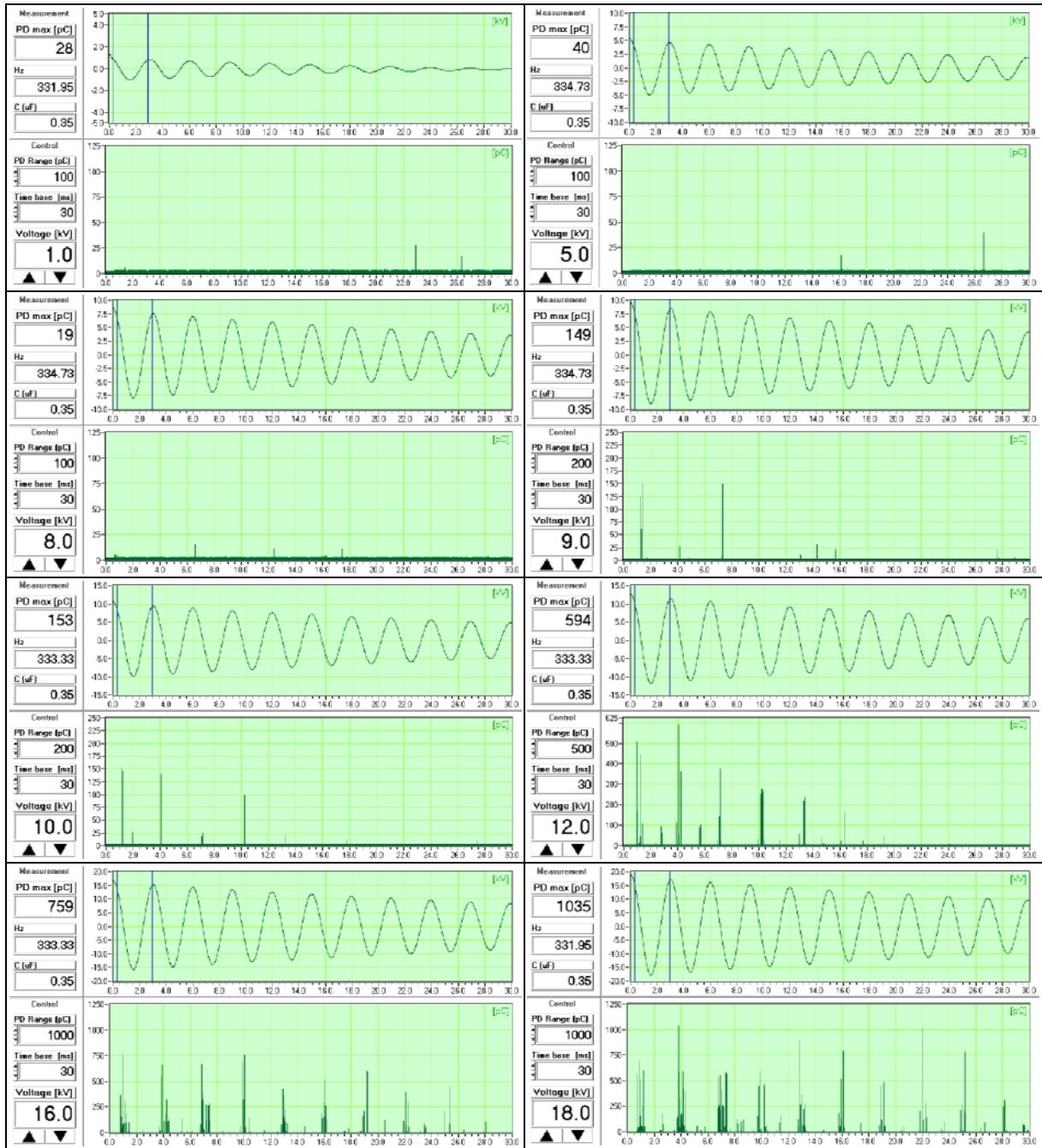


Figure 4.7: Measurement examples obtained from a 10kV XLPE cable sample. In this example, it is shown that by increasing the DAC voltage step by step, the PDIV for this cable sample can be determined as 9kV_{peak} . From the decreasing test voltages, the PDEV can be derived, which is in this example $7,5\text{kV}_{\text{peak}}$.

Due to the decay of the DAC voltage wave, the extinction voltage of a PD source can be determined from the applied voltage cycles, as shown in figure 4.7.

According to [53], the PDEV is the applied voltage at which repetitive PDs cease to occur in the test object, when the voltage applied to the test object is gradually decreased from a higher value at which PD pulses are observed.

For PD testing at DAC voltages this means that the PDEV of test sample is obtained from voltage cycles above the PDIV. That test voltage at which the internal PDs stop occurring is identified as the extinction voltage of the specific sample. For the example in figure 4.7, it can be derived from those voltages higher than 9kV_{peak} (PDIV) that the PD activity stops at $7.5\text{kV}_{\text{peak}}$, which is therefore the PDEV value for this test sample.

PD MAGNITUDES AT DIFFERENT VOLTAGES

According to [53], for alternating voltage tests, the specified magnitude of the apparent charge q is the largest repeatedly occurring PD magnitude.

The comparability and trendability of PD magnitudes is of importance for on-site diagnosis. Defect sources in different cable systems can be compared to each other or compared in time, trending. Furthermore, if measurement results are obtained in a standardised way, comparisons between different measurement equipment can be obtained, e.g. between on-site cable diagnostics and factory laboratory diagnostics. Performing the PD detection and the PD calibration according IEC 60270 recommendations, this comparability can be obtained.

The q-V relation for a detected defect gives important information on the nature of a PD source [19]. For PD testing with DAC voltages, this means that the PD level of a series of shots, at one specified test voltage, is calculated. For field application of the diagnostic tool, it turns out to be sufficient to make three different shots at one voltage level. In these three shots, enough data are collected for analysis purposes, without taking up to much time. For the described test cable, the PD levels are obtained for the increasing test voltages, as shown in figure 4.7. As a result, a q-V diagram may be derived as shown in figure 4.8, which shows the PD magnitudes at different voltages.

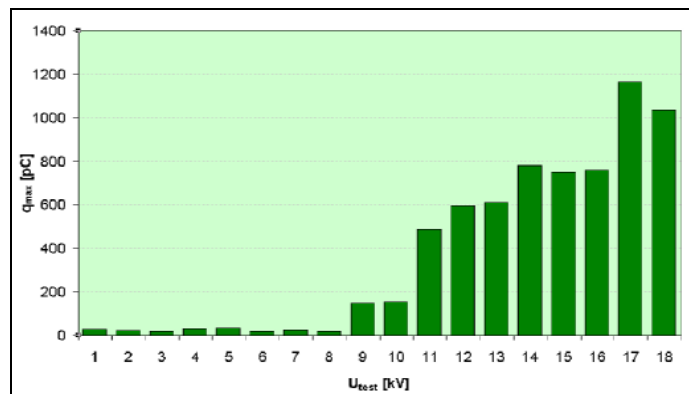


Figure 4.8: q-V diagram as obtained from PD measurements on a 10kV XLPE power cable sample, with a damaged semi-conducting screen.

PD PATTERN

The PD pattern is the representation of the appearing partial discharges as a function of the phase angle Φ_i of the applied test voltage.

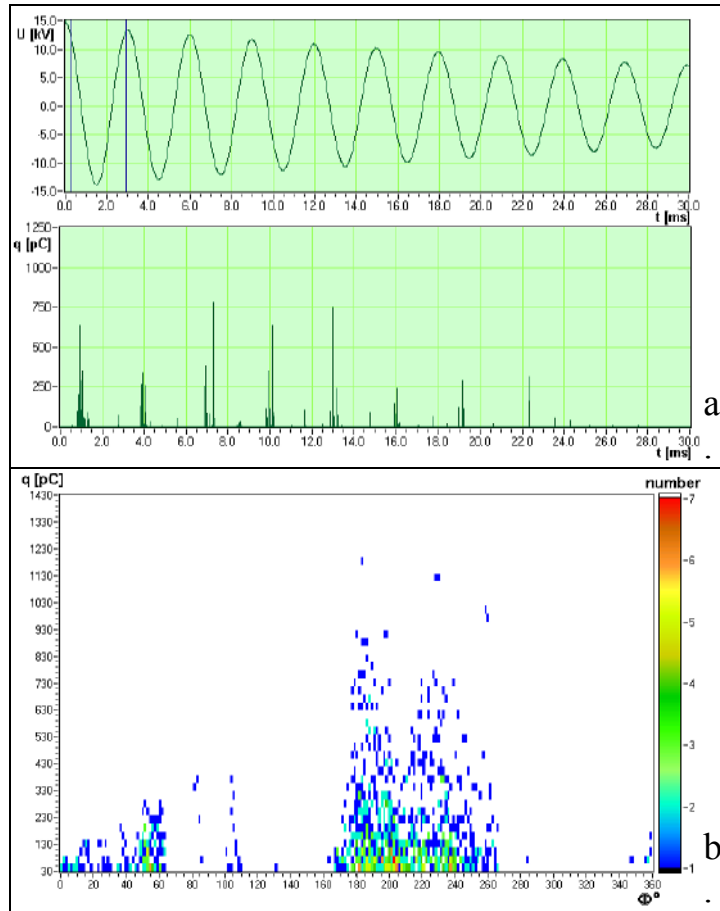


Figure 4.9: PD patterns at DAC test voltages:

- 2-dimensional pattern with the PD occurrence q versus the test voltage U on identical time base;
- 3-dimensional pattern with the PD occurrence represented in discharge magnitude, phase angle and number of PDs (by colour).

For PD testing at DAC voltages, two types of phase resolved PD patterns have been obtained:

- The 2-dimensional (2D) PD pattern, showing the applied DAC voltage and each occurring PD (with its specific magnitude) in identical time intervals;
- The 3-dimensional (3D) PD pattern, showing the occurring PD magnitudes as a function of the phase angle Φ_i of the applied DAC voltage. As the 3D pattern shows the collection of multiple DAC voltages, the intensity of the occurring PD is obtained.

In figure 4.9, the 2D and 3D PD patterns as measured on a 10kV XLPE power cable sample with a damaged semi-conducting screen are shown.

The type of defect can be determined by analysing the phase resolved PD patterns [19,74]. Performing PD measurements on the separate phases, different PD patterns may be obtained in the separate phases.

PD OCCURRENCE FREQUENCY

According to [53], the pulse repetition rate n is the ratio between the total number of PD pulses recorded in a selected time interval and the duration of this time interval.

The repetition rate can be obtained by counting the PD pulse occurring at one DAC voltage. More important is the PD intensity as located in a specific cable element, which can be determined after the location of the PD sources. This PD occurrence is related to the PD defect, as will be discussed in chapter 7. The PD

occurrence is the average number of PD events at a specific location in the mapping in one DAC voltage wave, see figure 4.10.

PD LOCATION MAPPING

Power cable systems are distributed, consisting of a combination of cable components like:

- cable joints;
- cable terminations;
- cable parts.

To determine the position and component type of detected PD sources, it is necessary to assess the location along the cable length.

Based on time domain reflectometry, each detected PD event, can be analysed for its location in the cable system, as described in chapter 4.2. A PD mapping of a cable system represents the distribution of all located PD events. Especially, the concentrations of PD events at one location represents a PD related defect, as shown in figure 4.10a. In this example, the result of the PD location analysis for the different DAC voltage levels is shown for a 3-phase PILC cable system of 577m. PD concentrations are found in a joint (*A*), in a termination (*C*) and in a cable part (*B*). The cable accessories are indicated as black dots at the horizontal axis. The PD mapping can be shown for each individual phase or for all phases together.

From the analysed PD location mapping, the PD occurrence frequency as a function of the cable length can also be derived, see figure 4.10b. The PD occurrence frequency in a location uses the total number of PD events inside a window of 1% of the total cable length (the general error in PD location [72,130]) for that specific location. In the example of figure 4.10, it shows that the overall intensity, as obtained for all measurements at different voltage levels is the highest for the PD concentration at the remote termination, which is on the right corner of the plot.

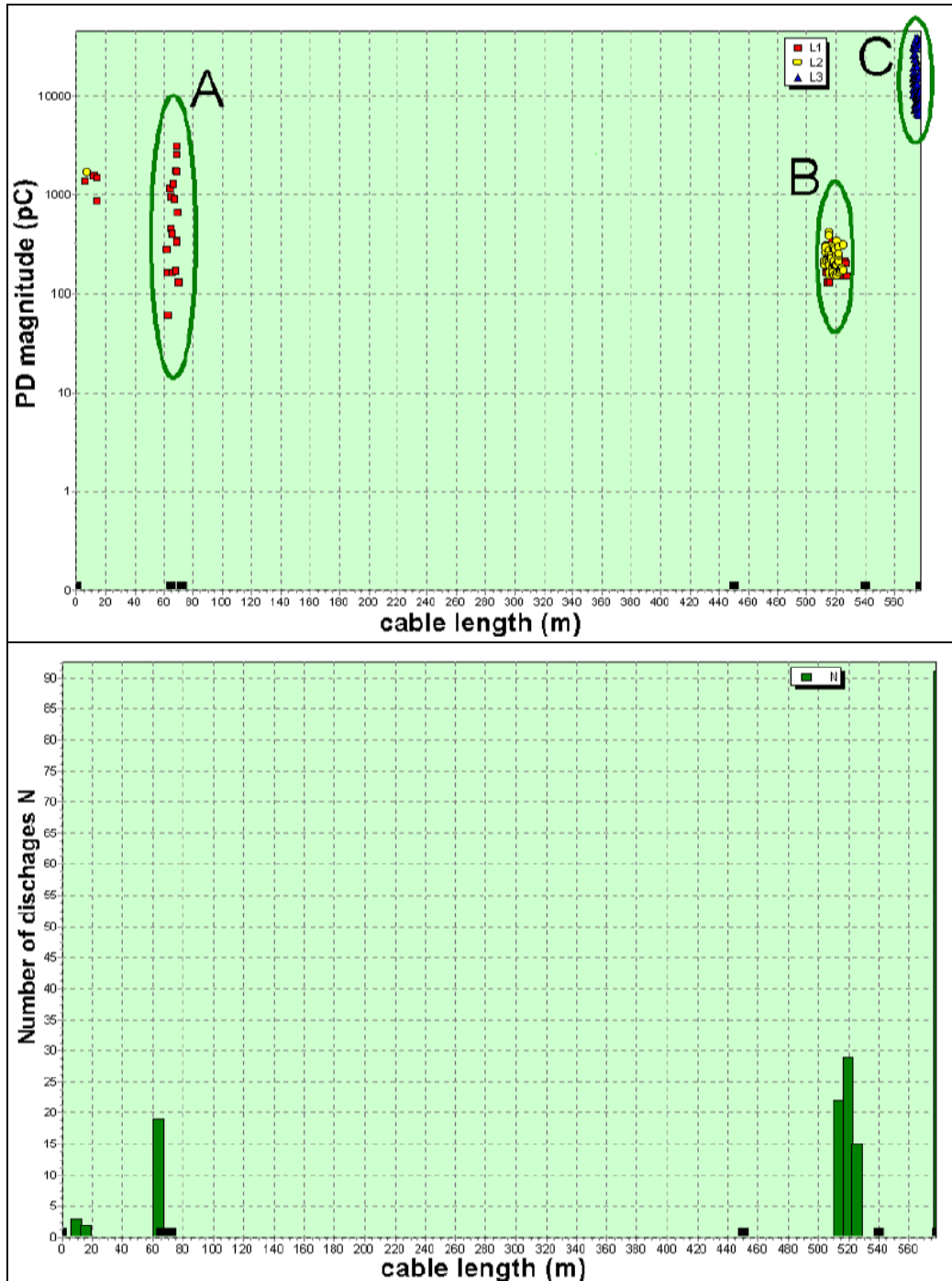


Figure 4.10: PD location view of a 3-phase PILC power cable of 577m:

- PD mapping, individual PD events as a function of the cable length, (different phases indicated by colour);
- PD intensity plot, the concentrations (inside 1% of the cable length) of PD events as a function of the cable length.

The PD mappings contain a lot of diagnostic information. Analysing this information needs certain knowledge in interpreting these data. Therefore, to use this information, an automatic database input-format is developed to extract the required information identically from the analysed PD mappings of a particular cable system [125].

From the PD location procedure, different derived PD properties are collected in a database for each component of the measured cable system. From manifold performed field measurements, we have derived that characteristic PD properties have to be collected after localisation for decision-making purposes. The properties are shown in table 4-4 for the test voltages between the PDIV and $2U_0$. From the data collection of these characteristic PD properties, different experience norms will be defined, as will be explained in chapter 6.

Table 4-4: Properties derived from a PD mapping. The properties are determined for each phase for the cable system and each of the accessories.

Test voltage	PD property
$U_{\text{test}} = \text{PDIV}$	Maximum PD magnitude [pC]
	Average PD magnitude [pC]
$U_{\text{test}} \leq U_0$	Maximum PD magnitude [pC]
	Average PD magnitude [pC]
	PD occurrence frequency [N/shot]
$U_{\text{test}} > U_0$	Maximum PD magnitude [pC]
	Average PD magnitude [pC]
	PD occurrence frequency [N/shot]

4.3 ON-SITE APPLICATION OF PD DIAGNOSTICS

4.3.1 PD OCCURRENCES UNDER SERVICE AND OFF-LINE CONDITIONS

Testing a 3-core belted power cable system, different insulation layers are investigated on PD appearances. During service conditions, all the capacitances in a cable will be stressed at the same time. The phase-to-ground voltage is defined as U_0 , whereas the phase-to-phase voltage $U_n = \sqrt{3} * U_0$. The electric stresses of the different insulation layers are shown in figure 4.11. For similar results, the on-site off-line measurements should be carried out on a single phase, while the other phases and the screen are earthed [44,71]. By testing all three phases separate, all the capacitances are diagnosed, as shown in figure 4.11. A disadvantage at off-line cable testing is that the capacitances are stressed different from operation conditions. On the other hand, due to the testing at all three phases, the distinction between the capacitances can be made.

The operation voltage between the phases (C_{12} , C_{13} , C_{23}) is $\sqrt{3}$ times as high as between the phases and the earth screen (C_1 , C_2 , C_3). To reproduce the operational stress, for off-line diagnostics, the application of a test voltage at one phase of at least the phase-phase voltage is necessary. The insulation between the phases and earth are in this way overstressed, in practice up to $2 * U_0$. In this way, the insulation between the phases is stressed up to 1.15 times the operational phase-to-phase voltage.

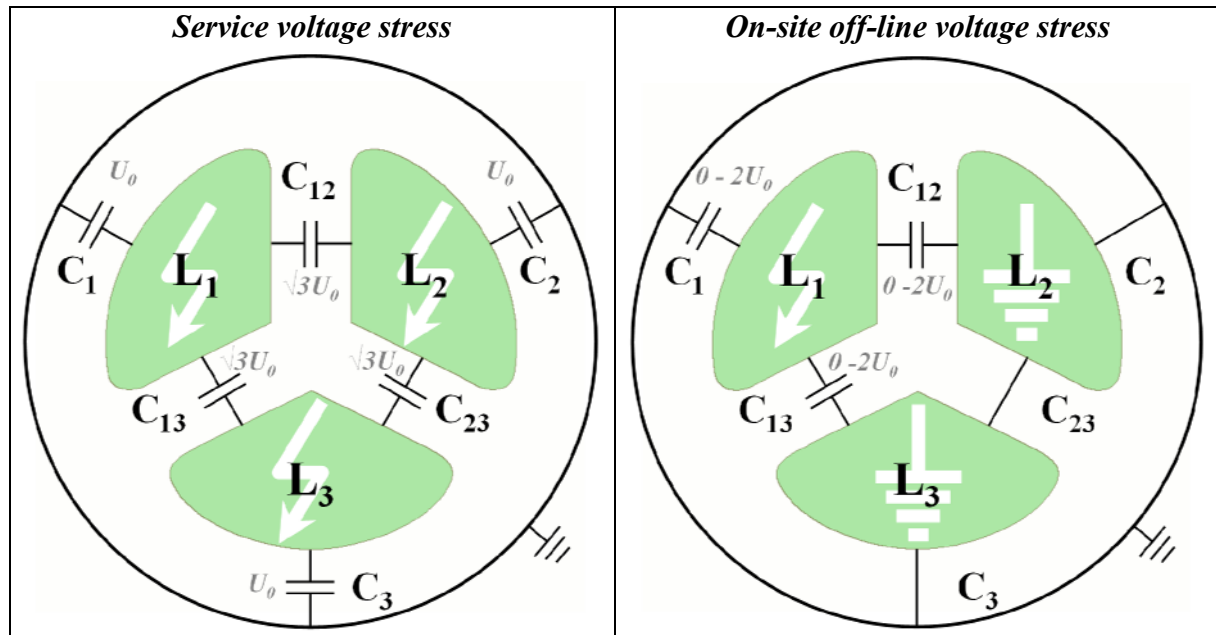


Figure 4.11: Schematic view of the capacitances between the phases and the earth screen of a 3-core cable, during service conditions and off-line energising. The off-line measurements are performed phase by phase.

In order to distinguish the PD sources between the phases (C_{12} , C_{13} , C_{23}) and those between the phase and earth screen (C_1 , C_2 , C_3), a measurement at all three phases together may be performed, at a test voltage of at least U_0 (without phase shift). Differences between the measurements at the single phases and at all phases together are related to the insulation between the phases.

Table 4-5: Different capacitances measured during off-line PD detection in power cables.

Phase	Capacitances
L1	$\Sigma(C_1, C_{12}, C_{13})$
L2	$\Sigma(C_2, C_{12}, C_{23})$
L3	$\Sigma(C_3, C_{13}, C_{23})$
L1&L2&L3	$\Sigma(C_1, C_2, C_3)$

as shown in table 4-5. Studying the PD activity at various voltage stresses, also above service stresses, makes the diagnosis of a cable system more predictable. The increased voltages may occur under service due to switching activities ($\sim 1.2 \cdot U_0$) or single phase faults ($\sim 1.7 \cdot U_0$ due to non-direct grounded network).

During the off-line diagnostics, the PD properties as the PDIV and the PDEV can be obtained, because the voltage level can be varied as a result of the external power supply. The PD behaviour at particular test voltages is detected for the different capacitances between the phases and earth screen,

4.3.2 TEST PROTOCOL

For systematic collection of diagnostic information at on-site measurements on large numbers of cable systems, we developed a test procedure. In this way, the

measurement results are generically collected for all types of diagnosed cable systems. The measurement data are independent from the measurement engineer and can be transferred to a database for norm definition, comparison analysis and trend analysis.

For off-line PD measurement with DAC voltages, the measurement protocol as developed for the investigations in this thesis is shown in figure 4.12. The following steps are carried out for each diagnosed cable system:

- I. After the disconnection of a cable system, the calibration of the system is performed at one of the phases. Calibration on one phase is sufficient as the differences capacitance and length will be minimal between the phases, even for single phase cable systems. The PD magnitude in [pC/nC] and the PD propagation velocity are calibrated;

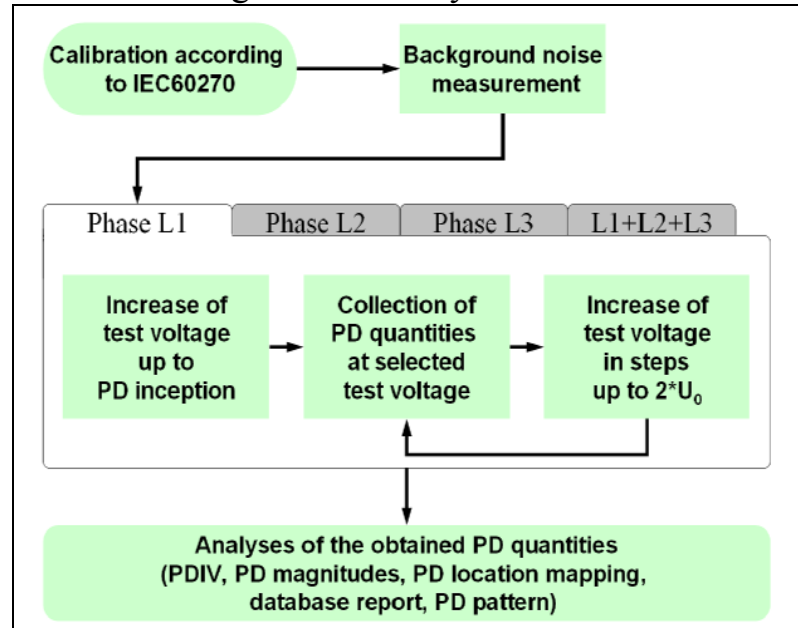


Figure 4.12: Measurement protocol as applied for off-line PD detection on power cables with OWTS.

- II. A PD measurement is performed at low (or no) voltage in order to obtain the background noise;
- III. The test voltages are increased by steps of 1kV_{peak} until the inception of PD is obtained;
- IV. Collection of the different PD properties at PDIV;
- V. Increment of the test voltages in steps (e.g. 3kV_{peak} per step) up to $2*U_0$. By testing up to $2*U_0$, also the insulation between the phases is overstressed, as may be necessary for the PD ignition. At each voltage level the different PD properties are collected;
- VI. Steps 4&5 are repeated for the other two phases and the phases together. For a cable system, existing of 3 single core cables, measurements at all three phases together are unnecessary;
- VII. Finally, the obtained PD properties are analysed for the origin location.

5

PD AT DIFFERENT VOLTAGE STRESSES

For on-site PD diagnosis of power cables in its most realistic way, the test objects should be energised by external voltage sources, which generate power frequency voltages. The use of a 50 Hz external energising method is however not always practically and economically feasible, because the cable capacitance results in a required high reactive power. For this reason, other methods that operate at different frequencies have been developed to reduce the capacitive charging power needed, as described in section 4.1.

The frequency (0,1Hz, 20-200Hz) and the voltage shape (damped or continuous AC) of the test voltages may vary for different available on-site PD diagnostic systems. Recent investigations have compared different diagnostic tools in their effectiveness on PD detection and voltage-withstand of power cables. The general conclusion is that the technical performance of PD detection is comparable for different systems with various excitation voltage types [21]. For voltage withstand tests, DAC and VLF voltages showed different sensitivity in detecting different types of defects [103].

In this chapter, the effects of the different test voltage shapes and frequencies on PD activities are investigated. Samples with dielectric bounded cavities are measured with 50Hz AC, damped AC at various frequencies and 0,1Hz voltages to study the PD activity. PD inception delay, PD magnitudes and PD phase resolved patterns are analysed. Measurements on other laboratory defect models and cable accessory models are diagnosed with 50Hz continuously AC voltage and damped AC voltages at different frequencies. In this way, also mutual comparison can be performed with damped AC voltage. The influence of test voltage shapes and frequencies are verified on-site.

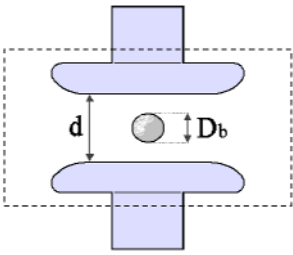
5.1 EFFECT OF VOLTAGE FREQUENCY AND SHAPE ON PD ACTIVITY IN DIELECTRIC BOUNDED CAVITIES

Several alternative energising methods are in use for on-site PD detection in power cables, which cover a wide range of test frequencies, from 0.01Hz-1000Hz [79,80,83,108] and the shape of the test voltages vary for the different methods. Continuous sinusoidal AC voltages, VLF voltages, transient pulses and damped AC voltages are practically used test voltages. Because of the differences in energising voltages, investigations are carried to study the effect of the voltage stress frequency and shape on the PD behaviour. Recently different studies are published which show corresponding results between PD detection at different test frequencies and other which show some dissimilarity in the PD properties for different test frequencies [38,49,91,104]. The investigation is performed on laboratory models representing dielectric bounded cavities, see figure 5.1. The specimens consisted of a spherical air-filled cavity placed between two brass electrodes cast in polyester resin ($\epsilon_r = 3.45$). Table 5-1 shows the dimensions of the four different test specimens as used for the study. To obtain a homogenous field between the electrodes, these are shaped with the Rogowski profile.



Figure 5.1: Example of the test specimen as applied for the study on influence of the test voltage frequency and shape.

Table 5-1: Sample dimensions of the dielectric bounded cavity samples as used to study the influence of the test voltage frequency and shapes.

	Sample dimensions	Sample A	Sample B	Sample C	Sample D
	d [mm]	3.90	2.80	3.15	3.85
	D_b [mm]	2.52	2.00	2.92	3.17
	D_b/d	0.65	0.71	0.93	0.82
D_b = bubble diameter & d = electrodes gap					

5.1.1 THEORY

The ignition of a partial discharge is a stochastic process controlled by:

1. a starting electron, which can be initiated from cosmic radiation;
2. the charge carriers deposited by previous discharge events (which cause the short-time memory of the process);

3. the external field applied to the test object;
4. the local physical properties which change gradually during aging and that are responsible for the long time drift of the process behaviour (long-time memory).

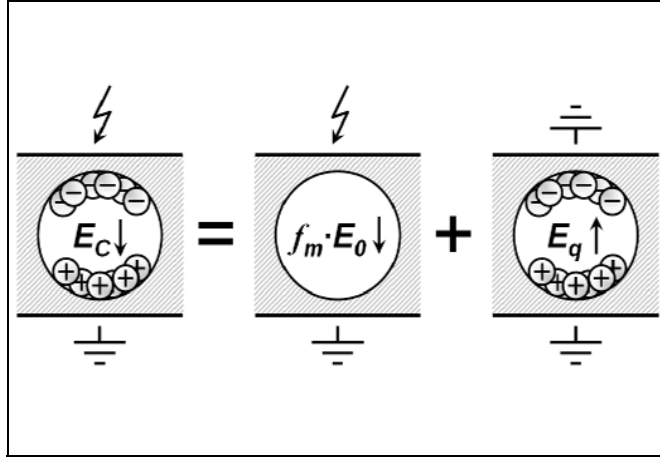


Figure 5.1: Influence of the deposited surface charge on the inception condition of a dielectric bounded cavity. Because of the presence of the surface charge in the void, the field inception condition can be fulfilled also when the applied voltage is below the inception voltage.

Two conditions are necessary for PD inception: a sufficiently high field at the defect and the presence of a starting electron. According to [99], the electric field E_c inside a cavity is composed of two contributing fields, as is shown in figure 5.1. The first contributing field is due to the defect shape, which causes an enhancement of the background field E_0 . The second contribution, E_q , is associated with the local space charges and/or surface charges q left by previous PD activity. Then E_C can be expressed for a spherical cavity as:

$$E_C = f_m \cdot E_0 + E_q \quad (5.1)$$

where f_m is the field modification factor that quantifies the defects field enhancement [22,41].

If the field E_C is higher than the inception field E_i for the streamer criterion [99] and if a starting electron is present, a partial discharge event occurs. The amplitude of the discharge depends on the field E_C that causes the discharge. The discharge magnitude q is proportional to the field inside the cavity at the inception instant. The minimal discharge magnitude is ignited, as the electric field in the cavity (E_C) is equal to the inception field (E_i). However, the maximal PD magnitude occurs when the field E_C is maximal.

The surface charge deposited by a PD event contributes to the potential difference across the cavity. This deposited surface charge represents a source of starting electrons for the ignition of a discharge. However, the deposited surface charge will decay with an average time lag τ_{cd} . By using the RC cavity model as proposed in [99], the time constant τ_{cd} can be evaluated as

$$\tau_{cd} = \varepsilon_0 \cdot D_b / 4 \cdot \sigma_s \quad (5.2)$$

where ε_0 represents the vacuum permittivity, D_b the cavity diameter and σ_s the cavity surface conductivity.

A starting electron triggers a PD occurrence. Two main groups of first electron generation mechanisms can be distinguished: volume and surface processes [99]. Volume generation includes radiating gas ionisation by energetic photons and field detachment of electrons from negative ions [41]. The second group is electron production from surfaces of insulating materials, which includes the generation of starting electrons from energy traps at the surface, electron release by ion impact and the surface photo effect [99]. In the latter case an approximate estimation of the number of electrons generated per second can be obtained if one considers these processes to obey to a Richardson-Schottky type of emission. In fact, in case of a cavity between insulator surfaces, at the surface of the insulators, traps with depths in the order of 0.1 to 1eV are present. If electrons from previous PD events have been trapped in such surface states, they could be detrapped for the successive PD events [99].

Taking into account that the duration of a PD pulse lies in the order of 10^{-9} s [99], the PD time is always much smaller as compared to the VLF or AC stress period. This means that the test voltage change during a PD event is negligible¹¹. The test frequency will therefore not directly influence the PD inception phenomenon. However, after each PD event, the surface charge inside the cavity decays in a specific time interval τ_{cd} . The surface charge is assumed to contribute to the successive PDs in this time interval that after the time τ_{cd} the value of the remaining charge is too small to contribute to PD inception phenomenon. Dependent on the combination of the surface charge decay time τ_{cd} and the various voltage stress periods T , the conditions under which PDs are ignited can be quite different. Three different situations of PD ignition may occur [7]:

$T/\tau_{cd} \ll 1$ The surface charge deposited by a first PD will be fully intact inside the cavity, at the successive PD inception instant. In this situation, the deposited charge will strongly contribute to the cavity field E_C driving the PD occurrence.

$T/\tau_{cd} \gg 1$ PD will be ignited in absence of surface charges inside the cavity. In this situation, the deposited charge will not contribute to the cavity field E_C driving the PD occurrence.

¹¹ The maximum change in the test voltage is reflected by $(\delta U/\delta t)_{\max} = 2\pi f \cdot U_{\max}$. During a PD event, the test voltage changes will therefore be less than 1%.

$T/\tau_{cd} \approx 1$ The surface charge left by a previous PD may contribute to the PD inception. The effect of field E_q depends on the portion of the charge deposited by a first PD and present in the cavity during the second PD occurrence.

To know to which frequencies the three ignition situations correspond, evaluation of the parameter τ_{cd} is necessary. The deposited charge decay time is strongly dependent on the conductivity of the cavity's surface (equation 5.1). For polymers that have not suffered from PD activity the conductivity is typically in the range of 10^{-16} - 10^{-14} S, while aged cavities have values as high as 10^{-12} - 10^{-11} S [99]. The charge decay time can therefore be in the range 10^{-3} - 10^2 s for cavities of a few millimetres diameter, dependent on the ageing state.

5.1.2 EXPERIMENTAL RESULTS

Four specimens have been tested to compare the different energising methods. Partial discharges in the specimens were ignited and detected by using 0.1Hz and 50Hz AC energising as well damped AC voltages at 265, 520 and 930Hz. In this way, multiple voltage frequencies and shapes were applied on the test samples from which PDs are detected.

For the 50Hz voltage measurements, a conventional PD detection circuit with coupling capacitor has been applied. The PD signals measured by the circuit were processed and analysed by TE571 PD analysing system. During the tests, sequences of pulses are recorded. Every pulse is characterised by its charge and its phase position of the AC voltage. The 0.1Hz measurements are performed using a HV power source at 0.1Hz combined with a coupling capacitor in series with a detection impedance. The phase-resolved PD pattern is obtained, using a multi-channel oscilloscope, triggered by the 0.1 Hz test voltage.

The DAC measurements are performed with the system as described in figure 4.3. As the capacitances of the test specimens are very small, additional capacitances are used parallel to the test object in order to obtain various frequencies, as shows in table 5-2. A 'blocking' inductor of 40 μ H is used to connect the parallel capacitances to the test object in order to avoid disturbing signals from these capacitors interfering with the measuring data.

Table 5-2: Applied combinations of additional capacitors in order to obtain various test frequencies for damped AC voltages.

f_{test} [Hz]	C_{add} [μ F]	Capacitors combination
265	0.5	2x0.5 μ F in parallel, in series with 2x0.5 μ F in parallel
520	0.125	4 x 0.5 μ F in series
930	0.036	4x0.5 μ F in series, in parallel to 2x0.1 μ F in series

To obtain a stable discharge pattern, all cavities were first conditioned for 1 hour at 50Hz energising. During the first minutes of PD activity, in fact, a change of the condition of the cavity walls can lead to quite sensitive PD property changes [89]. After this conditioning period, the PD measurements were performed at for different energising methods at various frequencies.

Characteristic difference between the 50Hz and 0.1Hz energising to DAC energising, is that DAC applies temporarily voltages. This implies that the data are collected on the base of multiple voltage cycles. For every measurement method, the PD inception delay time, PD magnitudes and phase-resolved PD patterns are obtained for the four specimens, listed in table 5-1.

5.1.2.1 PD INCEPTION DELAY TIME

To initiate a partial discharge a starting electron is required. The probability that this electron will become available within a certain time interval depends on the test voltage and on the diameter of the cavity [16,41,99]. The PD inception delay time as a function of the 50 Hz test voltage level is shown in figure 5.2 for the cavity samples. The delay time to PD inception depends on the applied voltage for each sample. The delay time is rather long for low voltages, up to hundreds of seconds. For higher voltages the inception delay time is considerably smaller.

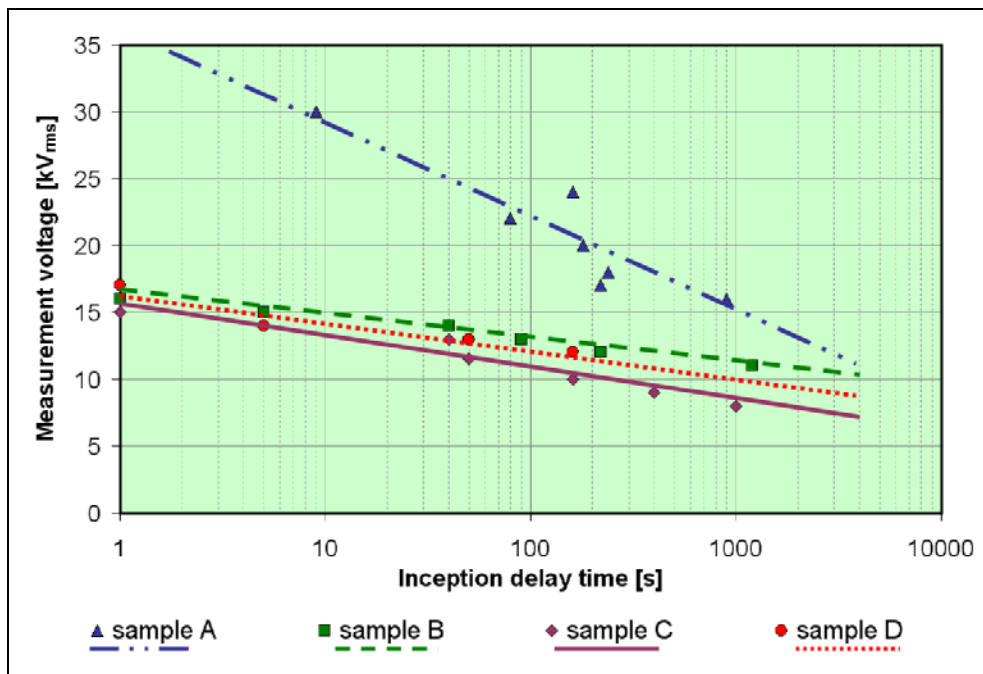


Figure 5.2: The PD inception delay time for the test specimens in table 5-1 at 50Hz energising. For increased test voltages, the PD inception delay time is smaller.

During the measurements with the VLF energising method, the inception delay time was also found to be voltage dependent. The PD inception delay times were similar as those obtained for 50 Hz energising.

Due to the decay of the DAC voltages, the sample is stressed only temporarily during tens of milliseconds, which will not result in a PD pattern for every voltage shot. The measurements of the inception delay time can only be performed in the order of these tens of milliseconds. Therefore, the measurements of the inception delay time is analysed in a different way for the DAC energising. Each specimen is measured according to the following test protocol. The measurements are performed in steps at increasing voltages, up to a maximum voltage of $30\text{kV}_{\text{peak}}$. At each voltage level, 20 DAC shots are carried out with a time interval of a few seconds. From these 20 DAC shots, the number of shots with a clear detected PD pattern is determined. This number of shots is determined as an indication for inception delay time (the probability of a starting electron). A high number of DAC shots with PD pattern is rated as a short inception delay time.

During the measurements at DAC voltages, the number of DAC shots with a clear PD pattern depends on the applied voltage for each sample, as shown in figure 5.3. This is in line with the inception delay time of the 50 Hz measurements. However, with regard to the order of the samples as a function of the voltage level, there is some dissimilarity between the DAC and 50 Hz measurements. The inception voltage levels of the sample D is different for DAC energising than for 50Hz energising. For the samples A, B and C, the inception voltage level is in the same range as for 50 Hz energising.

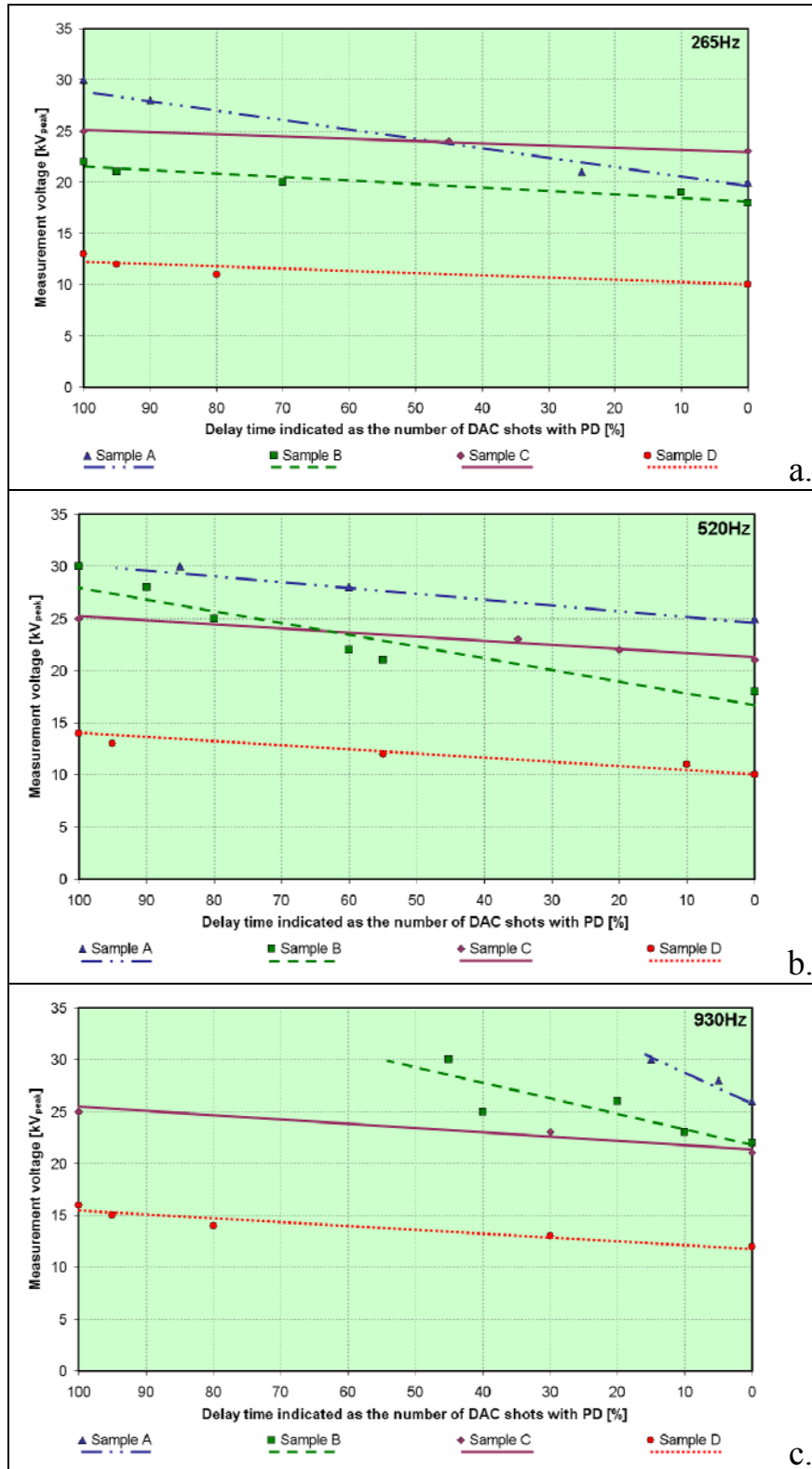


Figure 5.3: The PD inception delay time indicated as the percentage of shots with a PD pattern for damped AC test voltages for different test frequencies:

- 265Hz, voltage decay time of 30ms;
- 520Hz, voltage decay time of 15ms;
- 930Hz, voltage decay time of 8ms.

A strong relation was found between the DAC test frequency and the number of voltage shots required to obtain a pattern with PD. At higher frequencies the percentage of DAC shots with PD pattern decreases at corresponding measurement voltages, in particular for the samples A and B, see figure 5.3. For the samples C and D, this effect is detected to be less strong. These differences are explained by the dependence of the inception delay time on the test voltage and the cavity diameter [16]. This means that the probability of PD events is smaller at higher frequencies. However, at higher frequencies, more additional capacitors are connected in series to decrease the total circuit capacitance, as shown in table 5-2. Because of this fact, the dissipation of the circuit increases. Hence, the decay factor of the DAC voltage becomes higher.

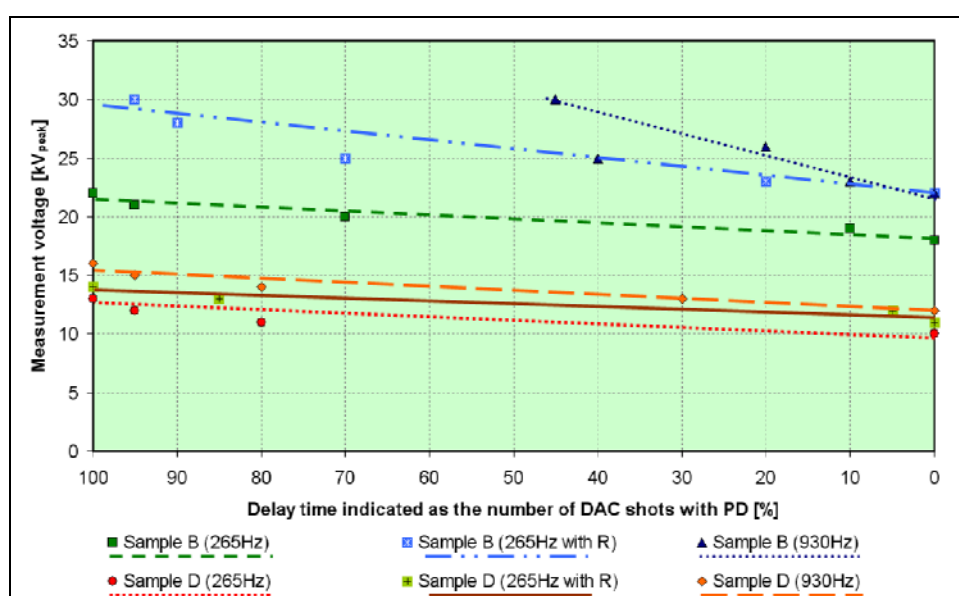


Figure 5.4: The PD inception delay time indicated as the percentage of DAC shots with a PD pattern for the test specimens in table 5-1. The voltage decay has less effect on the inception delay time than the frequency. The decay times are 30ms for 265Hz and 8ms for 265Hz with R and 930Hz.

To recognise if the difference in PD inception voltage observed for higher and lower frequency of the damped AC voltage measurements, are caused by the change in frequency or by the change in decay time, the following experiment has been performed. The samples are stressed with DAC voltages with a shorter decay time, by adding a 50 Ω resistor between the capacitors and the test circuit. The number of shots necessary to obtain PD occurrences was lower than for the previous measurements, see figure 5.4. This implicates that the dissimilarity observed in the samples is mainly caused by the differences in the voltage decay time rather than the changes in the frequency.

With regard to the decay factor, experiments show that this influences the probability of PD inception. The higher the decay factor of the DAC voltage, the shorter will be the time in which the PD inception criterion of the void is fulfilled, see figure 5.5. Thus, for a certain voltage level, the inception delay is longer for a higher decay factor. If the starting electron is not generated before the DAC voltage is below the theoretical inception value, no PD will be ignited. As a consequence, the probability to have PD occurrence is low for heavily damped voltage stresses.

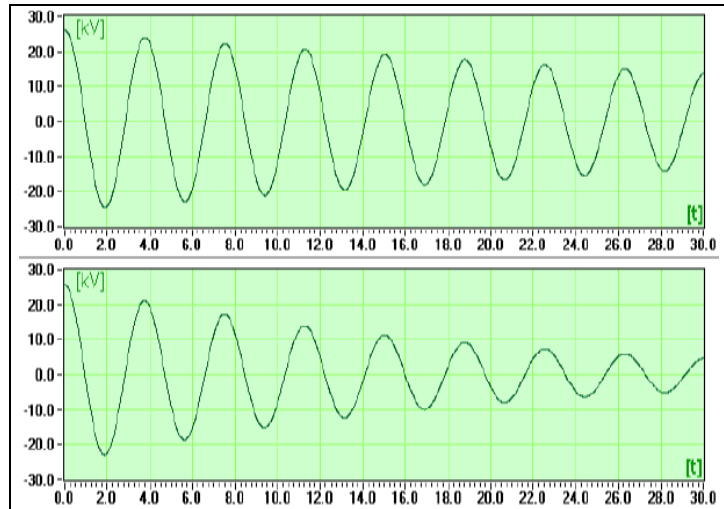


Figure 5.5: Examples of typical (upper) and heavily damped AC voltages (lower) at 265Hz.

DISCUSSION

Volume ionisation in the gas is the dominating electron generation mechanism if the cavity condition is in a virgin state. Before a cavity discharge occurs for the first time, a small portion of the surface energy states are filled with electrons. The inception delay time is expected to be relative long in the virgin state as compared to conditioned states. Due to the temporarily characteristics of DAC voltages, the probability that starting electrons appear due to volume generation only is small for cavity sizes of 2-3 mm diameter [99] and practically no PD would be ignited. However, in this investigation it is shown that it is possible to detect PD in the cavities with DAC voltages. It might therefore be supposed that the surface generation mechanism is active, in which the electric field at the cavity surface plays an important role.

Before the samples have been measured by the DAC method, they have experienced PD activity for 1-2 hours at 50Hz energising. In the obtained no-virgin state of the cavities, an increased portion of the surface energy states are filled with electrons and the surface generation processes are not negligible anymore. Figure 5.2 shows that for the no-virgin specimens the inception delay time depends mainly on the voltage rather than on the defect characteristics. In the presence of surface charge, the inception delay time shortens at increasing test voltages, as shown in figure 5.3 & figure 5.4. This effect of surface generation of electrons leads to a very short inception delay time for voltages sufficiently high. However, if the applied voltage is too low, a quite long delay time can be expected because the portion of surface energy states filled with possible starting electrons decreases.

5.1.2.2 PD MAGNITUDES

The PD magnitudes at different test voltage levels of the different test specimens are obtained during 2 minutes of 50Hz energising, 3 minutes of 0.1Hz energising and 20 shots of DAC voltages. In this investigation, the results for VLF and DAC energising are compared to the standard 50Hz energising results. Especially the maximum PD values, occurring in the five measurements sets at different frequencies are compared. For a controlled condition of the cavity, 50 Hz energising is applied for a short time before the DAC measurements are performed. The obtained PD magnitudes for the different samples are shown for the different frequencies in table 5-3. The measurements are performed at field strengths of 4.4 – 5.1 kV/mm, for which a stable PD activity is obtained for the samples.

Table 5-3: PD magnitudes as obtained from the measurements on the different samples.

	Time	Sample A	Sample B	Sample C	Sample D
Field strength [kV/mm]		5.1	5.0	4.4	4.4
50 Hz AC pd-level [nC]	2 min	5.5	12	45	15
265 Hz DAC pd-level [nC]	20 shots	2	> 5	> 20	15
520 Hz DAC pd-level [nC]	20 shots	1.2	4	> 20	15
930 Hz DAC pd-level [nC]	20 shots	0.8	> 2.5	> 15	> 7
0.1 Hz VLF pd-level [nC]	2 min	4.6	8	>20	3.6

For samples A and B with a smaller cavity, the PD amplitudes are lower energised with DAC than obtained at 50 Hz. Since a PD ignition is a stochastic process, the probability of a partial discharge occurring in the two minutes of a 50 Hz measurement is considerably higher than that occurring in the tens of milliseconds at DAC test voltages. Samples C and D give similar results for PD magnitudes by DAC and 50Hz energising.

The test results at DAC energising show that PD magnitude slightly decreases for the cavity samples at higher test frequencies. For instance, the measurements at 930Hz show a decrease in the PD amplitudes, as compared to 265Hz and 520Hz in table 5-3. The smaller cavities show more deviation at increasing test frequencies from 50Hz energising. The decay factor of the test voltage did not influence the PD magnitude, since the test performed with a shorter decay time did not show significant changes, as shown in figure 5.6.

The measurement results in figure 5.6 are obtained from sample B of table 5-1, at DAC energising with a test frequency of 265 Hz in a normal damped and a heavily damped voltage. The PD levels between the measurements are similar, which shows that the decrease of the DAC voltage does not influence the PD

amplitudes. The first PD occurring has the highest amplitude because of the absence of surface charge by previous PD events. The successive PDs occur in the presence of a cavity surface charge and are lower in magnitude.

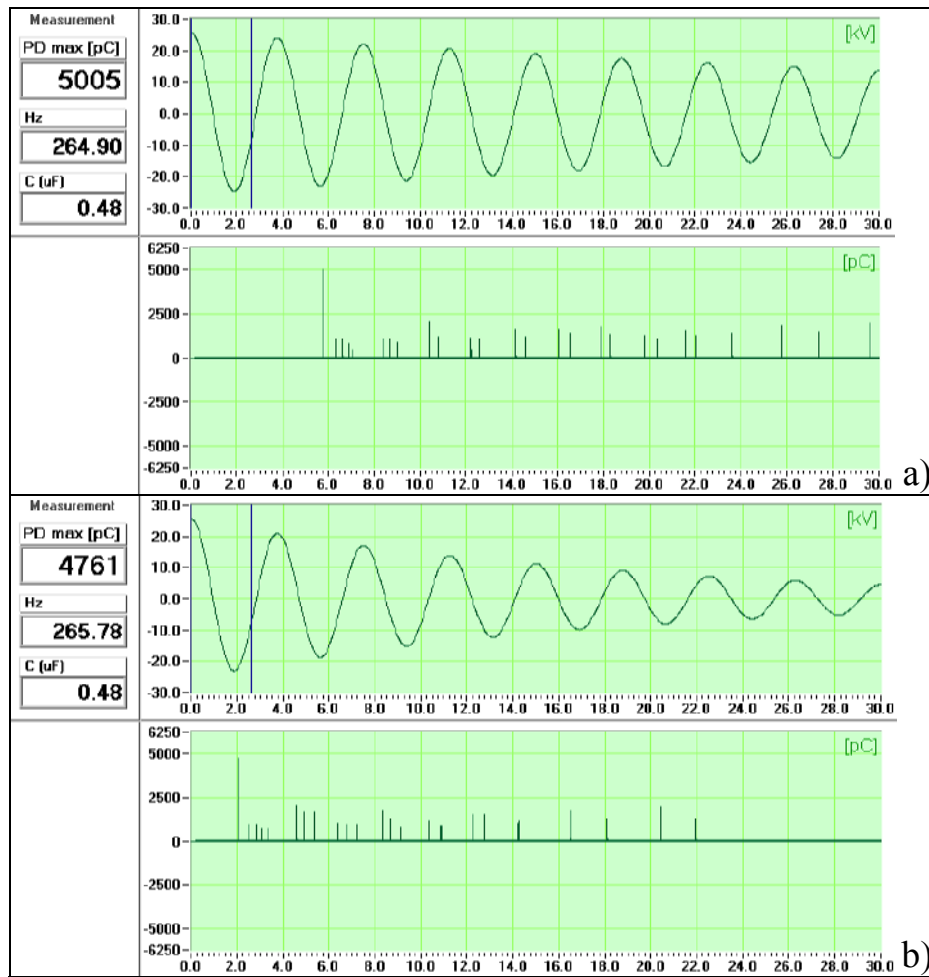


Figure 5.6: Measurement results as obtained from sample B at a test frequency of 265 Hz in a normal damped (a) and a heavily damped (b) DAC voltage. The decrease of the DAC voltage does not influence the PD amplitudes.

Even if the voltage decreases with time, the PD magnitude does not show a ‘long term’ reduction, except for the first PD, as can be noticed from figure 5.6. The explanation for this phenomenon is found in the theory as described in figure 3.2. When the applied voltage is far above the inception value, there is the possibility that more PD events happen in a half power cycle. On the other hand, when the applied voltage is quite close to the inception value, only one PD event can occur per half voltage period. If the surface charge delay time is longer than the maximum time between the successive PDs, the probability for a starting electron from the surface is quite high. The consequence is that the discharges ignite when the voltage across the cavity is close to inception. Hence, the magnitude of the recurring PDs is relative low to the first PD and they do not change.

With regard to very low frequencies, the PD magnitudes were similar (samples A and C) or lower (samples B and D) as compared to the magnitudes obtained at 50 Hz energising. However, it should be noticed that the test samples are stressed with the VLF generator for three minutes, which means a considerably less number of energising periods for obtaining PD activity, as compared to the two minutes of 50Hz energising.

According to equation 5.1, the surface charge delay time constant τ_{cd} of the four samples can be calculated. The measurements results as showed in table 5-3, are obtained while the samples were already exposed to several tests at 50Hz energising. The samples could therefore assumed to be non-virgin, whereas the surface conductivity σ_s may reach values in the range of 10^{-12} - 10^{-11} S [99]. This means for test samples with deposited surface charge that the delay-time will be in the range of 10^{-4} - 10^{-2} s.

DISCUSSION

The explanation for the decreasing PD magnitude at higher frequencies for some of the samples is the shallow trapping levels for starting electrons into surface states. After a PD, the electrons are trapped on the cavity surface, which therefore represents a reservoir of starting electrons for the next PD. Since the number of detrappable electrons decreases in time, the probability of a starting electron will be highest immediately after PD occurrence and then decrease with time [100]. When a PD occurs, the field inside the cavity collapses to the residual value and then it changes again: the time for reaching the minimal value necessary for the next PD inception shortens with increasing frequency. The probability of the presence for a starting electron is relatively high at higher frequencies. For these reasons, PD at higher frequencies will presumably be ignited at field strengths quite close to the minimal inception field. Therefore, slightly lower PD magnitudes may occur at test frequencies higher than 500Hz. An additional capacitor can be applied to the circuit to make sure that the test voltage frequency is not higher than this 500 Hz. To avoid the effect of a decreased probability of PD occurrence, the best result is to apply a low-loss capacitor, which will not cause extra damped voltage stresses

5.1.2.3 PHASE RESOLVED PD PATTERNS

For the investigation on the phase resolved PD patterns, the pattern at 50Hz energising is used as a reference for the patterns at VLF and DAC energising. Figure 5.7a shows a typical phase resolved PD pattern as obtained for 50Hz energising on sample D from table 5-1. The PD pattern is skewed to the left in relation to the voltage.

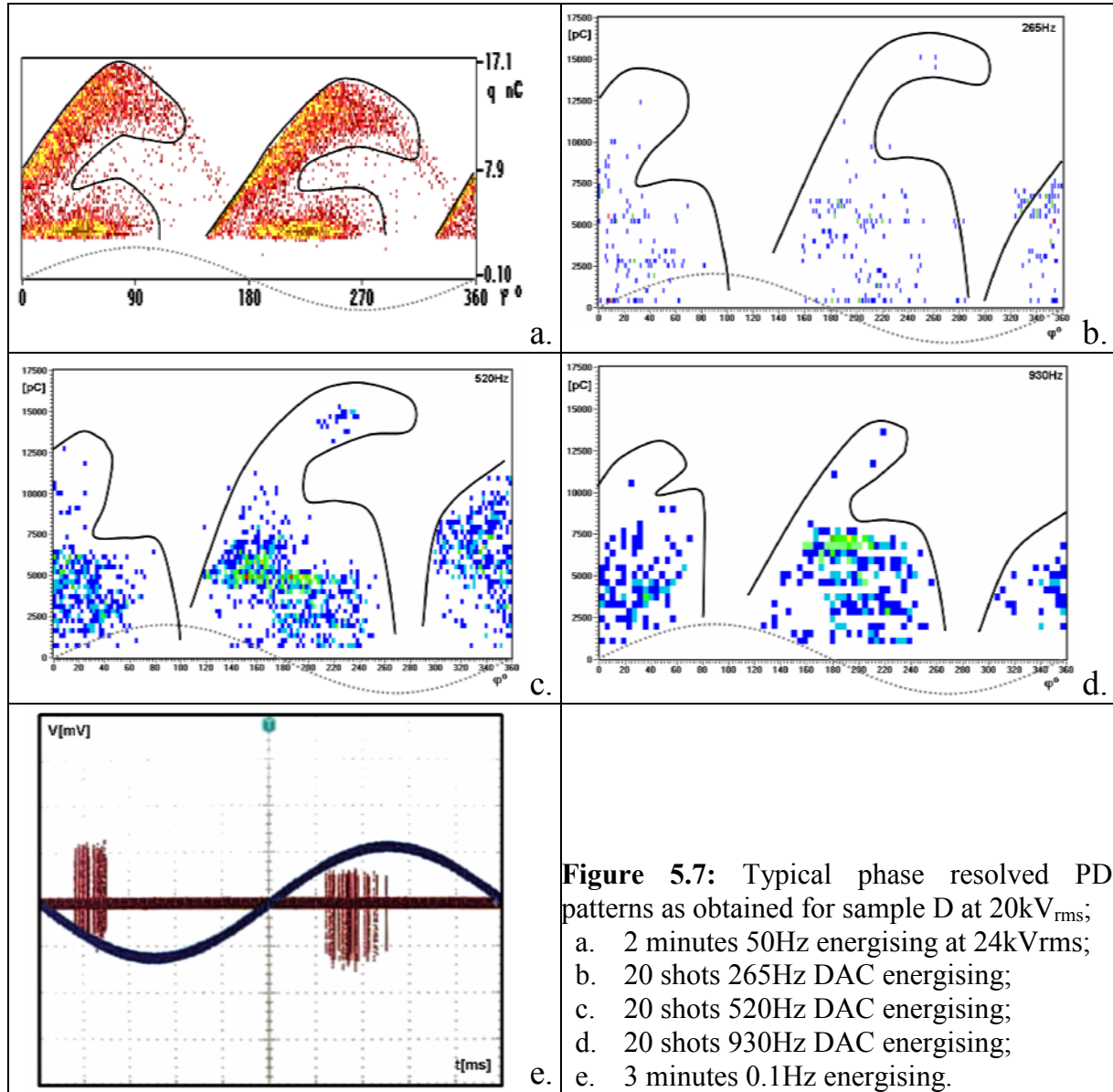


Figure 5.7: Typical phase resolved PD patterns as obtained for sample D at 20kV_{rms};
a. 2 minutes 50Hz energising at 24kV_{rms};
b. 20 shots 265Hz DAC energising;
c. 20 shots 520Hz DAC energising;
d. 20 shots 930Hz DAC energising;
e. 3 minutes 0.1Hz energising.

This skewness in the PD pattern [36] at 50Hz energising is also detected in the PD patterns of the samples tested at the different frequencies of DAC voltages. The probability of detecting a PD pattern with maximum magnitudes is related to the measurement time. The probability of large PDs is expected to be higher for the 2 minutes 50 Hz AC energising, than for the 20 DAC voltages. The PD patterns as obtained for different DAC frequencies are shown in figure 5.7b, c and d. Although the number of PD is much lower than at 50Hz energising, a pattern is recognisable. The higher PD magnitudes are less in number as compared to 50Hz. This is related to the measurement time and phenomenon of a relative long surface charge, which results in one large PD pulse and multiple lower PD pulses, as shown in figure 5.6.

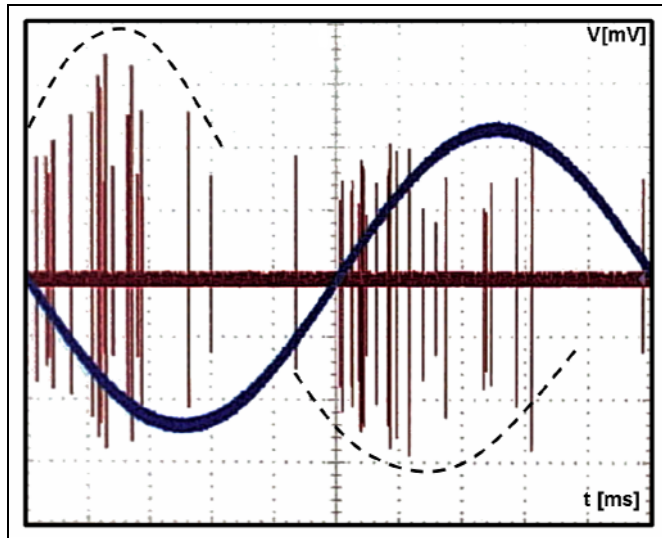


Figure 5.8: PD pattern at VLF energising for sample C.

With regard to lower frequencies, the extremely wide range of τ_{cd} -values can lead to different ignition characteristic for the different samples [7]. If the surface charge delay time is relative short compared to the period time of the test voltage, the time for a starting electron may be longer, whereas less PD may occur. The PD pattern at low frequencies may therefore be different compared to the PD patterns obtained at 50 Hz stressing. Experimental results

achieved at 0.1 Hz clearly showed this fact for sample D, see figure 5.7e. The other samples showed PD patterns at VLF energising which are more comparable to those obtained at 50Hz energising, as shown in figure 5.8.

5.2 DEFECTS UNDER DIFFERENT VOLTAGE STRESSES

To the above described defect type of cavities, in the field the methodology of PD cable diagnostics includes a large diversity of defects. As described in chapter 2, a number of typical defects can be defined which may occur in power cable systems. In [21], investigations are described which compare different commercially available energising methods, 50Hz energising, VLF energising, DAC energising at variable frequencies and DAC energising at fixed frequency on their technical performance, based on known defect in cable systems. The conclusion is that the overall performances of these systems were very much comparable with one another, related to the PD inception voltage, the PD magnitudes and the PD localisation.

In addition to our investigations on the effect of the voltage shape and frequency on PD activity in dielectric bounded cavities, other defect samples are used for further comparison between 50Hz energising and DAC energising at various frequencies. On the one hand, this investigation focuses on oil-related defect models as still most of the cable network in service consists of PILC cable systems with liquid insulated joints. On the other hand, the energising methods are applied on short polymeric cables and accessories with created defects. The comparisons are performed by the evaluation of PD inception, the measurable PD amplitudes and the phase-resolved PD patterns.

5.2.1 LABORATORY MODELS

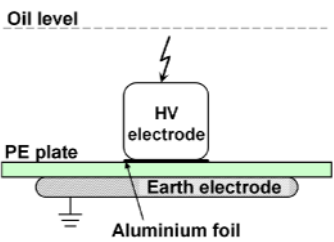
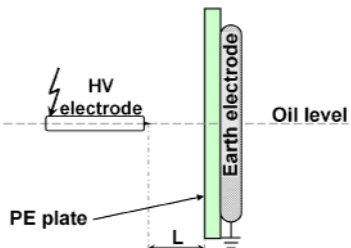
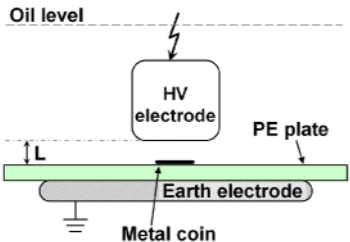
In order to make a comparison between the voltage stresses at different frequencies on the PD behaviour, three different models are used in laboratory set-ups. The following defects are modelled for the investigations:

- Surface discharges under oil;
- Sharp edges at oil surface;
- Floating parts in oil.

Table 5-4 shows the dimension of the test specimens and the applied electric field during the tests. The three samples, surface discharges and sharp edges, are stressed with the following voltage frequencies:

- 50 Hz continuous AC energising;
- 452Hz damped AC energising; an additional capacitor of $0.17\mu\text{F}$ ($0.25\mu\text{F}$ in series $0.5\mu\text{F}$) was used for obtaining the applied test frequency.

Table 5-4: Sample dimensions of models used to compare PD parameters at 50Hz energising and DAC energising at ca 452Hz.

Model	Surfaces under oil	Sharp edges at oil interface	Floating part in oil
Model representation			
Model dimensions	HV electrode $\varnothing 60\text{mm}$ ¹² PE plate $\varnothing 180\text{mm}$ d=5mm Earth electrode $\varnothing 110\text{mm}$	HV electrode with sharp chisel shaped tip PE plate $\varnothing 180\text{mm}$ d=2mm Earth electrode $\varnothing 110\text{mm}$ L = 45mm	HV electrode $\varnothing 60\text{mm}$ PE plate $\varnothing 180\text{mm}$ d=5mm Earth electrode $\varnothing 110\text{mm}$ L = 5mm

The measurement results of the three defect models for the different voltages are given in table 5-5. The AC and DAC results correspond for the measurements of surface discharges under oil regarding the PDIV and the PD magnitudes. The phase resolved PD patterns show for both energising methods a symmetrical pattern, with slightly higher PD magnitudes at the positive side.

¹² The aluminium foil ($\varnothing 60\text{mm}$) between the HV electrode and the PE sheath is used to create better inception conditions for the PD as would be obtained from the rounded electrode.

Table 5-5: Measurement results for three different cable defect models as obtained for the 50Hz AC energising and 457Hz DAC energising.

		PD inc. voltage	PD magnitudes	Phase resolved PD pattern
Surfaces under oil	50Hz AC	12.5 kV _{rms}	0.85 nC at 20kV _{rms}	
	452Hz DAC	12.7 kV _{rms} (18kV _{peak})	0.87 nC at 20kV _{rms} (28kV _{peak})	
Sharp edges at oil surface	50Hz AC	9.5 kV _{rms}	12 nC at 12.7kV _{rms}	
	452Hz DAC	12.7 kV _{rms} (18kV _{peak})	10.5 nC at 12.7kV _{rms} (18kV _{peak})	
Floating part in oil	50Hz AC	4.8 kV _{rms}	8nC at 8 kV _{rms}	
	452Hz DAC	5.7 kV _{rms} (8kV _{peak})	10nC at 7.8kV _{rms} (11kV _{peak})	

For the measurements on the model for sharp edges at the oil surface, the PDIV at DAC energising is 30% higher than at AC energising, whereas the PD magnitude is slightly lower for DAC energising, as compared to AC energising. The phase resolved PD patterns correspond very well; strongly asymmetrical with higher magnitudes on the positive period half.

The measurements on the floating part in oil show comparable results for the PDIV as well as for the PD magnitudes. However, the PD patterns are not comparable to one another. The pattern at DAC energising does not show PD at zero crossing, and less marked discharge groups before the voltage peaks.

5.2.2 CABLE ACCESSORY MODELS

Laboratory experiments have been performed to get insight into the inception conditions and measurable PD magnitudes. A series of PD measurements have been performed on 10 kV polymeric insulated cable joints and terminations for two defects:

- I. stress cone of the termination overlaps the semi conductive screen of the cable insulation too much;
- II. stress cone of the joint has no connection to the semi conductive screen of the cable insulation.

Successively, the same cables were energised with initially 50 Hz continuous AC voltage and then again using 59 Hz and 265 Hz DAC energising. The different frequencies on the respective cables, are obtained by using extra capacitances of 10 μ F (in fact 4x 2.5 μ F in parallel) and 0.5 μ F, parallel to the test object.

Figure 5.9 and figure 5.10 show the phase resolved PD patterns of the mentioned defects. Defect I shows a clearly asymmetric PD pattern, where PD are mainly located in the negative half of the sinus shaped test voltage. Defect II shows a symmetric PD pattern, as expected for surface discharges, with PD in the positive as well as the negative half.

The main difference in the PD patterns at 50Hz AC energising and the DAC energising is the intensity of the pattern. This is caused by the number of periods reflected in the 3D pattern, which is 6000 at 50Hz energising (2 minutes) and about 50 at the DAC energising, after 10 shots at the same voltage.

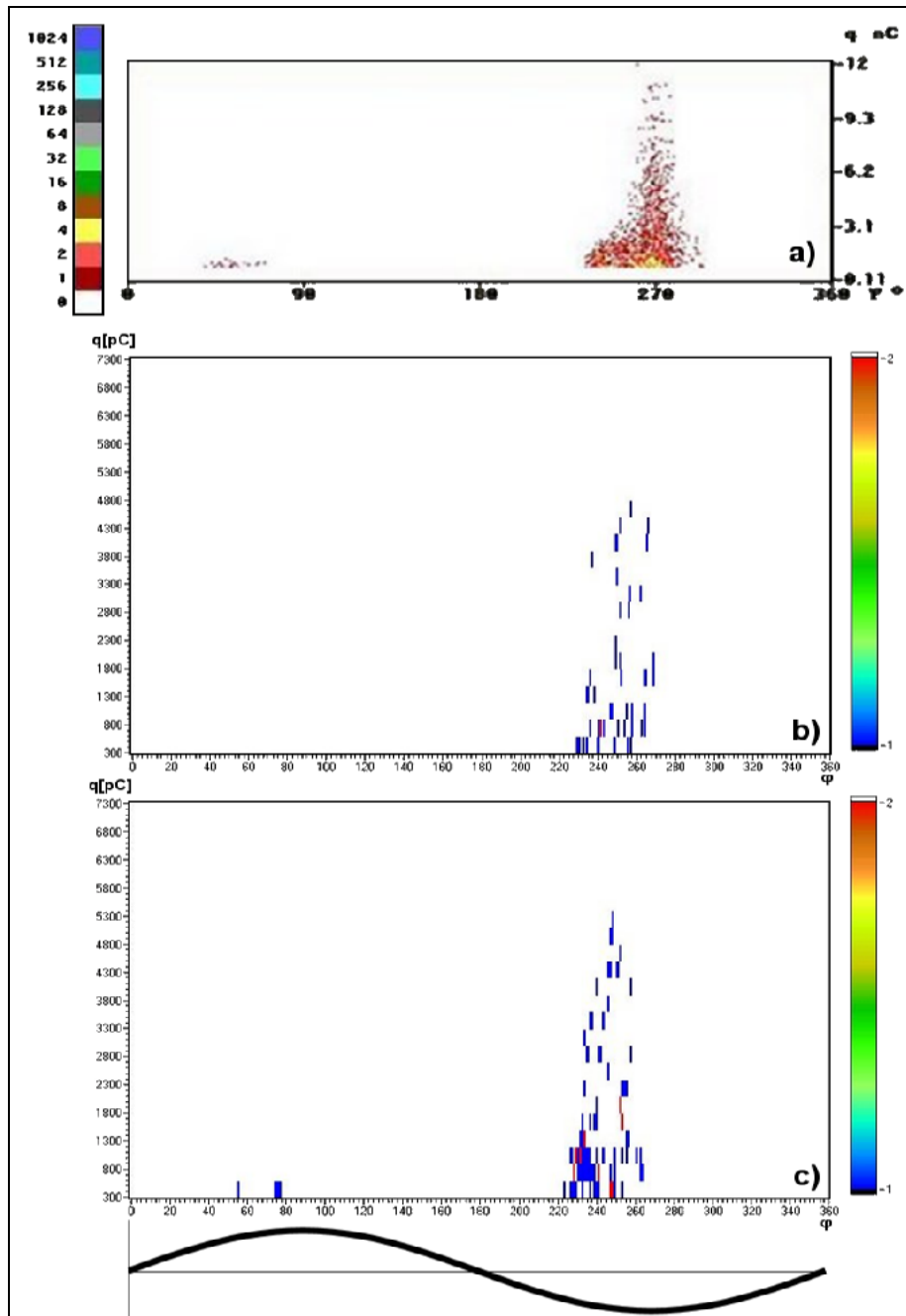


Figure 5.9: Phase resolved PD patterns as obtained for a cable termination with defect I, an overlap between the stress cone and the semi conducting screen of the cable at 6kV_{rms} ;

- a) 2 minutes 50Hz energising;
- b) 10 shots 59Hz DAC energising;
- c) 10 shots 265Hz DAC energising;

Asymmetric pattern is detected in each set-up.

Also in figure 5.10, the main difference in the PD patterns at 50Hz and DAC energising is the intensity of the pattern. Furthermore, the PD pattern at 59Hz DAC energising shows a lower PD level at the positive half of the sinus. This is related to the decay of the test voltage. To obtain a low test frequency additional capacitances are applied parallel to the test cable, which result in a bigger decay

of the voltage. As the DAC test voltage is already decreased at the first full positive half of the voltage shot, the magnitudes of the PDs occurring at the lower voltages are also lower. This effect is also perceptible at the test of 265Hz, but here the decay of the voltage is less for the above described effect.

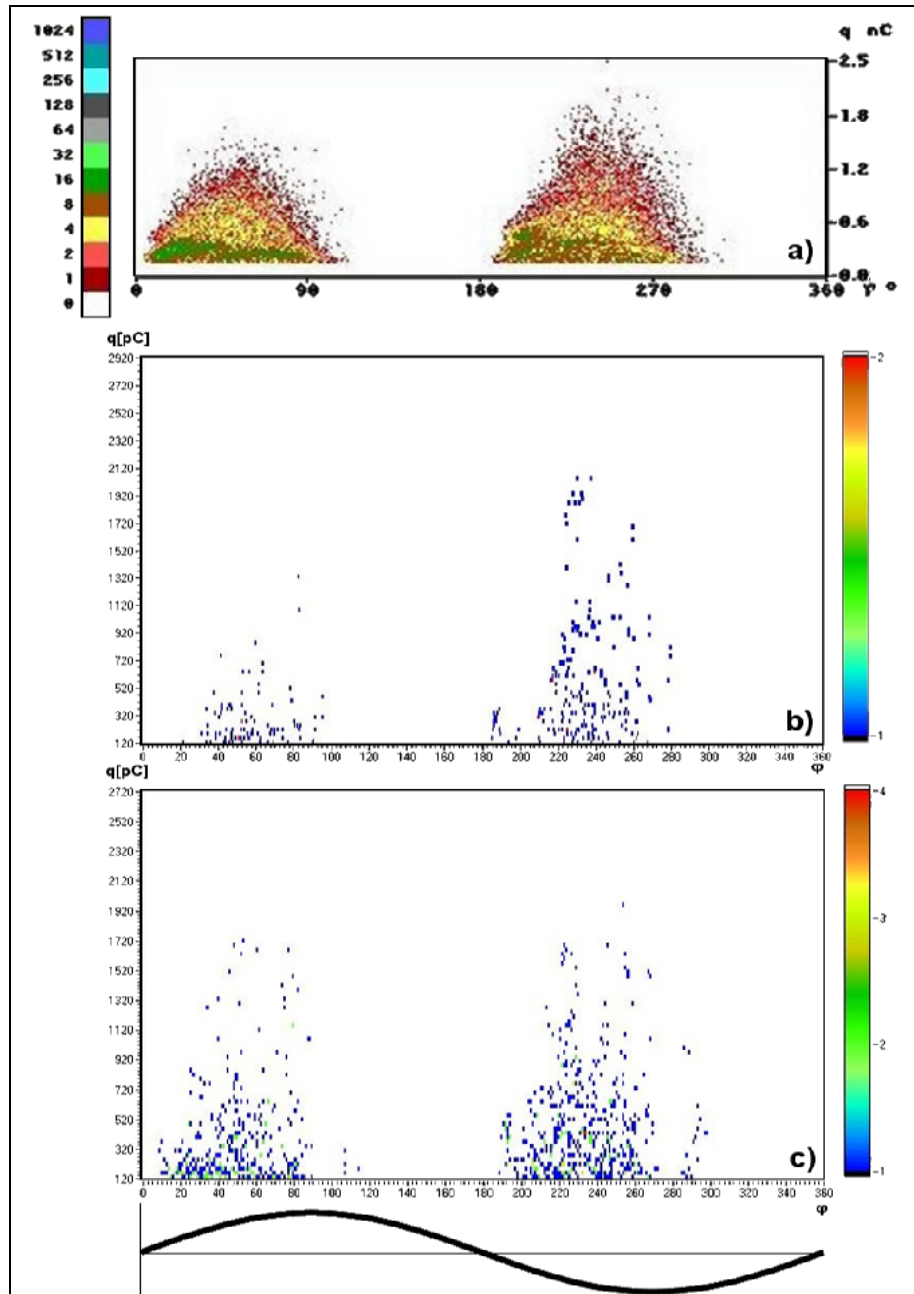


Figure 5.10: Phase resolved PD patterns as obtained for a cable joint with defect II, the stress cone has no connection to the semi conducting screen of the cable at $6kV_{rms}$;

- a) 2 minutes 50Hz energising;
- b) 10 shots 59Hz DAC energising;
- c) 10 shots 265Hz DAC energising;

Symmetric pattern is detected in each set-up.

In table 5-6, results of inception voltages and measurable PD levels are summarised for two types of defects, mentioned above. It follows, that the inception voltages are similar for the temporarily 59Hz and 265Hz DAC energising as for continuous AC energising. Also the PD magnitudes at DAC energising are in the same range as for 50 Hz AC energising, independent of the DAC test frequency. As a result, taking into account the stochastic behaviour of internal discharges, no significant difference has been observed between the energising methods or the test frequencies.

Table 5-6: PD parameters as obtained from the measurements on cable accessories with realistic mounted internal defects.

Energising method	Defect a.			Defect b.		
	PDIV [kV _{rms}]	PDEV [kV _{rms}]	PD level [nC]	PDIV [kV _{rms}]	PDEV [kV _{rms}]	PD level [nC]
50Hz AC	3.8	3.5	~ 5.1	5.3	4.2	~ 1.5
59Hz DAC	3.9 (5.5kV _{peak})	3.5 (5.0kV _{peak})	~ 5.2	5.3 (7.5kV _{peak})	3.2 (4.5kV _{peak})	~1.9
265Hz DAC	4.2 (6.0kV _{peak})	3.7 (5.2kV _{peak})	~5.0	5.0 (7.0kV _{peak})	3.1 (4.3kV _{peak})	~1.8

In general, between the measurement results obtained from oil related defect models and the polymeric cable samples with mounting faults, some small differences have been observed in the PD properties. For the samples which do show some differences, only one of the three studied PD parameters, PD inception voltage, PD magnitude or PD pattern does not correspond between the DAC energising as compared to 50Hz energising. Which PD parameter differs, depends on the type of defect.

5.3 PRACTICAL VERIFICATION

Besides the laboratory investigation of the influence of test voltage shapes and frequencies, field measurements have been performed in the field for comparisons between PD diagnostics based on 50Hz AC energising and diagnostics based on DAC energising. An 840 meter 10kV PILC cable system from 1983 was diagnosed on the same day by both systems. Figure 5.11 shows the analysed PD mappings for both diagnostics. The 50Hz AC measurements are performed by a resonance voltage source with a conventional PD detection.

The PD mappings show that the intensity of the DAC measurement is higher. This is related to the data collection method of the measurement equipment. Furthermore, the PD magnitudes are averagely higher for DAC energising than

for AC energising. The most important PD source in the joint at 143 meters is located by both. Additionally, also light concentrations of PD activity are detected in the joints at 200, 375 and 510 meters by both tools. As can be concluded from the above described field measurement, the DAC energising gives corresponding results to 50Hz AC energising.

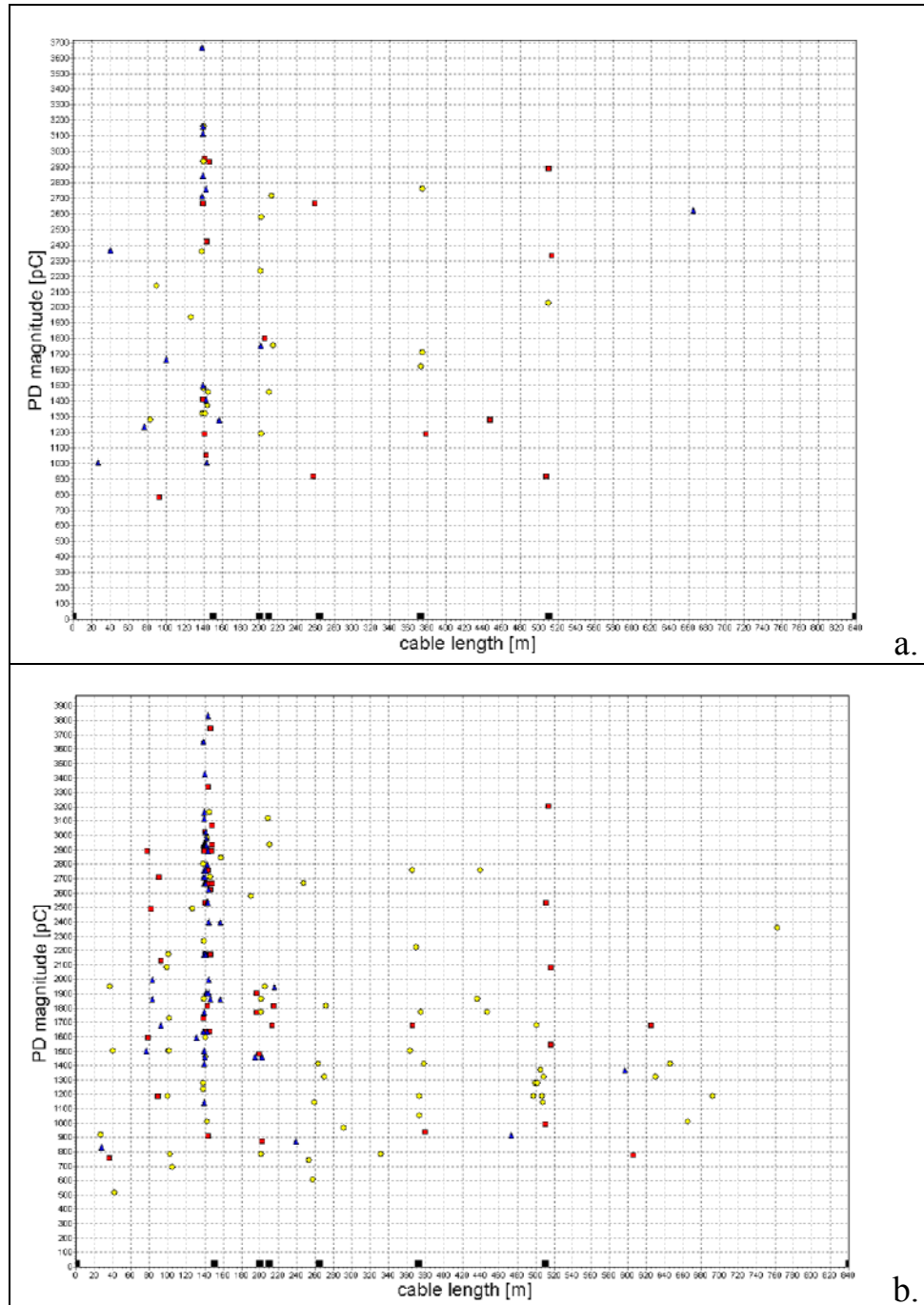


Figure 5.11: PD mappings from an 840m 10kV PILC cable system, measured with:

- 50Hz AC energising (resonance system, 2 minutes).
- 244Hz DAC energising (25 shots).

Another field experiment was the measurement at two different test frequencies with DAC energising, obtained by the cable capacitance only and an additional cable capacitance. The measurements are performed on one phase of a 220 meters long PILC cable with one joint. Figure 5.12 shows the PD mappings as analysed for the two test frequencies. The mappings are similar. Three PD concentrations are detected at 37 and 63 meters and in the joint at 137 meters. The PD magnitudes are equivalent.

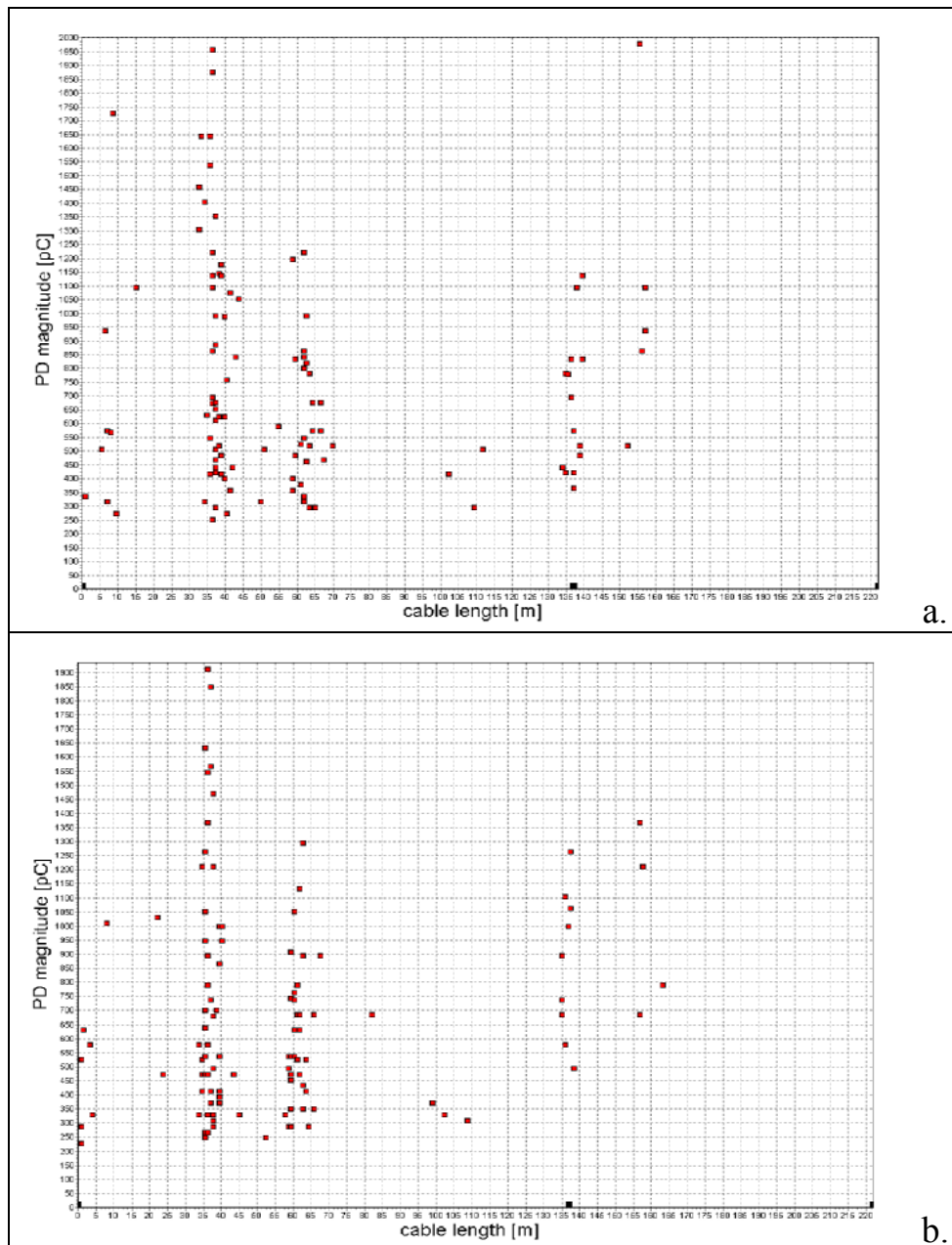


Figure 5.12: PD mapping from a 220m PILC cable system, measured at to different frequencies.

- At 597Hz, only the cable system.
- At 244Hz, cable system with a parallel C.

Apart from the PD mappings, the PD magnitudes and patterns obtained from the cable system are also analysed and shown in table 5-7. Only minor differences in the PD inception voltage and the PD magnitudes are observed.

Table 5-7: PD magnitudes from a 220 meter PILC cable measured with DAC voltages at two frequencies, at 597Hz and at 244Hz.

Test voltage [kV _{peak}]	PD magnitude [pC]	
	<i>At 597 Hz (PDIV = 4kV_{peak})</i>	<i>At 243 Hz (PDIV = 3kV_{peak})</i>
6	674	831
9	1917	959
12	1108	1224
15	1777	1786
18	1906	2051

The above described experiments show that the measurements at DAC energising correspond to 50Hz energising for practical applications. Independent on the voltage shape and frequency, the relevant PD sources (concentrations) are found by both systems. The test voltage frequency and shape only have negligible influences in practice to the measurements results. Although the influence of the test frequency is small, based on the results on dielectric induced cavities, as reflected in table 5-3, it is recommended for the practical application of DAC diagnostics to perform the measurement at test frequencies below 500Hz. During the measurement above this test frequency, lower PD magnitudes were obtained as compared to lower frequencies.

5.4 CONCLUSIONS

In this chapter, several fundamental aspects of PD detection at different voltage types on different defect types are investigated:

- 1) The effect of the test voltage shape and frequency for dielectric bounded cavities show that the remaining charge on the cavity surface after a PD event is of major importance on the inception conditions of partial discharges;
- 2) The deposited surface charge after a PD leads to a very short inception delay time for sufficiently high voltages. However, if the applied voltage is too low, a quite long delay time is obtained. In the latter case, the number of DAC shots should be increased for a stable PD inception;
- 3) Due to the inception relay time of PDs, the decay factor of the DAC voltages determined the number of shots necessary to obtain a pattern with PD than

the test frequency of the DAC voltage. For field measurements this means that an applied additional capacitor should have low losses;

- 4) The relation between the starting electron mechanism, the overvoltage (above inception voltage) and the frequency of the test voltage leads to a slightly decreasing PD magnitude at higher frequencies for dielectric bounded cavities;
- 5) Comparisons between PD detection at AC energising and DAC energising at increased frequencies on oil related defect samples and polymeric cable samples in the laboratory show no major differences for the PDIV, PD magnitudes and PD patterns;
- 6) From experiments on PILC cable systems, it can be concluded that in practice the influence of the effect of the voltage shape and test frequency is negligible.

6

DECISION SUPPORT SYSTEM FOR DEGRADATION DETERMINATION

For the classification of the quality of individual components and full cable systems, decision support is required to determine the necessity of successive maintenance actions, like re-diagnosing after a certain time interval or immediate replacement of deteriorated components. Not all the cable components with a detected and localised PD source need to be immediately replaced. A PD source in a cable component is not always harmful to the component's insulation in the short term. To distinguish between the different defect types and degradation state of the insulation, decision support needs to be developed.

To define critical levels of PD properties for different defect types in cable insulation is still not possible [76]. The variety of defects and the great number of influencing factors for power cables in service are the main reasons why the exact moment of failure cannot be predicted, based on diagnostics. The approach in this thesis is from the point of view of asset management, namely to reduce the number of outages (at least keep at the same level) and maintenance costs for acceptable risks.

In case a large number of field measurement data for a large number of cable components are available, data mining is an effective tool. The aim of data mining is to find intelligible patterns which are not predicted by established theory [85]. In this thesis, the experience norms for PD properties are determined by statistical analysis. The analyses will be carried out using a so-called condition database, as described in appendix C, which contains all the information of the cable system characteristics and the related diagnostic information. Using these experience norms, or a combination of the norms, the decision on follow-up maintenance activities reduces the probability of outages by insulation degradation. In case a defect below the experience norm(s) of the

PD properties will fail, the norm will be adjusted. The probability of failure of a cable component and the resulting outage will be decreased by the application of these experience norms.

The classification of the condition of a full cable system is a combination of the interpretation of the individual components. This chapter will describe the decision support system, resulting from the investigations in this thesis. The interpretation process will be clarified by means of measurement examples from field experiences.

6.1 AIM OF DECISION SUPPORT SYSTEM

To describe a PD process in a power cable system under investigation, a diagnostic tool generates multiple 1D, 2D and 3D properties. This variety of PD properties is related to the insulation deterioration processes. The combination of PD properties together with the localisation of the PD source contains the information to decide on the maintenance actions. For these conclusions, knowledge on the critical levels of PD properties is required. This knowledge on criticality of PD properties is obtained from PD diagnoses that are performed on multiple cable systems with a variety of cable component types.

Visual inspections of the replaced cable components are often performed after PD measurements. A confirmation of replacement actions is obtained by opening a cable component and making a visual analysis of those defects, which may have a relation to the detected PD activity. As the PD properties are known from the measurement, knowledge on PD properties may be related to a specific defect type.

However, it is very difficult to get the general relations between the PD symptoms and the forensic evidence. In most cases, when a cable component is inspected, only a limited view of the interior of the opened component is obtained. In order to open a component destructive actions are needed, which will influence the accuracy of the inspection. The analysis of the forensic evidence is often performed with the subjective judgements in the visual inspection. E.g., it is not possible to visually analyse if the electric field at the location of a cavity in the insulation is high enough to create PD activity.

Finally, when a cable component is opened usually more defects can be found. These manually constructed components often show additional defects enclosed. It is always difficult to visually find the relation between the found defects and the detected PD properties. Figure 6.1 shows an example of a visual inspection of a cable joint. The found evidence, protrusions on the press connector and

missing fabric wrapping in the middle (upper figure) can be related to the measured PD activity. However, evidences of continuing insulation degradation, as a result of the found defects, are hard to find.

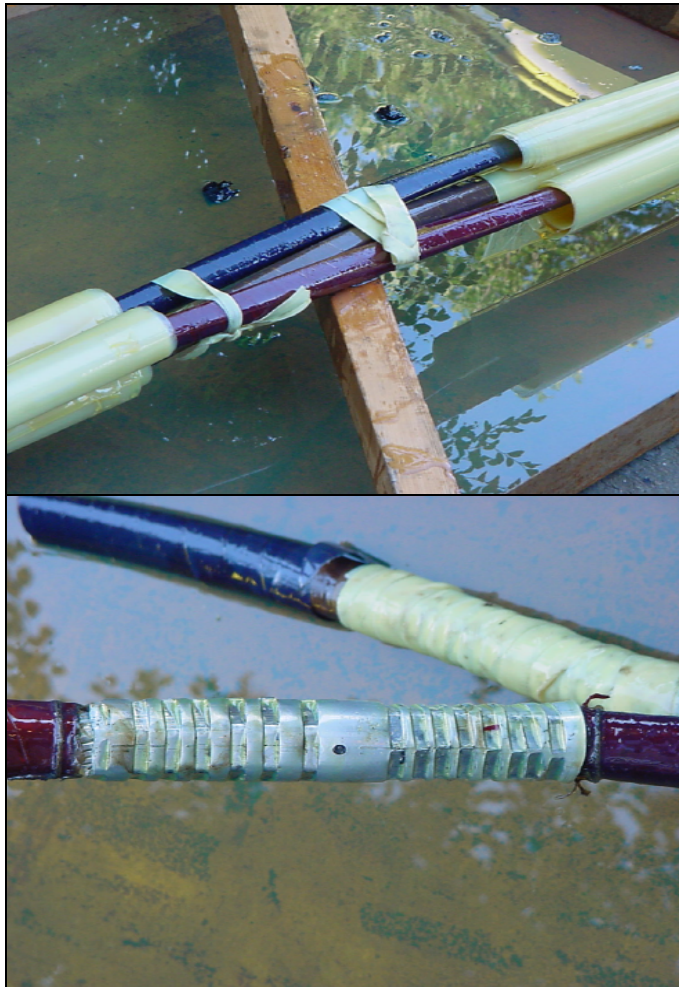


Figure 6.1: Analysis for forensic evidence in an opened cable joint, where PD activity is detected. Lacking wrapping in the middle and protrusions on the press connector.

The relation between the PD symptoms and the forensic evidence is mostly inaccurate. The solution for the analysis of a diagnosis of a cable system (or its components) is to make comparisons to other measurements results, which can be performed in two different ways, as illustrated in figure 6.2:

- Time analysis: comparison of a PD property to the properties as obtained in previous measurements on the same object. If the trend of a PD property is negative (e.g. increasing PD magnitudes), this indicates that from the point of view of that property the condition of that component decreases. Trending of power cable condition may be time and cost consuming, but shows the progress of a degradation process clearly. A trend-line together with a norm level will contribute to a failure prediction.
- Type analysis: Comparison of a PD property to that same type of properties, as obtained for the total population of the same specific component type. If a PD property of a specific component is out of the range of the typical observations, this indicates that from the point of view of that property the condition of that component deviates from the 'normal' condition of the total population. As a result, the statistical response of a PD property, as obtained in a measurement, can be compared to the true population of that PD property. To disclaim a sample belonging to a certain population, a sample is generally found outside the 90% or 95% confidence interval of the true population.

For both of the above described analysis, PD tolerance levels are necessary to assess the deviation. These levels can be determined by making statistical analyses for large amount of PD data. From these large amounts of PD data, the statistical distributions can be obtained for the different PD properties. The populations used for the statistical analysis should be representative for the total population of the full network. Application of a diagnostic tool tends to be performed on suspected cable systems (from earlier experiences), having an increased probability of detecting critical PD sources. As a result, the analysed distribution will be shifted to the negative side and the critical levels are influenced.

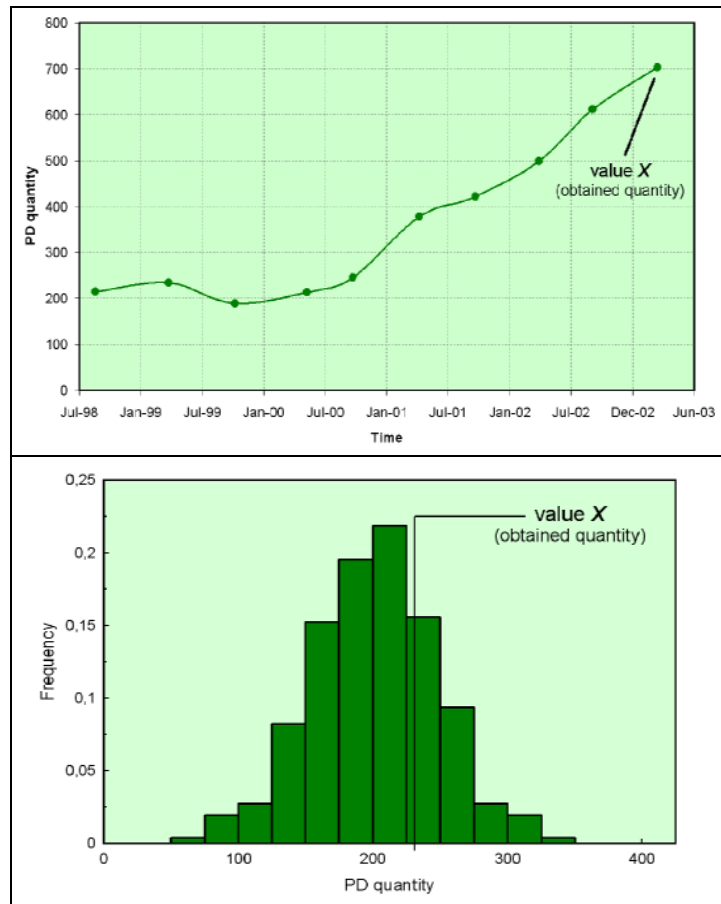


Figure 6.2: Example of time (upper) and type (lower) analysis of PD properties as obtained from a momentary diagnosis of cable components.

6.2 STATISTICAL DATA ANALYSIS PROCEDURE

The statistical analysis, as described in this section, is applicable for the so-called 1D diagnostic properties; PD inception voltage, PD level at U_0 (average and maximal), PD level at $2U_0$ (average and maximal), PD frequency occurrence per DAC shot up to U_0 and between U_0 and $2U_0$. The scatter in the distributions of the populations may be rather large, due to relative few observations. For statistical analysis of the different properties, the PD data can be indicated by the type and the shape of the distribution. Calculations on the representative distributions can be performed to determine the deviation of a PD property or to determine the deviation limits (norms) for a population of PD property.

In order to obtain experience norms, the different PD properties are gathered per type of cable component. After the determination of the type and the shape of a distribution, the required parameters are calculated. As the distribution

represents the true population, calculations can be performed for the definitions of the norm levels of the different PD properties. The distributions for the different PD properties are dependent on the type of PD property and the applied measurement protocol (voltage levels for detection).

6.2.1 PD INCEPTION VOLTAGE

The field measurements are performed up to a certain maximum test voltage (typically $2 \cdot U_0$). However, above this maximum test voltage, PD sources may also be ignited, but these are not taken into account for the distribution. As a result, only a part of the physical distribution is used for the calculations.

To make the statistical analysis independent from the voltage level of the network, the inception voltage is normalised (U_{inc}) according to equation 6.1:

$$U_{inc} = \frac{PDIV - U_0}{U_0} \quad (6.1)$$

In this way, applying a measurement interval of $[0, 2U_0]$, the interval of U_{inc} will be $[-1, 1]$. If the outcome is negative, the PDIV is smaller than U_0 . In the range up to $2U_0$, a random distribution is obtained as the measurements are performed in practice in voltage steps of $3kV_{peak}$. The distribution of the PDIV of an oil insulated cable joint is shown in figure 6.3. This distribution is based on 105 measurements results, collected in a database. The distribution shows that most of the test results are related to a positive U_{inc} , so above the nominal operation voltage.

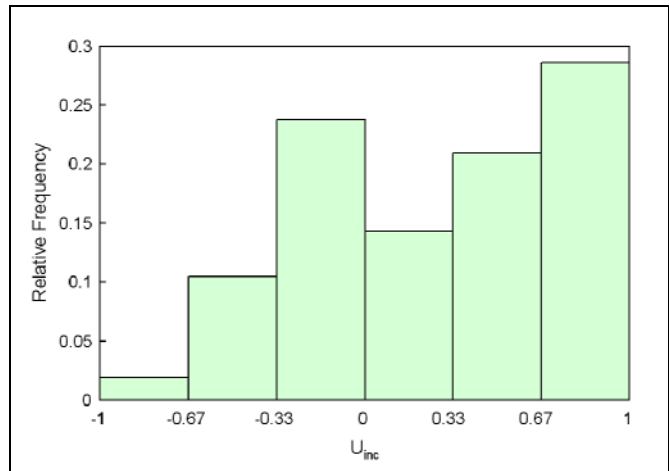


Figure 6.3: Histogram of the U_{inc} of the measurement results in the condition database from the oil insulated cable joints ($N = 105$).

The PD inception voltage distribution is not from a clear distribution type. Therefore, only the mean values of the PDIV distributions for the different components are used for the experience norms.

6.2.2 PD AMPLITUDE LEVEL

The distribution of the PD amplitudes per component type may have different shapes. Generally, low PD levels will occur more often in a population of cable components. However for some type of components or defects, it could occur such that the PD amplitude will occur in a specific range (e.g. between 4000 and 5000pC). If the failure rate of a specific component is relative high, experience has shown that the detected PD sources will generally indicate an increased state of insulation degradation around the defects.

Partial discharges are breakdowns across a small part of the insulating material as a result of locally increased field strength. Weibull statistics estimate the probability that the insulation of an object partially breaks down as a result of the weakest link. Weibull statistics are used in this thesis for PD magnitudes as a mathematical fitting of the distributions of the PD magnitude levels and not due to a physical base. The Weibull statistic deals with the different kinds of shapes of the distribution of PD amplitude levels.

The two parameter Weibull cumulative density function (CDF) is described by:

$$F(q) = \begin{cases} 0 & q < 0 \\ 1 - \exp\left[-\left(\frac{q}{q_0}\right)^\eta\right] & q \geq 0 \end{cases} \quad (6.2)$$

where q is the detected PD amplitude level, q_0 is the Weibull scale parameter and η is the Weibull shape parameter. The parameters η and q_0 can then be determined from the sampled measurement data. The confidence limits indicate a bandwidth of the scale parameter q_0 . The mean of the Weibull distribution is:

$$\bar{q} = q_0 \cdot \Gamma\left(\frac{1}{\eta} + 1\right) \text{ where } \Gamma(n) = \int_0^\infty e^{-x} \cdot x^{n-1} dx \quad (6.3)$$

An example of the Weibull analysis for the PD amplitude levels is shown in figure 6.4. The Weibull analysis of the maximal PD amplitude at test voltage up to U_0 , for oil insulated cable joints is shown. The shape parameter for this distribution $\eta = 1.24$ and the scale parameter $q_0 = 5101\text{pC}$. The 95% confidence interval of the scale parameter is [3914, 6222].

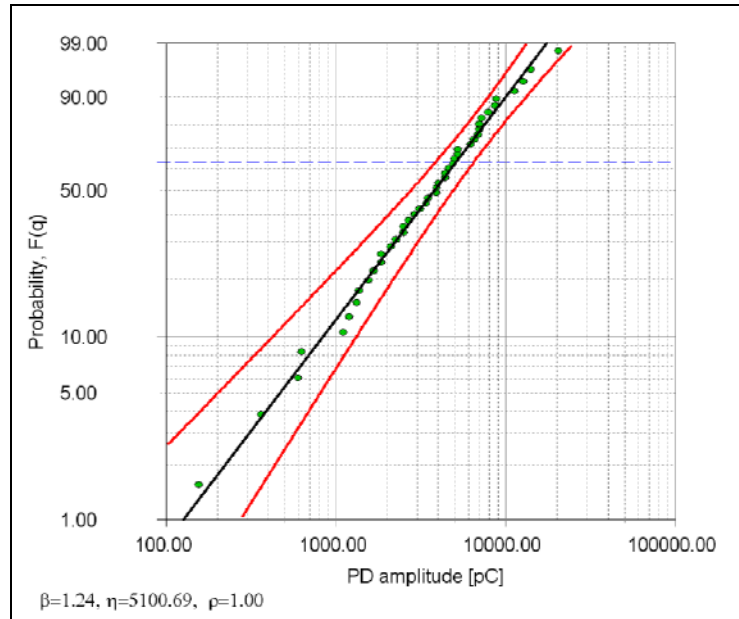


Figure 6.4: Weibull analysis of the PD amplitude at test voltage up to U_0 , for PILC cable insulation. The shape parameter for this distribution $\eta = 1.24$ and the scale parameter $q_0 = 5101\text{pC}$.

6.2.3 PD OCCURRENCE FREQUENCY

The PD occurrence frequency (PDOF) for the applied PD diagnostics will be assumed as a Poisson distribution. The PDOF is the number of PDs occurring in a specific time interval T . For the applied diagnostics, this fixed time interval is the time interval as is used for the PD location, which is approximately 2.6ms per DAC voltage. If this time interval is divided into n subintervals, a PD occurrence in one subinterval can be seen as the occurrence of an event. Each subinterval can then be viewed as a Bernoulli trial [81], which is independent from another. The probability of the occurrence of an event in a subinterval can then be reflected as $p = \alpha/n$, where α is the average number of events observed in the time span T .

The probability density function (PDF) of the distribution of the PD occurrence frequency is described by:

$$p_k = \frac{(\xi)^k}{k!} e^{-\alpha} \quad k = 0, 1, 2, 3, \dots \quad \text{and} \quad \alpha > 0 \quad (6.4)$$

The parameter ξ is proportional to the mean of the distribution of measured data to be analysed [81]. If the sample mean of the PDOF of a distribution is determined, calculations can be performed according to the PDF in equation 6.4.

6.3 DETERMINATION OF NORMS

With the distribution for the different PD properties, we have statistically determined experience norms for the condition assessment. These experience norms are referred to as critical levels which indicate the deterioration state of a defect. The norms do not directly relate to an individual defect as the PD properties are related to a component type. By using these experience norms the probability that a defect will end up in a breakdown in the short term decreases but has to be adjusted to practical feedback.

For the determination of the experience norms we made some assumptions because the results are obtained from service-aged components with unknown defects, contrarily to laboratory experiments:

1. only one type of defect occurs or one type of defect is dominant in a specific component type;
2. the criticality for a defect type increases proportionally with which the detected levels are surpassing the experience norms;
3. the detected different PD properties are independent of the age of the components;
4. for some defects a PD property may change reversibly before the actual breakdown occurs [76].

Because of the latter assumptions, some defects may eventually result in breakdown, whereas the PD properties were analysed below the experience norms. However, using the deviation from the norms as an indicator, the major part of the defects will be detected. E.g. the PD level may decrease during the final stage of the degradation process, before the actual breakdown [74,76].

The experience norms are applied to support decisions from the point of view of asset management. The latter focuses on the reduction of the number of outages (at least at the same level) for the cable network, while the maintenance costs are optimised under acceptable risk. For the determination of what level in the distribution should be applied for the experience norm, the following aspects are of relevance:

- a. the distributions are obtained from the field measurements and therefore represent the typically occurring levels of the different PD properties;
- b. the critical levels in the distributions are determined for the group of measurements above this norm, which is for this thesis set to 5%, which means that the top 5% of the distribution of the PD property is rejected;

As a result, the norm levels are determined at 95% of the distribution. The interval between diagnoses depends on the experiences, which may change over time or may be different on the network owner's strategy.

By applying this approach for the determination of the experience norms, the norm settings are dependent on the strategy of the company, the actual failure rate of a component type and the obtained measurement data. As a result, the norms may change over time or vary for the diagnosed network (part). If the failure rate of a component increases over time, due to e.g. systematic ageing, the experience norm can be adapted (to e.g. 10%) so that more defective components are replaced and the risk of failure decreases. If the maintenance strategy for cables changes to a longer condition interval, the norms are adapted and more maintenance actions will be performed decreasing the failure risk.

6.3.1 PD INCEPTION VOLTAGE

The average PD inception voltage with its confidence limits can be calculated. The experience norm of the PDIV is based on the average value of the obtained measurements. The average value of U_{inc} (see equation 6.1) is determined and compared to the operation voltage of the power network:

1. If the average U_{inc} is a positive value, the experience norm is set at the operation voltage.
2. If the average U_{inc} is a negative value, the applied experience norm is set at the average PDIV value.

Table 6-1: The definition of experience norms for the PD inception voltage of defects in insulation.

Average U_{inc} from distribution	Used norm level for PDIV
$U_{inc} \leq 0$	$PDIV$
$U_{inc} > 0$	U_0

The upper knowledge rules imply that it is critical when PD is active in the insulation at voltages below U_0 . A PDIV which is lower than the operating voltage means that the PD source is active during operation. However, an average PDIV below U_0 might be typical

for specific insulations and constructions of a component. PD activity below U_0 but higher than the average U_{inc} is indicated as less critical for these defects. The average PDIV is then used as the experience norm. The definition of the experience norms of PDIV is summed in table 6-1.

E.g. for paper oil insulation, it is typical that the PDIV is below the operation voltage. The layered structure of the insulation results in an increased probability of spread voids with PD activity at a low inception voltage, which is not harmful to the insulation. As a result, an inception voltage below the average PDIV is indicated as critical.

6.3.2 PD AMPLITUDE LEVEL

Using the cumulative distribution function (CDF) of the Weibull distribution (equation 6.2), the deviation of a PD amplitude value can be calculated from the distribution. A norm level for the PD amplitude can be defined as that point of the CDF where the deviation of the PD property is higher than 'typical' values. The norm level is determined by 95% level of the distribution. This norm determines that the remaining part of the distribution will not fail in the next maintenance period. The experience norms are dependent on the goals of the asset manager. If the failure rate of a component increases, the experience norm should be adapted so more defective components are taken out of service. Even so, if the condition assessments interval is increased from 5 to 10 years, the experience norm should be decreased to keep the risk level at the same level.

In figure 6.4, the scale parameter q_0 (5101) and the shape parameter η (1.24) of the PD amplitude level at U_0 of oil insulated joints are determined. The experience norm for this example is determined with the Weibull distribution. From the distribution, the experience norm can be calculated with equation 6.2 at 95%, as is illustrated in figure 6.5. The norm for this example can then be determined as 12358pC. The accuracy of the norm level is determined by the confidence bounds of the CDF.

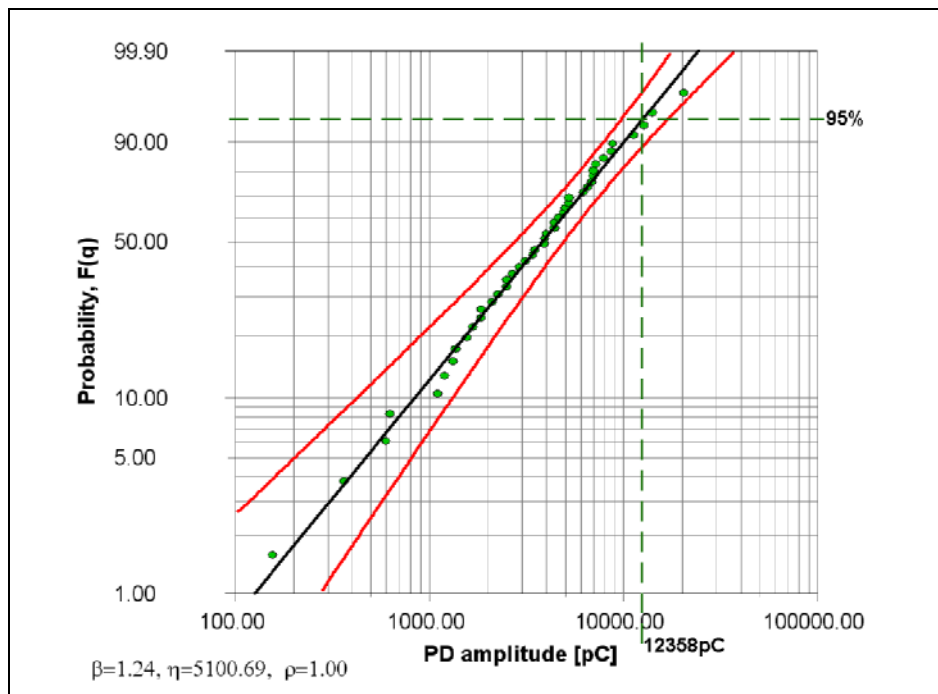


Figure 6.5: Example of the determination (oil insulated joints) of the experience norms for the maximum PD amplitude levels at U_0 ($N=44$).

In case that the disturbance rate of a specific component increases, the experience norm has to be recalculated. If a part of the network shows a higher

failure rate in a cable component type, the percentage of disturbed components will increase and as a result the norms for decision support are adapted and will decrease.

6.3.3 PD OCCURRENCE FREQUENCY

The experience norm of the PD occurrence frequency can be calculated from the obtained PDF of the PD occurrence frequency. When the mean value of the PD occurrence frequency is calculated from the distribution, see appendix C, the factor α of the Poisson distribution is known. If the norm is determined at 95%, with equation 6.5 the value of the norm can be calculated:

$$0.95 = P[N < x] = e^{-\xi} \left(\sum_{k=0}^x \frac{\xi^k}{k!} \right) \quad (6.5)$$

That value of factor k , which results in a value nearest but below the 0.95, is the obtained norm for the component type. This result can also be obtained graphically with the cumulative distribution.

6.4 EXPERIENCE NORMS

Based on numerous field measurements experience norms can be derived according to the descriptions in the previous section. The norm determination of the PDIV, average and maximum PD amplitudes (at U_0 and $2U_0$) and the PD occurrence frequency (at U_0 and $2U_0$) are described for one type of cable joint (resin/oil insulated). The calculations of the different norms are performed on a population of 131 measuring results for this joint type.

6.4.1 PD INCEPTION VOLTAGE

The distribution of the PDIV (normalised to U_{inc}) for resin/oil insulated cable joints is shown in figure 6.6. The mean of the U_{inc} for the resin/oil insulated cable joint type is determined at -0.07 with a 95% confidence interval of (-0.12, -0.02). This mean of the distribution of U_{inc} is negative. As a result, the norm for the PDIV is determined according to table 6-1 at average PDIV, which is in this case lower than the nominal phase to earth voltage.¹³

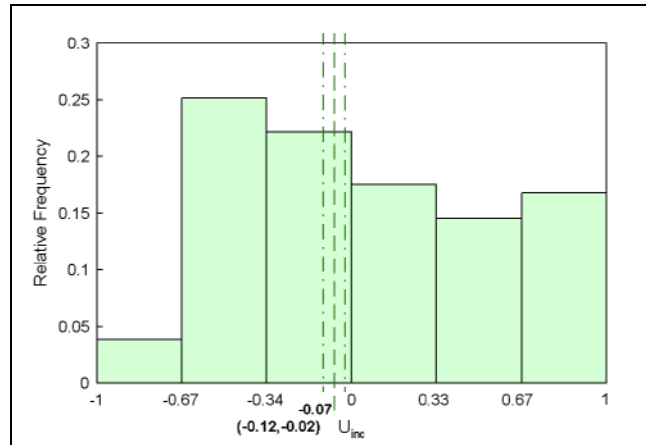


Figure 6.6: Histogram of the U_{inc} of all the measurement result (N = 131) in the condition database from the resin/oil insulated cable joints.

6.4.2 PD AMPLITUDE LEVEL

Table 6-2 shows the populations of the PD amplitude, average and maximum, as obtained at U_0 and $2U_0$ for the resin/mass insulated joint. For the four obtained distributions of PD levels, the shape parameter η and the scale parameter q_0 are determined (equation 6.3). Furthermore, the 95% confidence bounds of the Weibull distributions are indicated. As a result, with the obtained parameters critical PD magnitudes can be calculated. These obtained norms are characteristic for the resin/oil insulated joint type. The inaccuracy of the norm is determined by the confidence bounds of the Weibull distributions.

¹³ For power network without an earthed neutral, it is better to use the phase to phase voltage for norm level, as these voltage levels may occur on the phases after a one phase fault in the neighbouring network.

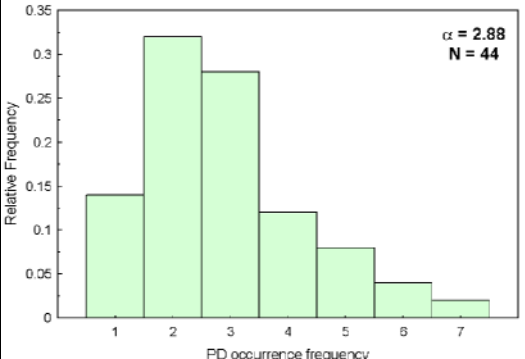
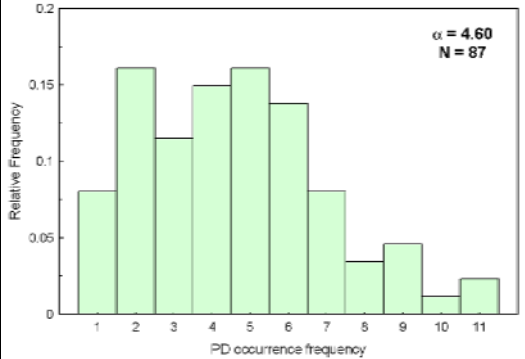
Table 6-2: Determination of the PD magnitudes norms for resin-oil insulated cable joints. By using the shape and the scale parameters of the Weibull distribution (with confidence bounds), the experience norm with variance can be calculated. The norm level is determined at 95% of the PD property distribution.

	Distributions of PD magnitudes	Scale & shape parameter number of meas. result	Applied norm (95%) PD magnitude
Max PD level U_0		$q_0 = 3622 \text{ pC}$ $\eta = 1.19$ $N = 44$	norm ($\text{PD}_{\max}$ at U_0) = <u>9106 pC</u>
Average PD level U_0		$q_0 = 2002 \text{ pC}$ $\eta = 1.29$ $N = 44$	norm (PD_{av} at U_0) = <u>4686 pC</u>
Max PD level $2U_0$		$q_0 = 5259 \text{ pC}$ $\eta = 1.28$ $N = 87$	norm ($\text{PD}_{\max}$ at $2U_0$) = <u>12392 pC</u>
Average PD level $2U_0$		$q_0 = 3006 \text{ pC}$ $\eta = 1.26$ $N = 87$	norm (PD_{av} at $2U_0$) = <u>7180 pC</u>

6.4.3 PD OCCURRENCE FREQUENCY

Table 6-3 shows the distributions of the PD occurrence frequencies, as obtained at U_0 and $2U_0$ for the resin/oil insulated joint. The means can be determined with their 95% confidence interval. With the obtained means, a Poisson distribution can be fitted. Identically to the PD amplitudes, the norm limits are determined at 95% of the PD occurrence frequencies distributions.

Table 6-3: Determination of the PD occurrence frequency norms for resin/oil insulated cable joints. By using the distribution means, the norm level can be calculated by Poisson distributions. In this case, the norm level is determined at 95% of the obtained distribution.

	Distributions of PD occurrence frequencies	Distribution mean	Applied norm (95%) PD occurrence freq
PD occ. freq U_0		m_n (PDOF at U_0) = 2.82 N/shot $N = 44$	norm PDOF at U_0 = <u>5 N/shot</u>
PD occ. freq $2U_0$		m_n (PDOF at $2U_0$) = 4.60 N/shot $N = 87$	norm PDOF at $2U_0$ = <u>7 N/shot</u>

6.4.4 DIFFERENT COMPONENTS

As described for the resin/oil insulated joint type, the PD property norms have to be determined for all the components separately. In order to perform reliable statistical analyses on the measurement data of a cable component type, there should be enough data available. As a result, an overview of the obtained norm levels is given in table 6-4 of the different components for which enough data is collected. The statistical distributions of the PD properties for these components are described in appendix C.

Table 6-4: Overview of the applicable norms for the 1D PD properties of the different cable components. Dependent on the number of samples in the distributions, the accuracy of the below described norms is determined. The more data, the more accurate is the norm value.

Cable component	U_{inc}	PD amplitudes [pC]				PD occ. freq. [N/shot]	
		Maximum at U_0	Average at U_0	Maximum at $2U_0$	Average at $2U_0$	At U_0	At $2U_0$
Joint type 1 Resin/oil	-0.07	9106	4686	12832	7181	5	7
Joint type 2 Oil	0.14	12358	8482	19456	11042	3	4
Joint type 3 Mass	0.14	10842	7235	15943	9677	3	6
Joint type 4 Resin1	0.10	2422	1458	677	3747	3	5
Joint type 5 Resin2	0.08	5491	3093	8162	5462	4	7
Joint type 6 Shrink	0.22	2439	1649	3608	2483	2	5
Term type 1 Mass 1	0.08	6116	5095	1359	7830	2	5
Term type 2 Mass 2	0.29	4218	1971	14631	7682	3	4
Term type 3 Shrink	0.67	-	-	19175	7580	-	3
Term type 4 Slip-over	0.56	2127	1586	4825	2670	2	4
PILC 1 <240mm ² Al	-0.18	12434	6727	18495	10531	7	9
PILC 2 ≥240mm ² Al	-0.15	10607	6353	16768	9654	7	10
PILC 3 <150mm ² Cu	-0.20	9774	5873	11499	7233	6	9
PILC 4 ≥150mm ² Cu	-0.28	20639	10206	23039	12246	7	9

From the different values of the diagnostic properties of the different cable components in table 6-4, it can be concluded that there is a relation between the different PD properties and the construction and applied materials of a component type. For some of the cable components, the PD inception voltage is typically below the operational voltage. In particular PD activity in PILC insulation shows this effect. The average and maximum PD level are strongly varying dependent on component type as well as the PD occurrence frequency. This means that the described PD properties can be applied for the recognition of the failure risk.

6.5 DECISION SUPPORT FOR CONDITION ASSESSMENT

In this paragraph, the decision-making of the condition assessment is described, in which all described and analysed PD properties have their contribution. The different PD properties exert their respective relation to insulation degradation of a cable system and its components, as is shown in figure 6.7. The PD properties should be taken into account for the determination of the insulation quality. The effect on the degradation of the insulation is dependent on the PD property. To discern the contributions of the different PD properties, we introduce weight factors for the PD properties. In figure 6.7, a general overview of the decision criteria for off-line PD measurements on power cable systems is described. These are knowledge rules, which are supporting the analysis of the measurement results. These knowledge rules are based on the different aspects of the cable's 'fingerprint' (the set of off-line PD properties, see chapter 6). The knowledge rules contain the effect of PD properties on the insulation degradation, determined by the detected PD property size and weight.

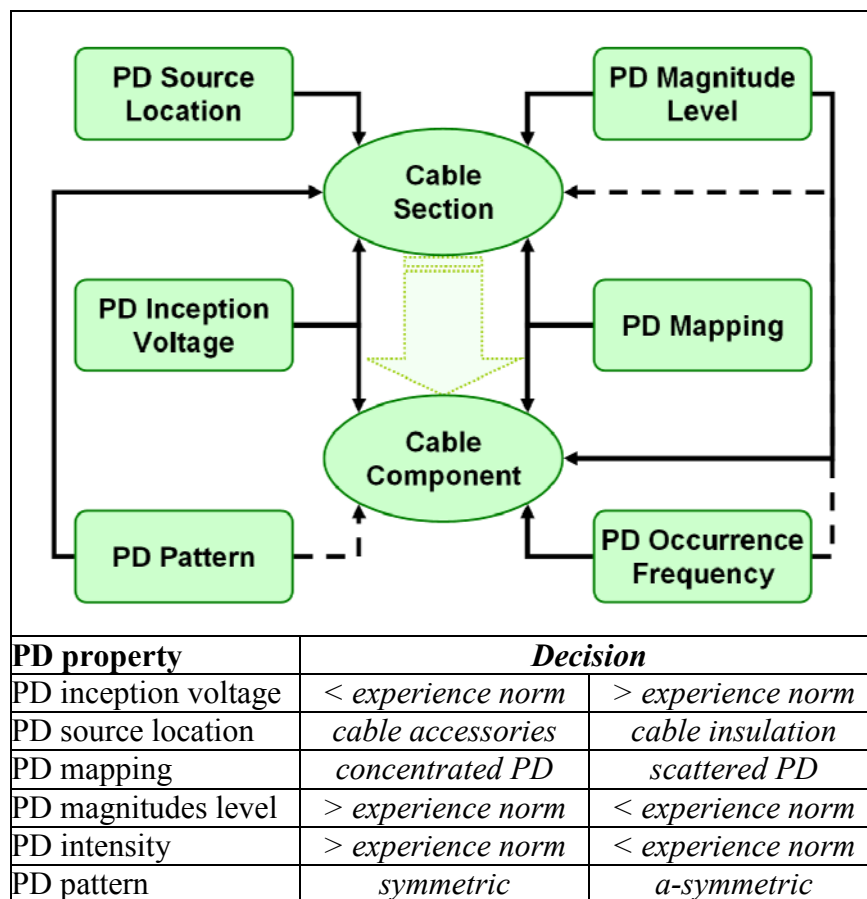


Figure 6.7: Relations of the directly and indirectly derived (analysed) PD properties to a total cable system and its components.

6.5.1 WEIGHT FACTORS FOR DECISION SUPPORT

For PILC cable systems, active PD sources are less harmful for the insulation as in synthetic base cable systems, as a result of the used materials and field strengths. In this section, the allocation of weight factors for the PD properties of the damped AC diagnosis, see chapter 4, is described. The weight factors are divided in two parts: the total cable system and the individual components.

CABLE SYSTEM

If the PDIV of the diagnosed cable system is lower than the system operating voltage, there is a high probability of local degradation sources, as during the service time of the cable system, the PD source will be ignited. However, if the PDIV of the cable system is a little higher than the operation voltage, a degradation process may become active in the cable insulation in the future. For this reason, the PDIV is allocated as the PD property with the highest weight factor.

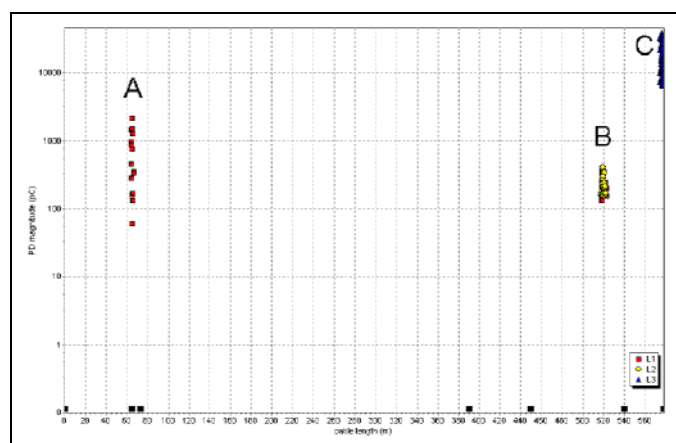


Figure 6.8: Examples of different types of PD location in a distribution power cable system:

- A. PD concentration in a cable joint at 65m, in phase L1;
- B. PD concentration in a cable part at 520m, in phases L1 and L2;
- C. PD concentration in a cable termination at the remote end, in phase L3.

The PD wave location method results in a PD mapping of the cable system, which informs if the PD are located in the accessories or in the cable insulation, as shown in figure 6.8. The failure statistics, appendix A, have shown that the main cause of outages related to insulation degradation is related to cable joints. The PD concentrations in these cable joints need extra attention as compared to the other components. The PD mapping is therefore the important information for condition assessment after the PDIV.

If the PD is located in the cable insulation, it should be analysed if this PD is concentrated at a specific location or scattered over the length of a cable part or the total cable system. This fact especially is relevant to the paper-oil insulated power cable. As this fact is related to PILC insulation, the weight factor is low. The PD mappings in figure 6.9 both show PD inside the cable insulation itself. However, in the lower mapping the PD is concentrated in specific locations (in this case at 240m and 265m from the measuring side of the 350m long

diagnosed PILC cable system). The upper mapping however shows a different pattern of PD in also a PILC cable system (ca 1000m long), whereas scattered PD activity appears in the cable parts between the 2nd and 4th joint.

The scattered PD may be an effect of the pressure and temperature changes in the paper-oil insulation after switching of the cable system in the temporarily cooling process. During this specific time span the layered cable insulation cools down, from the inside to the outside. Multiple small cavities will appear over a length of the insulation between the layers, resulting in scattered PD, which are not related to actual deterioration.

Concentrated PD in PILC insulation however is related to insulation degradation. The PDs appear at a specific location along the cable length. The PDs indicate the presence of a defect or are related to the degradation, which results in an energy bombardment at a small part of the insulation, resulting in degradation process, as described in chapter 2. Consequently, the PD scattering or concentration in the cable part of a PD mapping are indicated as the least important information of a cable system.

INDIVIDUAL CABLE COMPONENTS

The decisions for insulation condition assessment cannot be performed based on the directly obtained measurement properties of the cable system without the localisation. In table 6-4, it is shown that the typical PD properties differ for the different components. Therefore, after the localisation of the PD sources, the

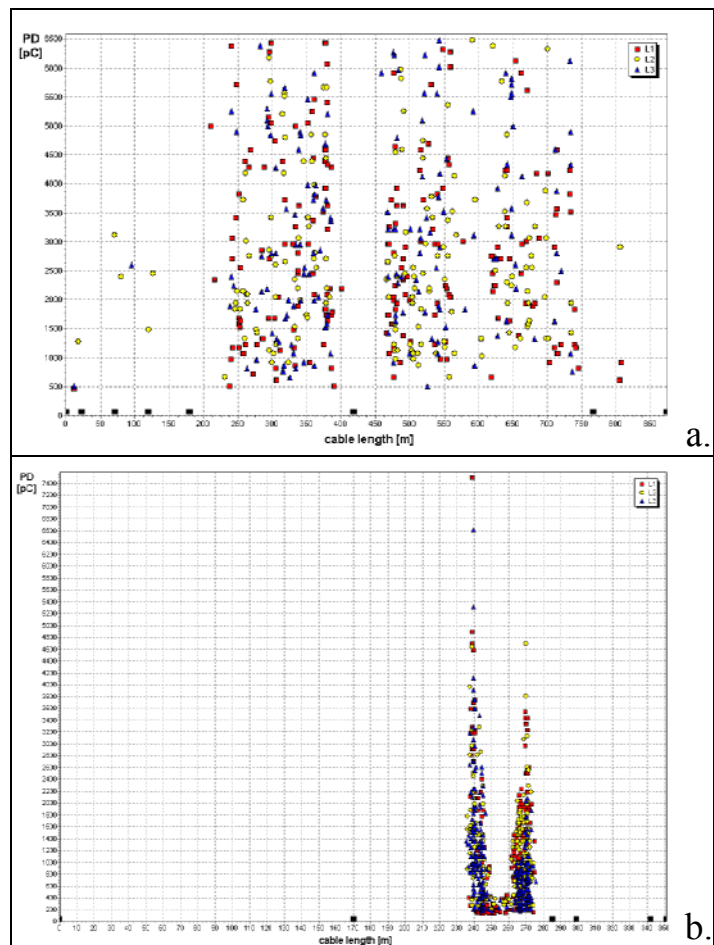


Figure 6.9: Two examples of PD activity in paper-oil insulated power cables, with different backgrounds for degradation:

- scattered PD activity, no degradation of the insulation;
- concentrated PD activity, degradation of the localized insulation.

analysis is deepened for each individual cable component. The weight factors of the different PD properties are based on their multiplicity in contributing to insulation degradation.

We indicated the PDIV as the most important PD property for condition assessment. The PDIV for a cable component indicates a locally active PD source. If the local PDIV is lower than the experience norm, the degradation of the insulation is continuous during service of the cable system. However, as is shown in table 6-4, for some cable components the norm is lower than the operating voltage.

The PD inception voltage is directly related to the generation of partial discharges at a defect:

1. A low PDIV indicates that the field strength around the defect is high enough to ignite PD at relative low voltages;
2. A low PDIV indicates that starting electrons are easily released at the defect site, as necessary for the ignition of a PD, is occurring from the insulation at the defect location;
3. The PDIV can further be used as a prognostic property. When the PDIV of a cable component is just higher than the norm level, this indicates that the insulation around the PD source may be degrading even more seriously in the future. A defect with a PDIV just above operation voltage and a PDEV just below may be ignited by a (short-term) overvoltage in the network e.g. as a result of switching activity, as is shown in the example of figure 6.10.

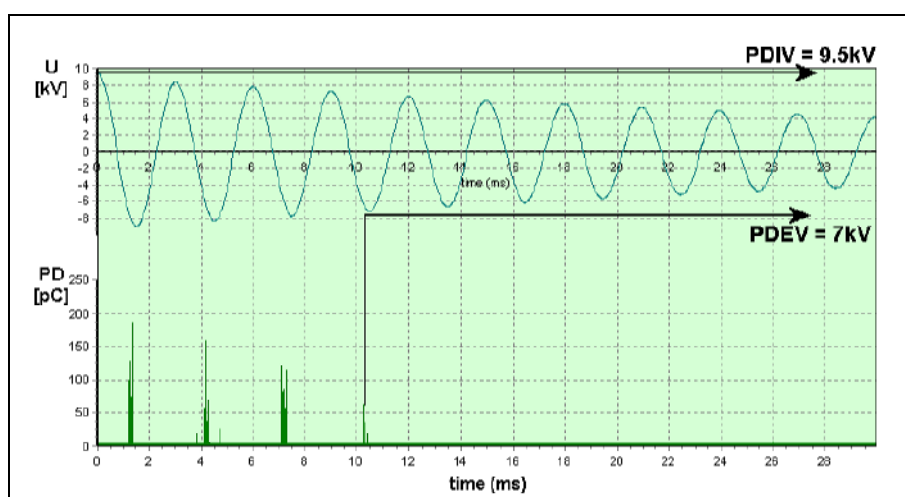


Figure 6.10: PD measuring result where PDIV is just above U_0 and PDEV just below U_0 (8.2kV). In case of an overvoltage, the PD source will be ignited and discharge during service.

The next important PD properties are the PD magnitude and the PD occurrence frequency. The weight of the average PD magnitude and the PD occurrence frequency are identical for the comparable voltages:

1. Both of the PD properties are related to the nature of the PD source. E.g. PD allocated to surfaces will be characterised by a low repetition rate and a relative high PD amplitude, while PD allocated to treeing will be characterised by a high repetition rate and a relative low PD amplitude;
2. The degradation of the cable insulation by the major part of the defects is caused by PD activity. Degradation due to PDs can be reflected by the energy content of the PD bombardment (chapter 3), which is related to the magnitude and the occurrence frequency of the PDs at the defect. PD activity with relative low amplitude levels and relative high occurrence frequency is just as harmful for the insulation as PD activity with a relative high amplitude level and relative low occurrence frequency.

The maximum PD magnitude is of less importance than the average PD magnitude. The maximum PD magnitude may be related to a single PD event, while the general PD magnitudes of the other PD events may be much lower, as can be seen in figure 6.11. In this example, the average PD magnitude in the joint for phase L1 is 1249pC, while the maximum PD magnitude is 5773pC. The average PD magnitude gives a better indication of the dissipated energy by a PD source than the maximum values. However, the maximum PD magnitude still gives information that this high PD activity occur at a defect site.

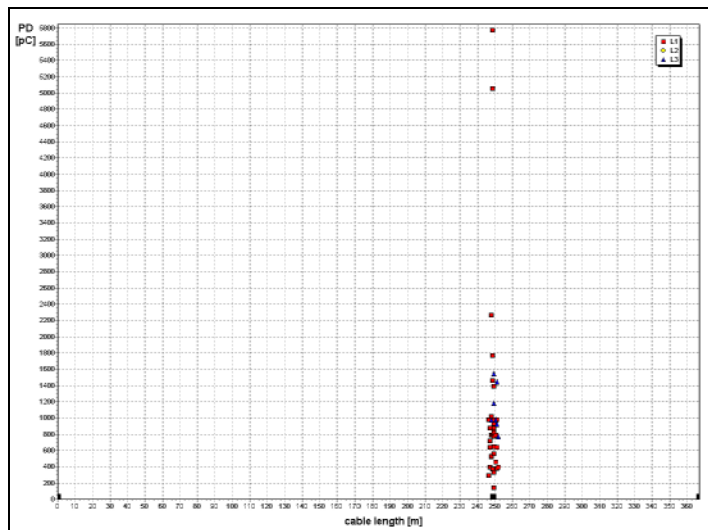


Figure 6.11: The difference in the average PD magnitude and the maximum PD magnitude can be rather large. In this case the average PD magnitude in the joint for phase L1 is 1249pC, while the maximum PD magnitude is 5773pC.

The PD magnitudes and PD occurrence frequency at U_0 are of prime importance as these are directly relevant to the operational degradation processes. Furthermore, the PD activity information at $2*U_0$, the test voltage at which all capacitances in the cable are overstressed, is also important. The failure statistics show that 1-phase defects occur most often. The information at increased test voltages is of importance for the condition assessment:

- In case of defects between two phases, the direct operational voltage is $1.7*U_0$, whereas the PD property are directly related to the operation;
- For power network without an earthed neutral, voltages of $1.7*U_0$ may occur between the phases and ground as a result of a single phase to ground

fault. As a result of this increased operation voltage, additional failures may occur in other components than the first failure.

- The PD information at test voltages above U_0 may give a prognosis on defects that may occur or that may cause insulation degradation in service in the future. E.g. as a result of operational or environmental changes a crack may grow in the insulation, but which is at the moment of measurement too small to ignite under service voltages. Even so, the PD magnitudes at increased test voltages give information on the nature of a defect.

The phase-resolved PD pattern is allocated with the lowest importance, as generally its information content is low for on-site power cable condition assessment. The PD pattern can give additional information of a detected defect type. If one defect is present in the full cable system, the detected PD pattern will be related to this defect. However, in most of the PILC cable systems there will always be some PD activity in the paper layers of the insulation. As a result, the interpretation of the PD pattern is difficult as it is in most cases related to multiple defects. For power cables which are constructed of only synthetic insulation, the probability of multiple defects is lower and PD pattern analysis can be more valuable.

Based on the contributions of a PD property to insulation deterioration and on the value of a PD property for the recognition of a deterioration stage, we have performed the final allocation of weight factors. The weight factors for the different PD properties, as applied in the condition assessment with DAC voltages, are shown in table 6-5.

Table 6-5: Allocation of weight factors to the different PD properties.

	PD property		Weight factor
Cable system	PD inception voltage		4
	PD source location		2
	PD mapping		1
Individual cable components	PD inception voltage		8
	PD magnitude	Average at U_0	4
		Maximum at U_0	3
		Average at $2U_0$	2
		Maximum at $2U_0$	1
	PD occurrence frequency	At U_0	4
		At $2U_0$	2
	Phase resolved PD pattern		2

For the total cable system, the weight factors are related to the importance of the properties. As described in the previous part, the PDIV contains the most important information on a PD source. The PDIV indicates if there is PD activity in the cable system, while the other two properties indicate if there is local insulation degradation, located in the cable accessories or in the cable insulation (concentrated). A high PDIV indicated that during operation there are no active PD sources. The least relevant property, PD mapping, is allocated a weight factor of 1. The following properties are allocated to a weight factor of twice as high as the previous property, leading to a weight factor of respectively 2 and 4 for the PD source location and the PD inception voltage.

For the analysis of individual cable component, the height of the weight factor is related to the described indications and contributions of insulation degradation in the previous pages. The four main properties, PDIV, PD magnitude, PD occurrence frequency and PD pattern are arranged to a distribution of 4:2:2:1. The PDIV is indicated as the most important PD property. The PD average magnitude and the PD occurrence frequency are indicated the same relevancy, due to their effect on the distributed energy in a PD source, as described in the previous pages.

The average PD magnitude and the PD occurrence frequency at test voltages of $2U_0$ are indicated as less important, as they are not directly related to the degradation under service conditions and are therefore ordered by 2:1. The maximum PD magnitude at U_0 is less important than the average PD magnitude at U_0 , but more important than the average PD magnitude at U_0 , as described in previous pages. The PD magnitudes are for this reason ordered by 4:3:2:1.

As a result of the above described criticality of PD properties, a distribution of the weight factors is obtained as shown in table 6-5. A maximum of 26 points can be allocated for the indication of the condition of a cable component, where the higher the sum the more critical the condition is. If three or more PD parameters are out of range, the condition is indicated as critical. For the allocated points, this means that a value of more than 15 points.

6.5.2 INSULATION CONDITION QUALIFICATION

For supporting the decision-making based on the insulation quality of a cable system, we have developed a flow diagram in which the different PD properties are used, as shown in figure 6.12. Analysing the derived measurement data following the diagram, the cable systems insulation condition is determined in one of the three classes:

- cable system NOT OK: defective cable component (or meters) in the cable system should be replaced, as multiple PD properties are outside the experience norms;
- cable system TRENDING: possible degradation, trending on the cable component is required (e.g. 1 year 3 years), as some of the PD properties are outside the experience norms;
- cable system OK: no weak spots in the cable system, cable system is OK, as none of the most important PD properties are outside the experience norms.

The order of the PD properties as applied in the decision diagram is on the contribution and the recognition value of PD properties for degradation processes, as described in the previous section.

On the hand of these weight factors, a decision-matrix can be formulated for the qualification of the insulation condition. As all phases are measured and analysed separately, the decision-matrix is applied for each phase. The phase with the worst condition is decisive for the successive maintenance actions. For this matrix in table 6-6, the knowledge rules for the PD properties, as shown in figure 6.7, are applied together with the weight factors. The knowledge rules are transformed to numbers: a '0' for inside the norm and a '1' for outside the norm of a property. These interpretation numbers are multiplied with the weight factors. As a result, the sum of the product of the weight factors and the interpretation numbers values will qualify the degradation per individual component.

Table 6-6: Example of the decision support matrix for condition assessment on power cables. The condition of cable components is indicated by the sum of the weight factors and the interpretation (0 or 1).

	PDIV	PDOF		PDLav		PDLmax		PD pattern	Total
		U ₀	2*U ₀	U ₀	2*U ₀	U ₀	2*U ₀		
Weight Factor	8	4	2	4	2	3	1	2	
Termination 1	1	0	0	0	0	0	1	0	9
Cable Part 1	0	0	0	0	0	0	0	0	0
Joint 1	1	1	0	1	1	0	1	0	19
Cable Part 2	1	1	1	0	0	0	0	0	14
.....	0	0	0	0	0	0	0	0	0
Cable Part N	0	0	0	0	0	0	0	0	0
Termination 2	0	0	1	0	1	0	1	0	7

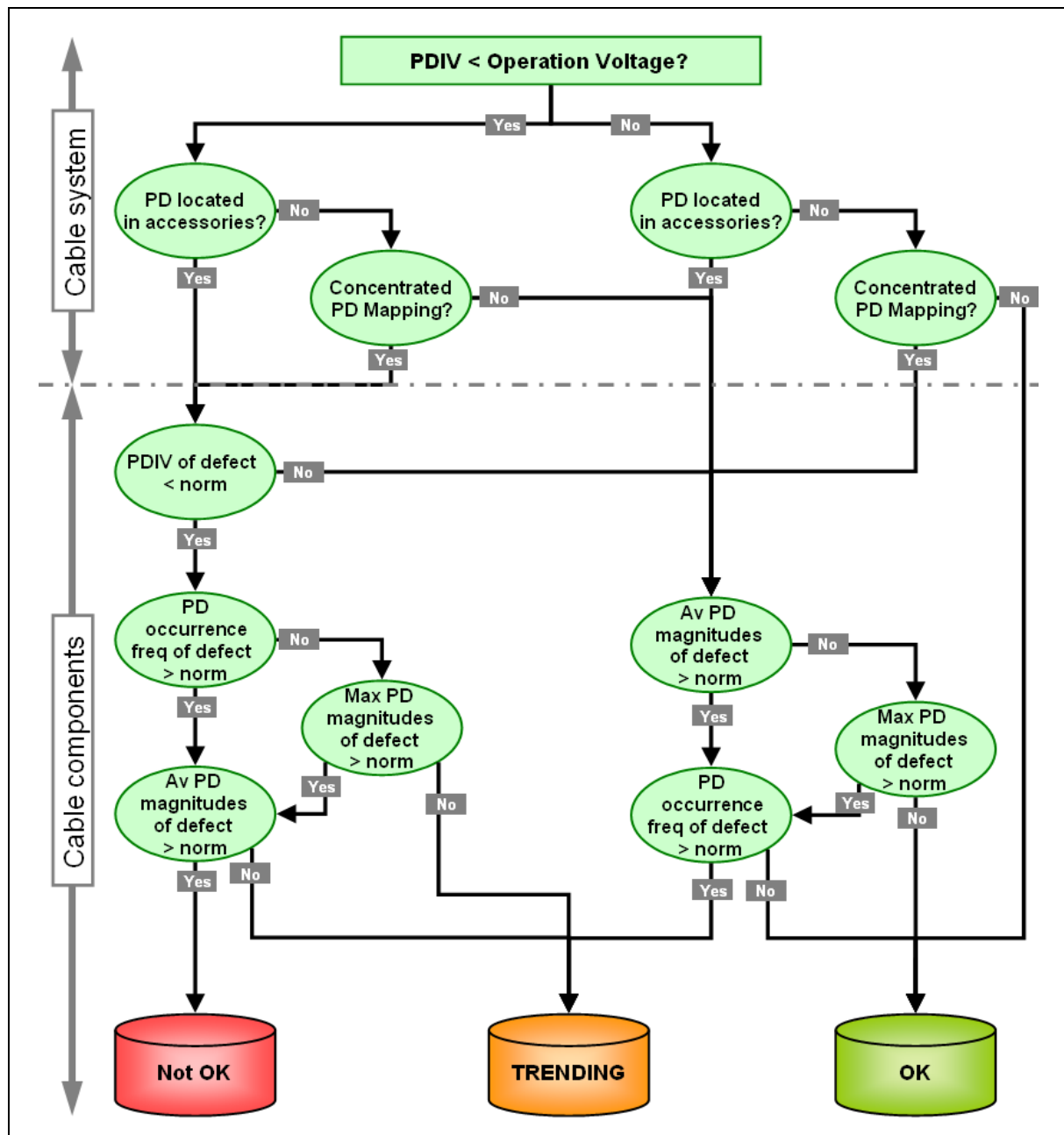


Figure 6.12: Decision support flow-diagram for PD diagnosis on power cables. By going through the diagram step by step, an indication of the cable system insulation condition can be determined in the three categories OK, TRENDING and NOT OK.

The cable component is indicated as not OK, when multiple of the most important PD properties are outside the experience norms. This is when the total of the sum per component is larger than 15. As a result, maintenance actions (replacement or repair) should be undertaken within reasonable time. If the total of the sum is smaller than 5, none of the most important PD properties are outside the experience norms. The cable component is then indicated as OK. The area of the sums between 5 and 15 indicates that PD activity is present in

the component, whereas some of the PD properties may be out of range, and that trending of the cable system is necessary.

Summing the condition of the individual components, the quality of a cable system can be indicated, e.g. as not OK, trending or OK. The above-described approach gives the opportunity of sustaining the advised maintenance actions in case of a critical decision. Per component in the diagnosed cable system, the measurement values and the norms can be compared.

The condition assessment is the technical input for the overall decision. Economical influencing factors, as outage costs, or the social influencing factors, as imago loss in case of an outage, may result in the another successive maintenance action as is resulting from the condition diagnosis.

6.6 CONCLUSIONS

In this chapter, the generation of experience norms and their application for decision support is presented. For the optimal application of PD diagnostics for condition assessment, knowledge on the criticality of the different PD properties is required. Due to the large diversity of components in cable systems, there are no standard international norms available for the determination of the quality of insulation which is affected by a defect. The following conclusions can be drawn:

- 1) The complexity of finding the general relations between the PD symptoms and the forensic evidence is affected by:
 - a) only a limited view of the interior of the opened component is obtained;
 - b) objective judgements occur during the visual inspection;
 - c) one will usually find some defects in the insulation, as these components are often constructed in the field, there is an increased possibility that small defects are enclosed
- 2) The criticality of PD properties should be based on practical experiences. In order to perform statistical analysis the PD properties of a cable component, the different PD properties are allocated to a type of distribution. After the determination of the type of distribution for a PD property, the characteristic parameters are determined:
 - a) the population of the PD magnitude of a component type can be analysed by Weibull distributions;
 - b) the population PD occurrence frequency of a component type is Poisson distributed;
 - c) for the PD inception voltage, no distribution type is used, but these distributions are also restricted due to the maximum test voltage.

- 3) By analysing the collected data, belonging to groups of component types, experience norms can be obtained for the different PD properties, based on determined distributions of the 1D properties. A norm level can be defined as the part of the distribution that is deviated too much. In this thesis, a deviation level of the top 5% of the PD property distributions is applied. This contains the acceptable risk according to the actual failure rate of cable joints over the condition assessment interval of 5 years. The experience norms are determined at 95% of the distribution. This level can be adapted if the failure rate of a component increases or if the maintenance strategy changes to a longer condition interval for a cable system over time.
- 4) The actual condition of a cable system and its components can be determined by using the combination of different PD properties. The weighted PD properties are combined with their deviation from the experience norms, whereas the insulation condition of each individual cable component and therefore the cable system can be categorised as NOT OK, Trending or OK.
- 5) By the systematically approach, the opportunity is given of sustaining the maintenance advice in case of a critical decision.

7

APPLICATION OF ON-SITE PD DIAGNOSIS BY DAC VOLTAGES

Condition assessment has different backgrounds for new cable systems as well as cable systems in service:

1. Quality check: mainly related to new cable systems, whereas a cable system is checked on mounting and laying quality;
2. Risk reduction: mainly related to cable systems in service, where a cable system is diagnosed to reduce the risk of outages;
3. Reliability increment: mainly related to a cable system or a cable strand in service, where the cables are diagnosed to increase the reliability of the power network.

Three elucidating practical examples of the above-mentioned cases of the application of condition assessment with PD diagnosis are discussed. The examples are related to XLPE and PILC insulated cable systems. The final section of the chapter will contain the application of a condition database to support the decision of the asset manager. This database contains the measurement results and the cable data of more than 300 cable system. Each new measurement that is performed and analysed is added to the database. When a numerous amount of condition data is added, the experience norms are recalculated and adapted if necessary.

7.1 CASE 1: QUALITY CHECK - AFTER-LAYING TEST OF AN XLPE CABLE SYSTEM

To check the mounting and laying quality of a new cable system, after-laying test are performed. New cable systems are constructed in the power network continuously. The cable systems are mounted in the field, which may lead to the introduction of defects. One of the applications to check the insulation quality at

the start of a lifetime of a cable system is the diagnosis for PD activity. Contrary to PILC insulation, in XLPE insulation, no PD activity is allowed.

To make sure that all new cable systems are free of defects at the start of its life-time, after-laying test procedures are applied. These test procedures of new cable systems consist of three parts:

A. Voltage withstand test:

No breakdown in the cable system may occur during the application of increased test voltages of $1.7 \cdot U_0$ for a period of 5 minutes [55]. The applied test voltage shape and frequency may be of different types. National standards recommend for paper insulated systems tests at a DC voltage of $4 \cdot U_0$ or an AC voltage of $2 \cdot U_0$ or a VLF voltage of $3 \cdot U_0$ [25,60,93]. The latter two variants are also recommended for extruded insulated cable systems [26,94]. The duration depends on the voltage source type according to the standard varying from 10 to 60 minutes [103]. Voltage withstand tests by damped AC voltages is recommended for extruded cable systems in the transmission range [56]. For temporarily voltages, the norms prescribe the application of multiple shots (generally 50) at $3\text{--}4 \cdot U_0$;

B. Outer screen test:

Testing of the outer screens of the cable system. A DC voltage of 3-5kV is applied between the earth screen (disconnected from station earth) and the ground. The leakage current should be in the range of several μA , otherwise somewhere along the cable length, the screen has been damaged [25,94];

C. Partial discharge diagnosis:

Detection and location of possible defects (that did not directly caused breakdown during the withstand test) at a very early stage of the life-time of a cable system. The PD diagnosis is indicated as an important method for assessing the insulation condition according to [59]. In the Dutch standard for extruded cable, the PD diagnosis after voltage withstand test are under deliberation [94]. There are no acceptance levels of PD sources in the standards. However, it is generally applied that PD activity in the cable insulation should be below noise level (max 10pC) up to $1.7 \cdot U_0$.

In the authors opinion, PD diagnosis will replace the voltage withstand test in the acceptance test of new-layed cable systems. In practice, the test voltages for sensitive PD measurements are not higher than $2 \cdot U_0$, which is below the levels for the voltage withstand test, according to the standards. During the PD measurements, a form of withstand test is performed during the data collection time. Those defects that would have failed during the withstand diagnosis will also fail during the PD measurement time or at least been identified by the PD diagnosis. Additionally, from practically experiences we have established that the PD diagnosis will detect defects which have not failed during the withstand test. PD diagnoses are therefore more sensitive for acceptance tests than voltage

withstand diagnosis and actually are the most important part of the after-laying diagnosis.

7.1.1 PRE-SELECTION FOR DIAGNOSIS

The cable drums are analysed for PD activity (no PD activity above noise level of maximal 10pC) in the factory after production. In general, the applied cable parts in the field will not contain internal defects in the insulation, but as a result of the laying of long length cable parts, damages to the outer layers may occur. Cable accessories are also tested in the factory, but contrary to cable parts, they are mounted in the field. As a result of this on-site mounting, different types of defects occur, as is described in chapter 2. After-laying test are necessary to ensure a good start of the life time of a new cable system. Furthermore, the test can be used as a takeover assurance for delivered work.

7.1.2 CABLE SYSTEM

The 10kV cable system in this example is 561m long and composed from 240mm² three-core XLPE insulated cable parts. The cable system contains two cable joints. Both the cable terminations and the cable joints are shrinkage insulation type accessories. On the cable system, which has been taken in service in the year 2000, an after laying test with DAC voltages is performed, as described above. The voltage withstand test and the outer screen test were passed successfully.

7.1.3 ON-SITE PD DIAGNOSIS

Figure 7.1 shows the PD activity as observed in the XLPE cable system. It follows from this figure that phase L1 shows PD activity up to 100pC at test voltages below the operating voltage. The PDIV and PDEV of phases L2 and L3 are higher than U_0 . The PD source of phase L1 was located in the near termination, as is shown in the obtained PD mapping of figure 7.1. The PD magnitudes for the termination are not extremely high for this type and are within the experience norm, specified in table 6-5. The PD occurrence frequency of the defect source is higher than the norm level.

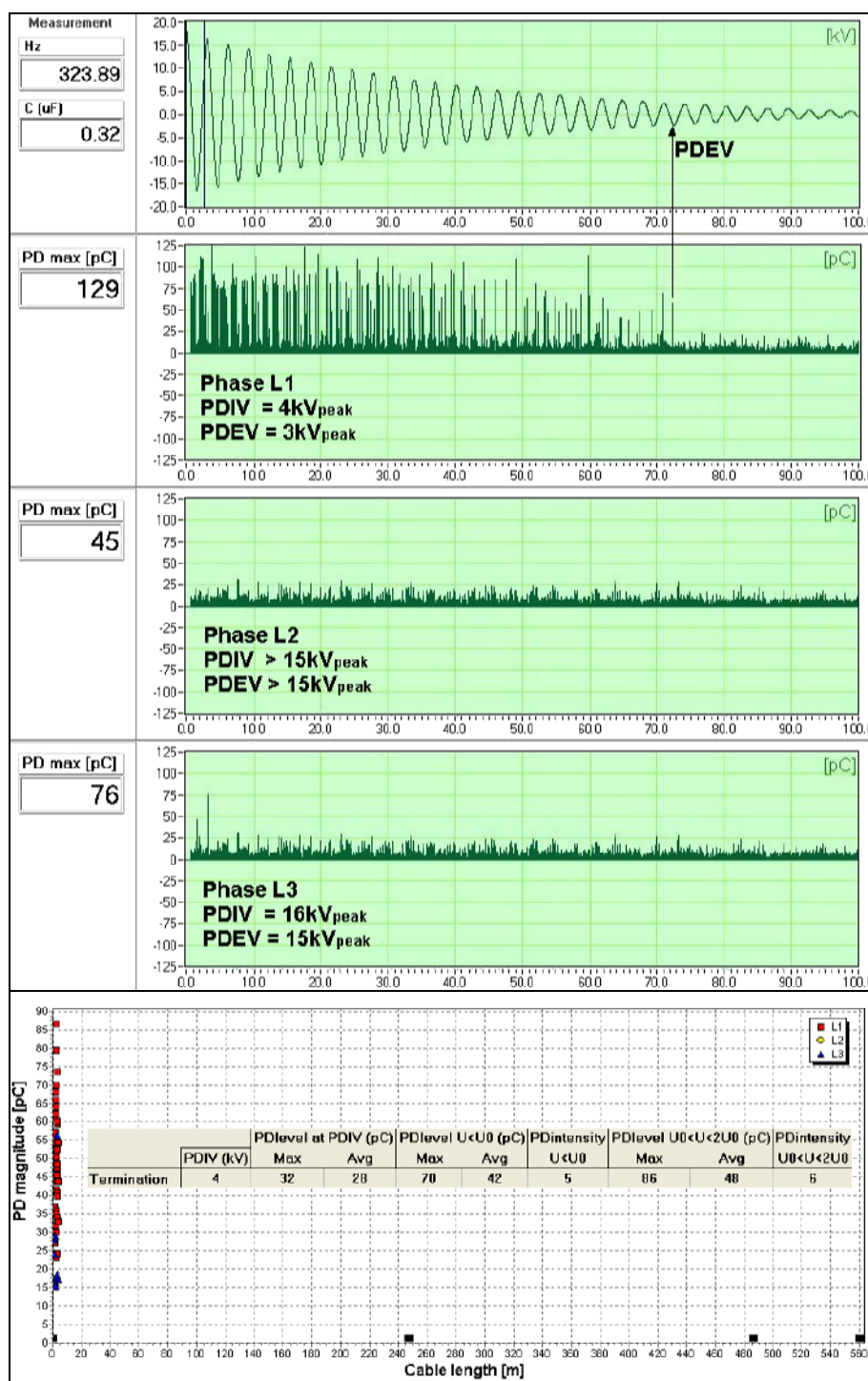


Figure 7.1: PD diagnosis results obtained from three phases of a 561m 10kV XLPE power cable system, showing the applied DAC voltage with the PDIV, PDEV and PD magnitudes for each phase and a PD mapping, showing a PD concentration in the termination.

As the detected PD activity from the total cable system is originating from only one component, a more in depth analysis is made by means of pattern analysis. In figure 7.2, the phase-resolved PD pattern of the defect in phase L1 is shown. It is concluded that the defect type causing the PD is most probably related to dielectric bounded cavities. To obtain more information about the PD processes,

the PD behaviour as function of the stepwise increased DAC test voltages is investigated, which is shown in the lower part of figure 7.2. For the detected PD source in the termination, it follows from this analysis that the PD magnitude is slowly growing with the increasing test voltage. It is known from [67], that this PD behaviour is characteristic for large flat cavities.

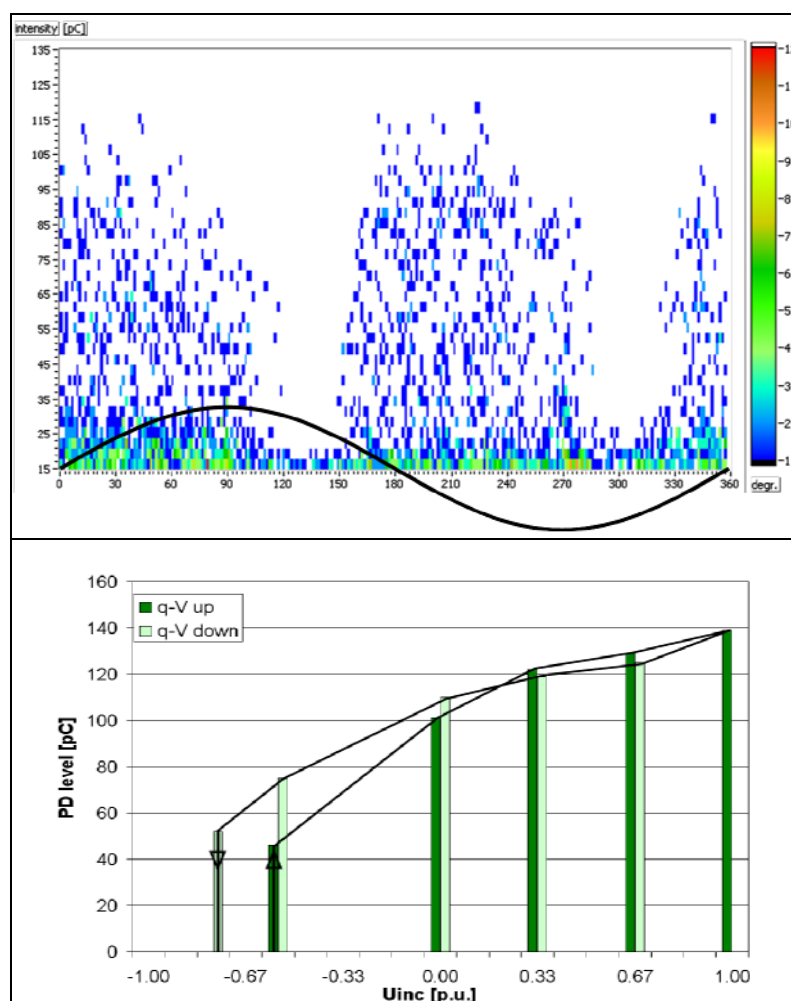


Figure 7.2: Phase-resolved PD pattern (upper part) and q-V diagram (lower part) of the PD source in the termination the XLPE insulated cable system under investigation.

7.1.4 CONDITION ASSESSMENT AND MAINTENANCE DECISION

In the former section, the defect type is identified as flat cavities in the termination. Usually, these cavities are situated at the boundary of the cable insulation and the shrink cover of the termination. Deterioration of the XLPE insulation occurs due to tracking from the semi conducting screen. This fact combined with a low inception voltage, which reveals a continuous ignition of PD at operating voltages, will support the decision to replace the termination. This analysis is usually reported as a decision matrix in table 7-1, which is explained in chapter 7. The matrix outcomes shows that on the bases of the PDIV, the PD occurrence frequency and the PD pattern characteristics, the total sum of the weight factors for the cable termination is 16. Hence, based on the descriptions of table 7-6, the decision of the condition assessment is to take immediate maintenance actions on the termination in question.

Table 7-1: Outcome of the decision support matrix for the diagnosed polymeric cable system of figure 7.1.

Component	Type	Phase	PDIV	PDOF		PDLav		PDLmax		PD pattern	Total
				U_0	$2*U_0$	U_0	$2*U_0$	U_0	$2*U_0$		
WF →			8	4	2	4	2	3	1	2	
Term 1	Slip over	L1	1	1	1	0	0	0	0	1	16
:	:	:	:	:	:	:	:	:	:	:	:
Term 2	Slip over	-	0	0	0	0	0	0	0	0	0

This example shows that after-laying diagnosis of new cable systems provides a warning for future defects before any deterioration has occurred to the insulating material. In most cases, easy repairs are sufficient to restore the cable system insulation condition. As a result, the probability of a failure is decreased. Also from this example, the sensitivity of PD diagnosis towards the voltage withstand test is demonstrated.

7.2 CASE 2: RISK REDUCTION - DIAGNOSIS OF A PILC CABLE SYSTEM IN SERVICE

The PDIV for impregnated paper insulation is generally relative low, due to the layered structure. From experiences it can be concluded that for this insulation a certain PD magnitude and intensity is allowed. Due to the PD activity in layered insulation over the length of the system, a mapping will contain a complicated view of the PD activity in a cable system. As a result, it is important to find that relevant information from a PD mapping, which is useful for optimal decision-making about the insulation condition of the components in a cable system.

7.2.1 PRE-SELECTION FOR DIAGNOSIS

To diagnose all the cable systems in a power network is not efficient, as the amount of cable system in the power network is simply too large. Cable systems in service are for the most part selected on bases of their history, the previous experiences in a specific cable system or in part of the network. Also the location of a cable system in the network can be decisive, which is generally the number or the importance of the clients that are fed. Feeding cable systems of important large consumers are often diagnosed from the point of view that outages directly result in a costly production interruption.

7.2.2 CABLE SYSTEM

The 10kV cable system in this example is 3204 meters long and composed from 240mm² three-core belted paper insulated cable. The cable system contains seven joints, which are oil insulated. The terminations are mass insulated. The cable system has been laid in the year 1998.

The occurrence of a failure in one of the joints of the neighbouring cable system was the reason for diagnosing the cable system, which is one of the feeders of a large chemical plant. As the cable systems are of the same age and contain the same cable components types, the estimation of the risk of failure is the target for the condition assessment. Especially the cable joints are under suspicion, as these are presumed to have decreased oil-levels as a result of the oil-extraction by the different cable parts.

7.2.3 ON-SITE PD DIAGNOSIS

After the location analysis of the collected PD events, PD mappings are created for test voltages up to U_0 and for test voltages up to $2U_0$. Figure 7.3a and figure 7.4a show the PD mappings of the cable systems for respectively up to U_0 and up to $2U_0$. Also, the histograms with the number of located PD events as a function of the power cable length are shown in figure 7.3b and figure 7.4b. These histograms are for all phases together. The PD concentrations are better interpretable in the histogram than in the mapping. The 8 joints in this cable system are indicated by the black dots at the length axis.

In this example, the mappings and the histograms show PD concentrations at different joints, especially in the second half of cable system. Also in the cable parts, PD events have occurred, but no concentrations of PD are found. These PD activities in the cable parts may complex the interpretation of the PD mappings, as they may disguise the PD concentration in the joints.

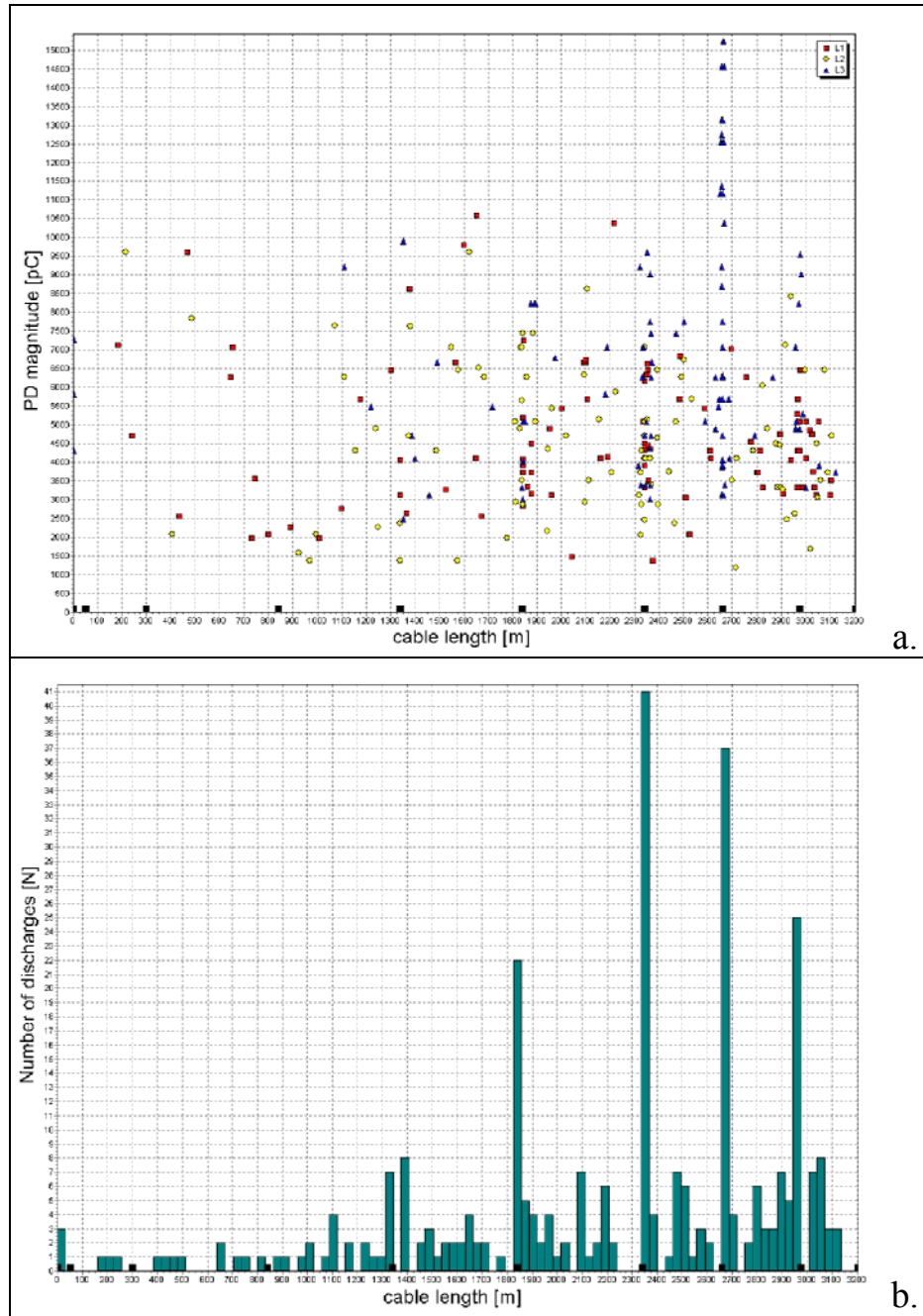


Figure 7.3: Measurement result up to U_0 of a 3204m PILC cable system with 8 joints (indicated with black dots at the length axis):

- PD mapping for various test voltages up to U_0 ;
- PD histogram (three phases) for test voltages up to U_0 .

From the PD mapping for test voltages up to U_0 , it is clear that joint 7 shows higher PD amplitude in phase L3, as compared to the other joints. The maximum PD level in joint 7 is around 15000pC, while the other maximum PD magnitudes are around 10000pC. The histogram of the cable locations indicates PD concentrations in joints 5 to 8. However, the concentration in joint 7 is related to only one phase.

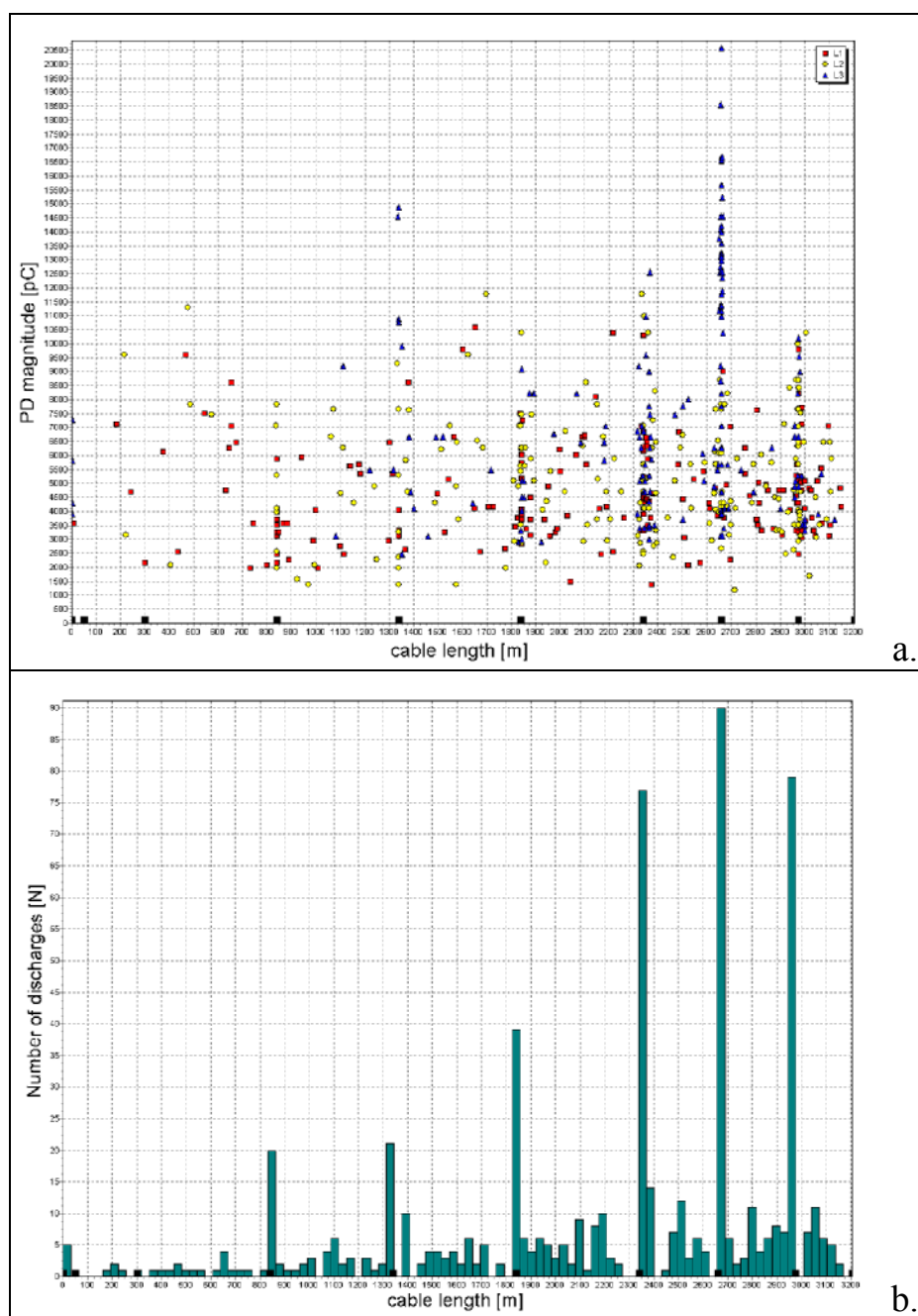


Figure 7.4: Measurement result up to $2U_0$ of a 3204m PILC cable system with 8 joints (indicated with black dots at the length axis):

- PD mapping for various test voltages up to $2U_0$;
- PD histogram (three phases) for test voltages up to $2U_0$.

The PD mapping for test voltages up to $2U_0$ shows that the PD amplitudes have increased for the different joints. The maximum PD magnitude for cable joint 7 has increased to around 20000pC, while also the number of discharges in the joint has increased. For more accurate information of the PD mapping, a database report is generated, which summarizes the different properties of the individual components in all three phases, as shown in table 7-2.

Table 7-2: Report of the PD properties derived from mappings in figure 7.3 and figure 7.4.

		PDIV [kV _{peak}]	U=PDIV		U≤U ₀			U ₀ <U≤2U ₀		
			PD max [pC]	PD av [pC]	PD max [pC]	PD av [pC]	PD occ freq	PD max [pC]	PD av [pC]	PD occ freq
Phase L1	Termination 1	15	3564	3564				8235	5899	1
	Cable part 1									
	Joint 1									
	Cable part 2	6	7129	7129	7129	5917	1			
	Joint 2	18	2178	2178				2178	2178	1
	Cable part 3	3	1980	1980	9608	4734	1	8614	7819	2
	Joint 3	10	4118	3791				5882	3530	2
	Cable part 4	3	2772	2524	5686	3178	1	6471	4508	2
	Joint 4	9	4059	3273	4059	3273	1	5347	3700	1
	Cable part 5	6	10594	5131	10594	6772	3	9804	5120	2
	Joint 5	9	7255	4340	7255	4340	1	7525	4743	1
	Cable part 6	3	1485	1485	6733	4514	2	10392	4964	2
	Joint 6	6	5174	4344	6877	5278	3	10297	5911	2
	Cable part 7	3	3069	2508	6832	3807	2	5686	4424	2
	Joint 7	12	9020	5044				9160	5289	1
Cable part 8	6	7030	4973	7030	4493	2	7624	4669	2	
Joint 8	6	5686	4705	6471	4600	2	9804	5099	3	
Cable part 9	6	5098	4218	5098	4110	2	7059	4719	1	
Termination 2										
Phase L2	Termination 1									
	Cable part 1									
	Joint 1									
	Cable part 2	6	9608	9608	9608	9608	1	3168	3168	1
	Joint 2									
	Cable part 3	6	7843	4961	7843	4961	1	11287	9369	1
	Joint 3	12	7843	4689				87333	4865	2
	Cable part 4	3	2277	1749	7647	3735	2	6667	5660	1
	Joint 4	9	2376	1881	2376	1881	1	9307	5556	1
	Cable part 5	3	1386	1386	7624	5150	2	11765	7247	2
	Joint 5	6	5098	3984	7451	5282	2	10392	5837	2
	Cable part 6	3	2178	2178	8628	4939	2	7843	5648	2
	Joint 6	4	9608	5550	10608	8692	2	13549	10699	4
	Cable part 7	6	6733	4706	6733	4880	2	8317	4927	2
	Joint 7	11	4706	4706				8713	5571	2
Cable part 8	3	3267	2574	8431	4463	3	5882	5125	2	
Joint 8	9	6471	4549	6471	4549	1	10396	5859	4	
Cable part 9	3	1683	1683	4510	3264	1	6471	5621	2	
Termination 2		9608	5550	10608		2	13549	10699		
Phase L3	Termination 1	9	7282	5807	7282	5807	1	5922	5922	1
	Cable part 1									
	Joint 1									
	Cable part 2									
	Joint 2									
	Cable part 3									
	Joint 3									
	Cable part 4	6	9223	9223	9223	7978	1	5490	3921	1
	Joint 4	6	2490	2490	11902	8496	1	14902	11904	3
	Cable part 5	9	6667	4823	6667	4823	4	6667	5882	3
	Joint 5	9	5098	4113	5098	4113	2	9098	5111	2
	Cable part 6	4	6124	6124	8235	7517	2	8235	6176	1
	Joint 6	6	5149	3649	5149	3649	2	11765	5778	2
	Cable part 7	6	7767	7767	7767	6573	2	8039	5646	2
	Joint 7	4	5686	4872	15243	8788	2	20588	11820	4
Cable part 8	6	6275	6275	6275	5490	1	5490	4804	1	
Joint 8	6	7059	5751	9549	5249	2	10196	5890	4	
Cable part 9	5	3725	3725	3922	3856	2	5340	4533	2	
Termination 2										

As can be derived from figure 7.3, figure 7.4 and table 7-2, some of the PD properties are outside the range compared to the other components. The cable parts, except for cable part 1, all show PD activity characterised by low PD inception voltages and relative high PD levels. However, no concentration of PD was found in the different cable parts, whereas these PD activities are not related to insulation degradation, as shown in figure 6.9.

From the point of view of the PDIV, joints 4, 6 and 7 show deviation from the different joints in the cable system, especially in phase L3, as indicated by the dark textboxes in table 7-2. The average PD magnitudes at $2U_0$ as obtained for joints 4 & 6 are outside the range of the other joints. For joint 7, the average and maximum PD magnitude also the PD occurrence frequency in phase L3 are the highest for the cable joints of the system. As a result, from this analysis it is derived that the joint 7 is indicated as the most suspicious cable joint, by comparing its PD properties to the other cable joints.

7.2.4 CONDITION ASSESSMENT AND MAINTENANCE DECISION

As the values of the different properties are known from table 7-2 and if the types of the different components are known, the decision matrix as described in chapter 6 is used for the final analysis on the insulation condition. As the phases are measured and analysed separately, the cable components are assessed by phase, which contains the most relevant PD property values, shown in table 7-3.

As is shown by this decision matrix, two of the cable components, joint 4 and joint 7, have a total score of respectively 16 and 20, which exceeds the threshold value of 15 for immediate maintenance actions, as described in chapter 7. These two cable joints are subjected to immediate maintenance actions. The joint type of these components is oil insulated type 2, meaning that they are constructed with sheets around the conductor connection. The decreased oil level may cause a critical surface between the different electrodes in this joint type. As this joint type has the possibility to be reopened, joint 6 was opened in the field. As it showed a decreased oil level inside, the oil content was adjusted to its original level. The oil level in the joints will decrease due to the load cycling of this cable system, as described in chapter 2.

Table 7-3: Outcome of the decision support matrix for the diagnosed PILC cable system in table 7-2. The scores column on the right shows that two of the cable components, joints 4 and 7 are above the threshold value of 15, which indicates a critical condition.

Component	Type	Phase	PDIV	PDOF		PDLav		PDLmax		PD pattern	Score
				U_0	$2*U_0$	U_0	$2*U_0$	U_0	$2*U_0$		
WF →			8	4	2	4	2	3	1	2	
Term 1	Mass	-	0	0	0	0	0	0	0	0	0
Cable part 1	PILC 240	-	0	0	0	0	0	0	0	0	0
Joint 1	Oil type 2	-	0	0	0	0	0	0	0	0	0
Cable part 2	PILC 240	L2	1	0	0	0	0	0	0	0	8
Joint 2	Oil type 2	L1	0	0	0	0	0	0	0	0	0
Cable part 3	PILC 240	L1	1	0	0	0	0	0	0	0	8
Joint 3	Oil type 2	L1	0	0	0	0	0	0	0	0	8
Cable part 4	PILC 240	L2	1	0	0	0	0	0	0	0	8
Joint 4	Oil type 2	L3	1	0	1	1	1	0	0	0	16
Cable part 5	PILC 240	L1	1	0	0	0	0	0	0	0	8
Joint 5	Oil type 2	L2	1	0	0	0	0	0	0	0	8
Cable part 6	PILC 240	L1	1	0	0	0	0	0	0	0	8
Joint 6	Oil type 2	L3	1	0	1	1	0	0	0	0	14
Cable part 7	PILC 240	L3	1	0	0	0	0	0	0	0	8
Joint 7	Oil type 2	L3	1	0	1	1	1	1	1	0	20
Cable part 8	PILC 240	L2	1	0	0	0	0	0	0	0	8
Joint 8	Oil type 2	L3	1	0	1	0	0	0	0	0	10
Cable part 9	PILC 240	L2	1	0	0	0	0	0	0	0	8
Term 2	Oil type 2	-	0	0	0	0	0	0	0	0	0

Joint 7, with the highest total score, was removed from the cable system, and further investigated in the laboratory, as described in appendix E. From these investigations, a decrease of the oil level in the removed joint is observed. Due to a decreased oil level, surface discharges have occurred over the paper surface of the upper phase, between the HV conductor and the earth screen.

7.3 CASE 3: RELIABILITY - DIAGNOSIS OF PILC FEEDERS

From trend analysis of PD measurements, conclusions are drawn from one or more of the parameters from the PD fingerprint. Comparing actual values to those obtained for the particular cable system in the past and analysing critical changes are important factors for condition assessment.

7.3.1 PRE-SELECTION FOR DIAGNOSIS

Factory plants often have their own distribution network, which is connected to the power network of a utility. The outages in these networks are directly related to production losses and therefore these companies are very cautious for the

condition quality of their networks. The power cable in this example is a part of the distribution network of a chemical plant, where PD diagnoses are performed on their cable systems. In all the cable systems no PD activity was found except in that cable system discussed in the example below.

7.3.2 CABLE SYSTEM

The 10kV cable system in this example is 260 meters long and constructed from 150mm² Al three-core paper insulation. The cable system contains no joints. The terminations are mass insulated. The concerned cable system is the feeder of a cold storage room, without backup of the energy supply, which means that no unexpected outage should occur.

7.3.3 ON-SITE PD DIAGNOSIS

The example shows condition assessment in a PILC distribution power cable using PD property trending, with a time interval of three months. PD measurements have been performed in May 1999 following the standard measuring procedure as described in chapter 6. From the first measurements, a clear PD source in the cable insulation was detected at 90 meters from the measuring side. The PD mapping of the measurement are represented in figure 7.5, PD inception voltage was $1.1 \cdot U_0$, just above the operating voltage of the power cable.

Because of the danger of power loss at the chemical plant, three months after the first measurement, the cable system was measured again. PD mapping is also shown in figure 7.5. PD patterns and intensity were unchanged, but the amplitudes were increased from 4500pC to 7800pC. The PD inception voltage was decreased from $1.1 \cdot U_0$ to $0.9 \cdot U_0$. Due to the decrease in inception voltage and the increase in PD amplitudes, the cable insulation was suspected for further deterioration.

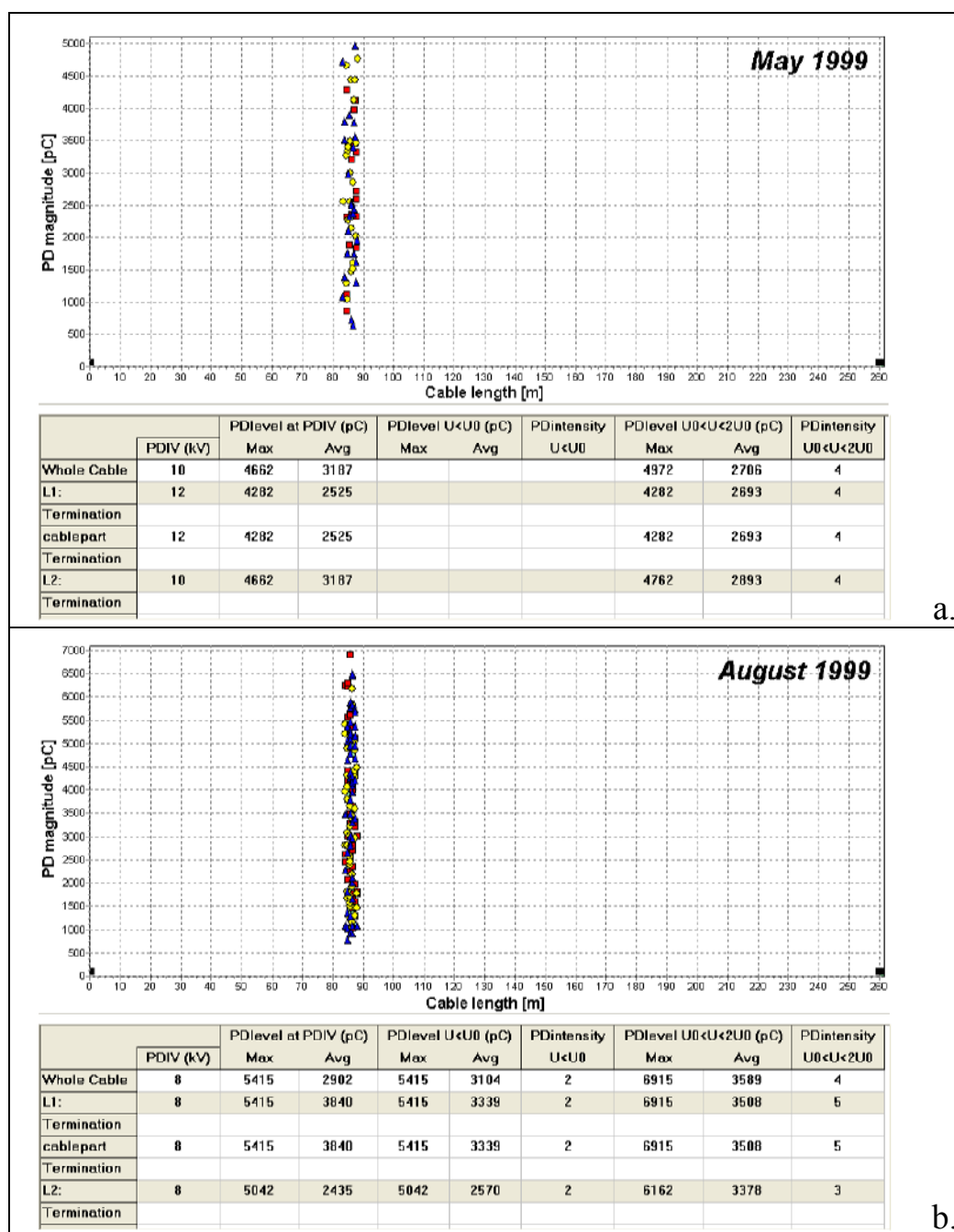


Figure 7.5: Measurement result obtained from a 261 m PILC cable system in a time interval of 3 months:

- PD mapping from May '99;
- PD mapping from August '99.

7.3.4 CONDITION ASSESSMENT AND MAINTENANCE DECISION

The detected PD properties are all within the norms, except for the PDIV, the defective meters of the cable circuit are replaced. The changes in PD inception voltage outside the experience norm and the PD amplitudes within the experience norm contained in this case enough information to replace the

defective meters of the power cable. The main reason was not the actual condition assessment, but the importance of this specific cable system. The possible outage costs would have been much higher than the replacement costs. During the after-repair test, the power cable appeared to be PD free up to test voltages of $2*U_0$.

7.4 DATABASE APPLICATION FOR CONDITION ASSESSMENT

In the condition database, the cable system component data, the condition data from the diagnostic inspections and the experience norms are combined for condition assessment [111]. As a result, based on the decision support of chapter 7, an overview of the diagnosed cables in the network (or part of the network) is obtained, as is shown in figure 7.6. The database contains more than 300 cable systems and measurements and is still growing.

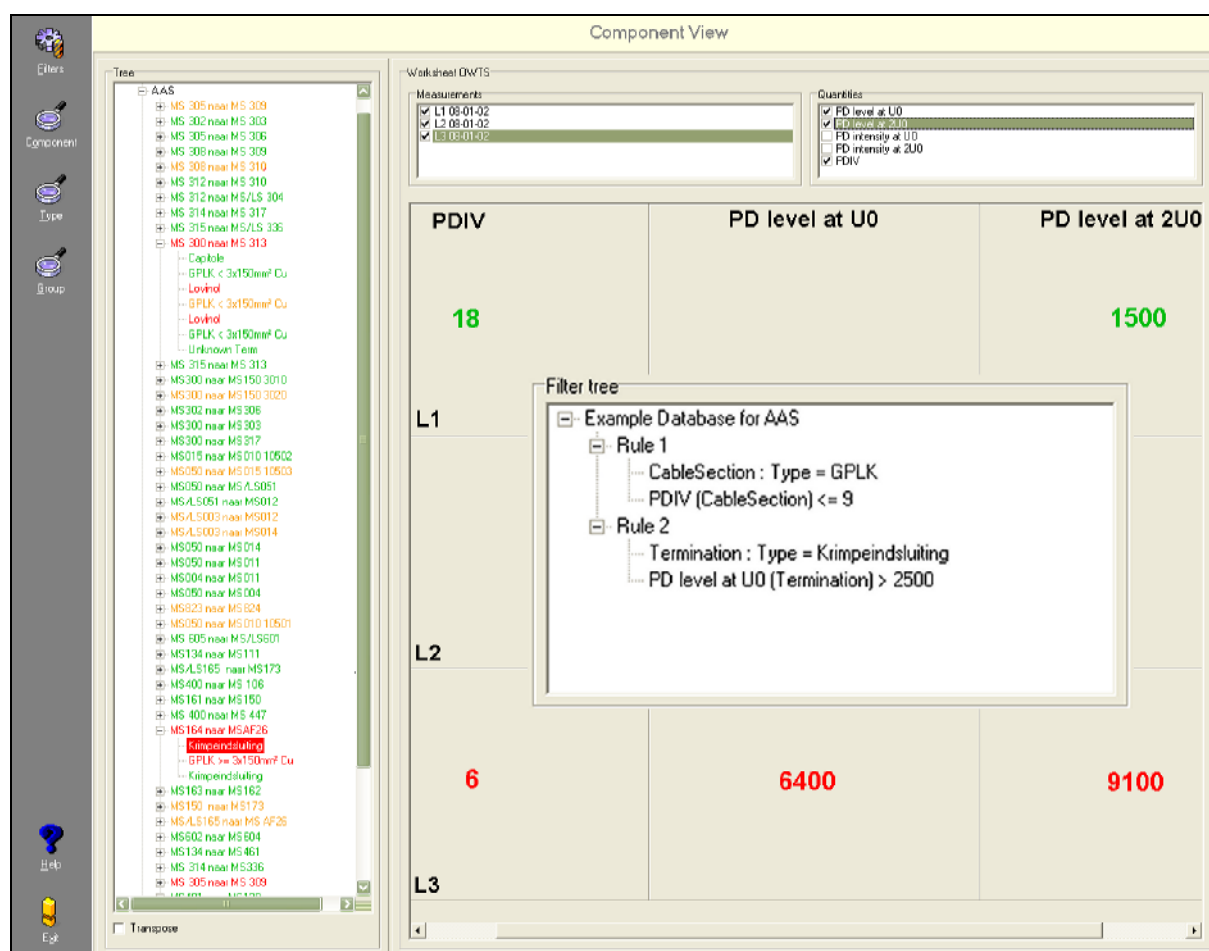


Figure 7.6: Database view of the different diagnosed cable systems of a specific network owner, with a list of cable systems on the left and the condition data of the selected cable system on the right.

The figure shows a database view of the different diagnosed cable systems of a specific network owner. The tree of the cable systems, in the figure on the left side, shows the different conditions of each cable system by colour (red, orange and green). As a cable system consists of a series of different components, its overall condition is actually determined by that component with the worst insulation condition. Therefore, the tree can be extended to show the different components of that cable system with their individual insulation condition.

As all the PD properties are stored in the database, it is possible to trace back the criteria on which the decision is based. A filter can be created to decrease the total amount of data for analysis or condition assessment, as described in appendix C. On the right side, the different PD properties of a cable component are reflected with the applied filter, which indicate on which PD properties the condition of that component is determined. On the right side, the PD properties of a diagnosed cable termination are shown, which indicate that its condition is determined by the PD activity in phase L3. The PDIV is below operation voltage (9kV) and the PD levels at U_0 and $2U_0$ are above the experience norm for the shrink termination. Phase L1 also shows PD activity in this termination, but the PD properties are not critical.

8

PD DIAGNOSTICS FOR TRANSMISSION POWER CABLES

Due to the greater impact of an insulation failure in the service life of transmission power cables, extensive voltage withstands test as well as sensitive PD tests are applied during the factory acceptance testing. However, after installing the cable system on-site, different types of voltage withstand tests are applied. HV energising systems which can generate high voltage stresses on-site are [45]:

- I. 50/60 Hz power frequency using transformer circuits or tuneable reactor circuits,
- II. 20-300Hz tuneable resonant circuits;
- III. 50-300Hz temporarily AC voltages.

For on-site application of mobile HV systems, a number of preferred characteristics have been pointed out [45]:

- low specific weight measured with kg/kVA,
- compactness versus output voltage,
- system assembling and voltage erecting effort,
- required power demand.

In dependence of the rated power nowadays the characteristics as mentioned above result in a solution of large truck(s) (systems I and II) with 1.500 kg weight and higher. To fulfil the above demanded characteristics better, we started the development of an OWTS for transmission voltage levels analogous to the medium voltage system [40] described in chapter 4. In the past, DAC excitation is already introduced as a withstand-voltage test for XLPE-insulated transmission cables for commissioning purposes, however using gap-fired switches [2,3,29,78,106]. In this chapter, the DAC voltages are also applied for PD diagnosis of transmission power cables.

8.1 TEST VOLTAGE EXCITATION SET-UP

Figure 8.1 shows the set-up of the new DAC method using solid state switching techniques resulting in a new solution for a high quality factor Q , low weight HV resonant circuitry. In the laboratory of a cable manufacturer the system was tested on a new 220kV single core XLPE cable. In the back, the fixed resonance system of the laboratory is visible. The dimensions of the new DAC system are rather smaller than the conventional methods, ca 2.0 by 1.6 meters.

For the generation of DAC voltages, the power demand remains low due to the cable charging with a DC power supply. The cable sample, representing a capacitor, is charged linearly with a DC power supply. After charging-

up, the cable is promptly switched in series with an external inductor, which is 3.5H. Due to the application of a continuously loading by a DC current, directly followed by a switching and oscillation period no “steady state” DC voltage conditions occur [40]. The damped AC voltage which follows is used as an excitation voltage for PD detection. Sensitive PD detection is possible due to the compactness of the system and the disconnected voltage source during the measurements. Figure 8.2 shows the scheme of the energising method of DAC voltages applied for PD detection in transmission cables. The test frequency of the oscillating voltage wave is the resonant frequency of the circuit.

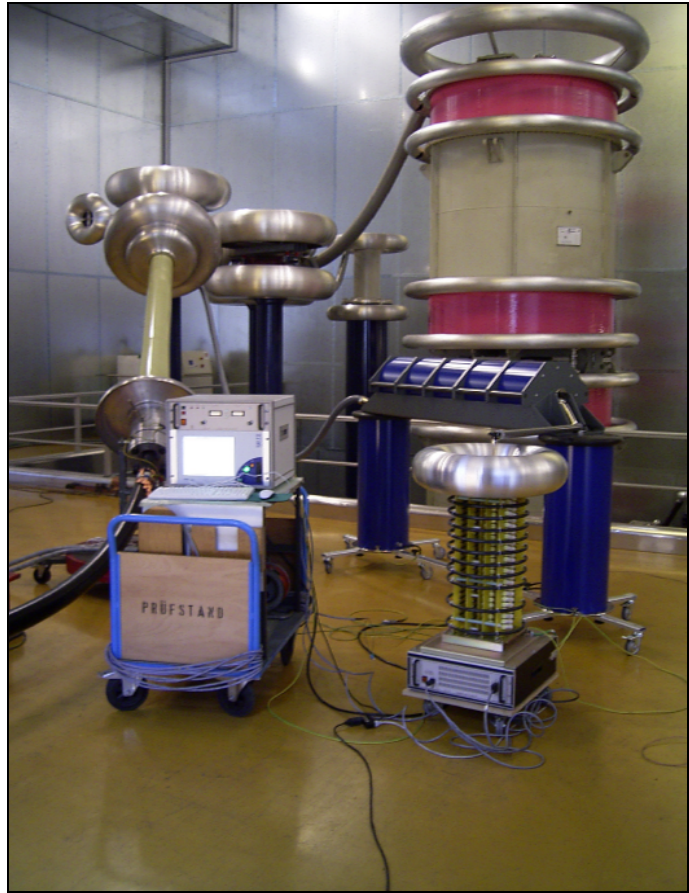


Figure 8.1: Application of the Oscillating Wave Test System (OWTS) on a cable sample in test laboratory at Kabelwerke Brugg. A fixed resonance system is shown in the background

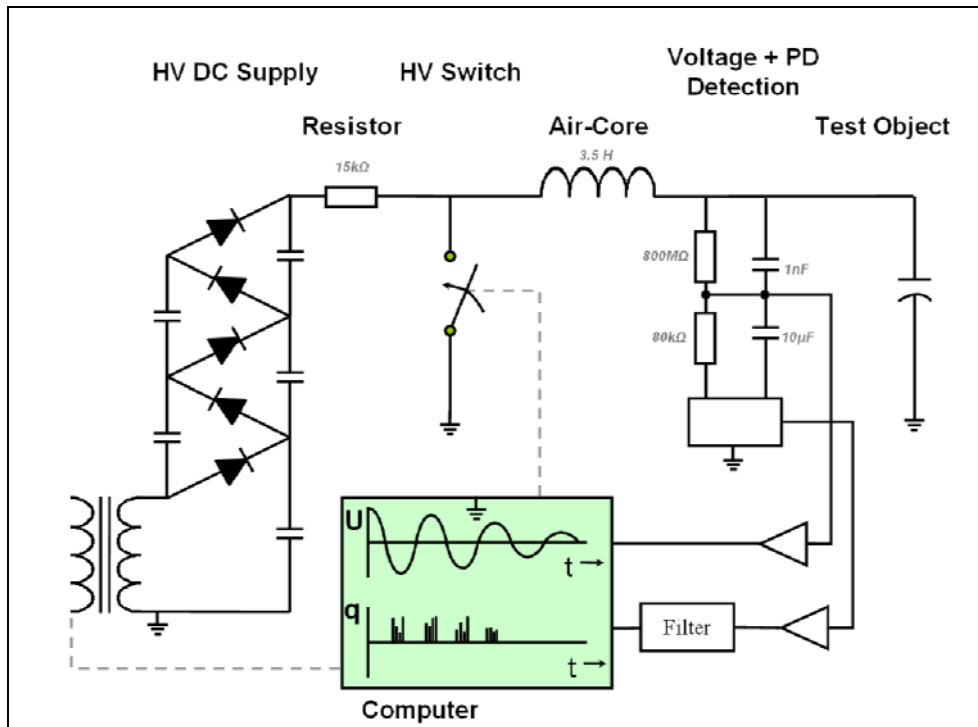


Figure 8.2: Schematic view of the OWTS250 diagnostic tool for transmission power cables.

The charging time of a cable can be calculated according to equation 4.6. The charging time depends on the maximum load current of the DC supply ($I_{load,max}$), the test voltage (U_{test}) and the capacitance C . The charging time for various cable capacitances and test voltages are shown in figure 8.3, based on the maximum load current of 8mA of the applied DC supply.

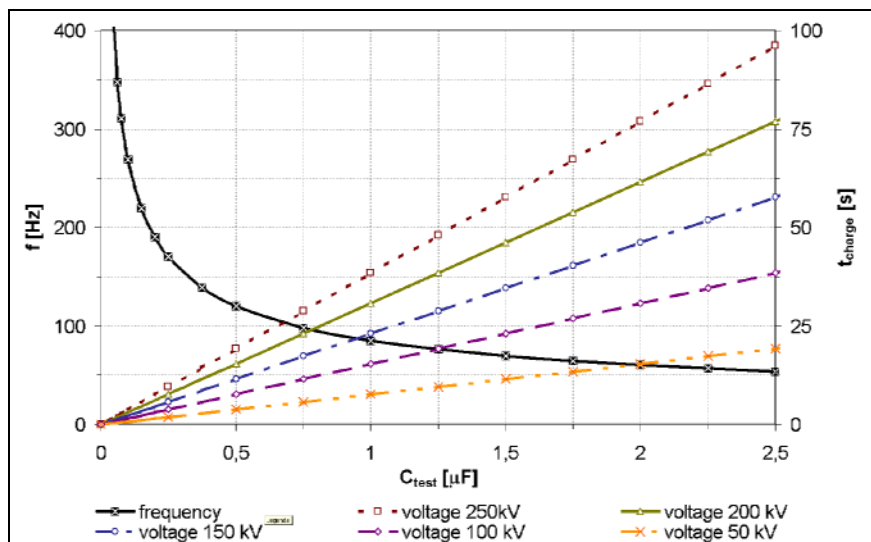


Figure 8.3: Dependency of the charging time (for a DC source of 8mA) and the test frequency on the cable capacitance.

As the charging time, also the AC stress frequency is variable. The quality factor Q of the resonant circuit, which is responsible for the attenuation of the oscillations, can be expressed by:

$$Q = \sqrt{\frac{L}{C \cdot R_A^2}} \quad (8.1)$$

where R_A is the equivalent circuit resistance. The quality factor Q of the resonant circuit remains high, being 30 to more than 100, depending upon cable capacitance and losses. Slowly decaying damped AC voltages with a decay time up to 0.3s can be applied to the cable up to test voltages of $250\text{kV}_{\text{peak}}$.

The maximum power cable capacitance which can be tested at DAC stresses using the 250kV test system can be calculated in dependence of maximum voltage applied (figure 8.3):

$$C_{\text{max}} = \left(\frac{I}{U}\right)^2 \cdot L \quad (8.2)$$

where L represents the air-core inductor of 3.5H. Figure 8.4 shows the curve of the maximum capacitance and the test voltage. The 250KV test voltage can be applied for a maximum capacitance of $5\mu\text{F}$, which corresponds to a cable system of about 25km (the capacitance of a 150 kV polymeric cable is approximately 200pF/m).

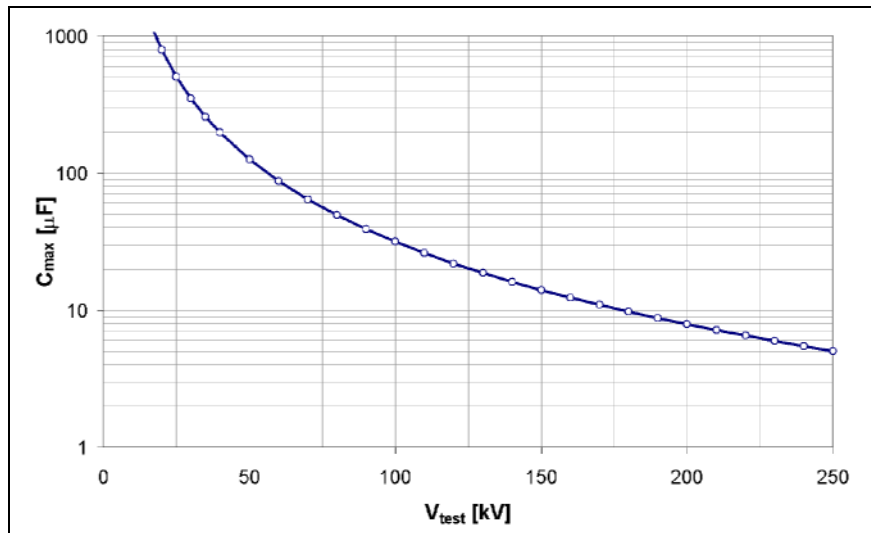


Figure 8.4: Dependency of the maximum test voltage on the cable capacitance.

8.2 SYSTEM COMPONENTS

The energizing system with the PD measuring circuit is shown in figure 8.5. In the table 8-1 the basic sub-systems are described.

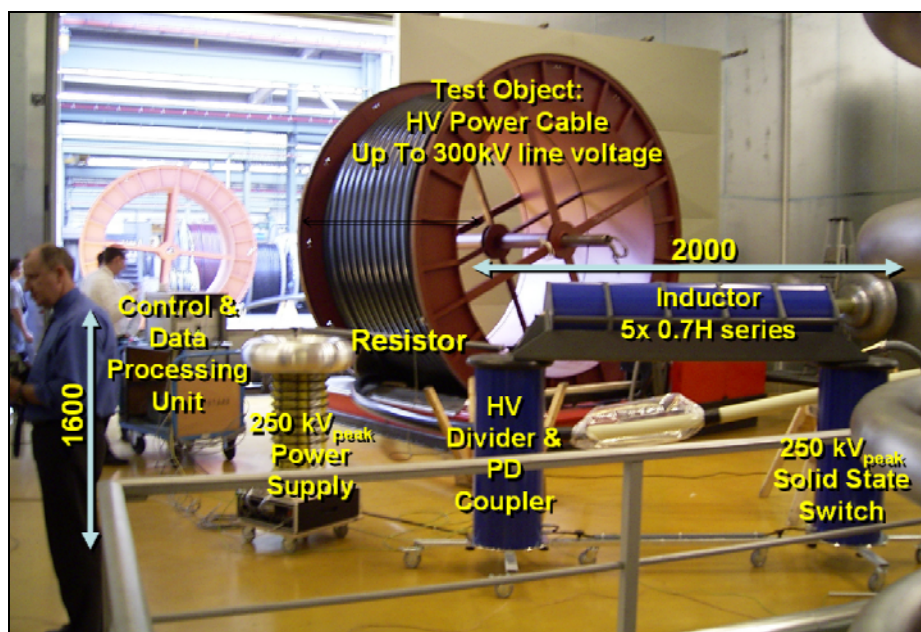


Figure 8.5: Different components of the DAC system, which are put together for measurement purposes. Total weight 300kg; occupied space 1.6m x 3m x 2m.

HV POWER SUPPLY 250 kV

To load the power cable capacitance up to 250kV HV dc voltage supply has been used with a circuit effective load current of 8 mA. In figure 8.3 the charging time in function of the charged capacitance is shown.

HV SOLID-STATE SWITCH

The function of the 250kV switch is to establish a series resonance circuit between the charged HV power cable and the air inductor L . As a result damped AC stresses may occur in the cable sample.

INDUCTOR

The system's inductor consists of five in series connected air coils with a total inductance of 3.5H. To make it sure that the damping of the voltage waves is mainly depending on the test object losses the inductor is air core type. Also the epoxy insulation of the windings provides an excellent PD behaviour of this part.

Table 8-1: Technical parameters of the OWTS HV PD diagnosis system.

Component	Specifications
HV power supply	Primary power 4 kW; Output power 13 MVA (e.g. load 0.8uF); Max. Voltage 250 kV; Load current 8 mA; Weight 50kg, Type dc multiplier
HV solid-state switch	Max voltage 250 kV; Maximal current 300 A; Weight: 20kg; Type: solid-state switch, turn-on resistance < 1Ω; Switching time, 1μs
Inductor	Number of coils 5 Total inductance 3.5H / 75Ω Weight: 5 x 30kg = 150kg Type: air core inductor epoxy insulated, PD free
HV Divider	AC/DC divider C= 1nF; R= 800 MΩ; Weight: 27kg; PD free; PD coupling device
Resistor	15kΩ to limit the switching discharge current of the power supply to max 16 A
Control unit	250kV voltage control unit Weight: 25kg
Test Objects	HV power cables up to 290kV voltage rating Cable length: 100m -20km
Data processing unit	Pentium 4, 1.5GHz; PD detector IEC 60270; Time Domain Reflectometry; PD mapping generator;

8.3 DETECTION OF PARTIAL DISCHARGES

Due to the fact that for the above described technique, the frequency of damped AC voltages is in the range of power frequency of acceptable HV test systems and a number of power cycles is applied to the cable sample providing ignition of PD sources similar to operating conditions.

The PD circuit is not connected during the charging time and switching time of the DC supply. The PD detection circuit and the compactness of the system provide a sensitive

detection of the discharge signals during the energising time, as shown in figure 8.6, during which the voltage source is not connected. The measurement bandwidth of the PD detection circuit is chosen in accordance with IEC 60270

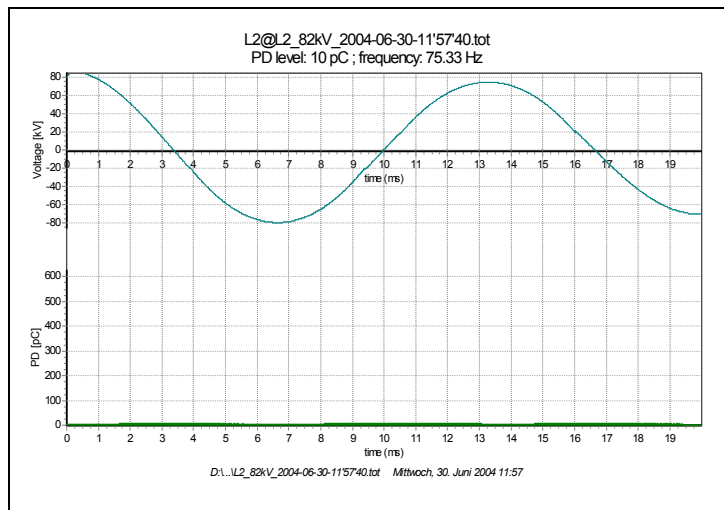


Figure 8.6: Background noise during the measurement on a 50kV cable system at $2U_0$ is only 10pC. As a result, PD activity of 140pC can be located in the cable length of more than 6km.

recommendations. For the purpose of PD localisation by travelling waves, the bandwidth of the system amplifier is increased up to 10 MHz combined with a 100 MHz digitiser.

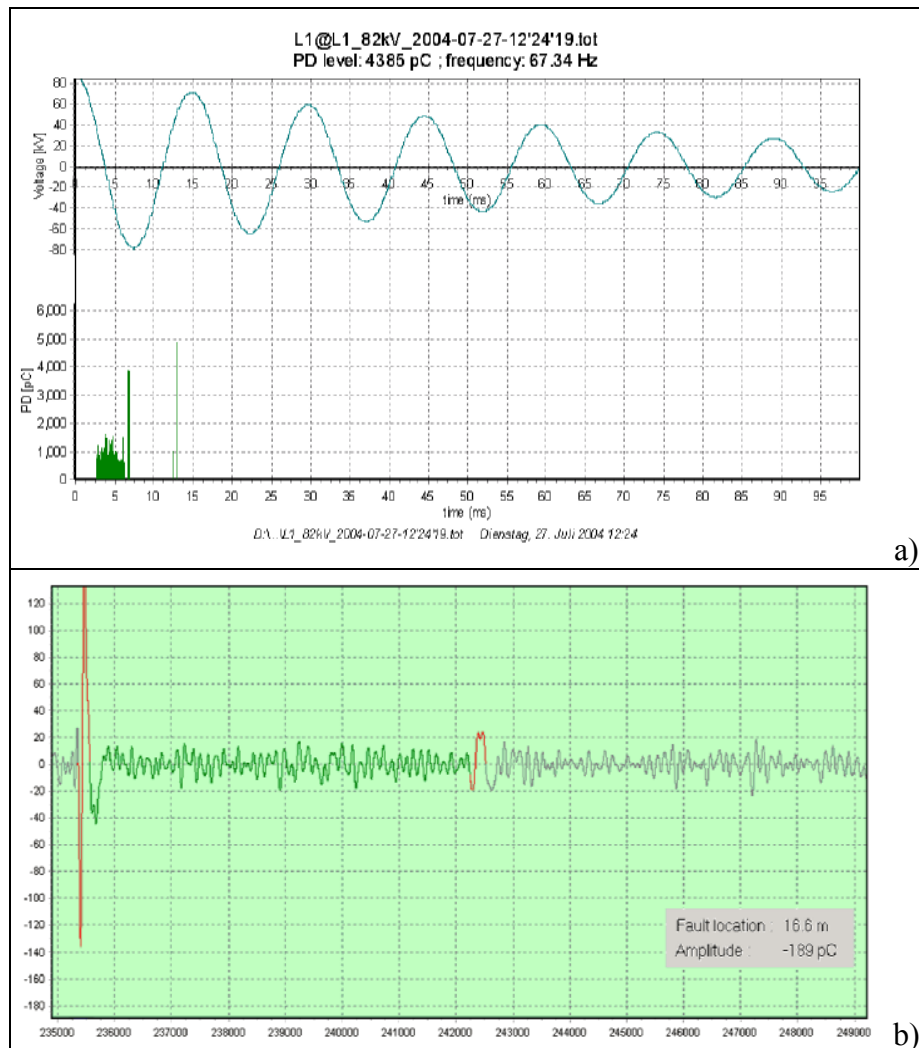


Figure 8.7: Examples of DAC voltages as generated using OWTS HV system and PD detected:

- a) voltage wave with detected PD pattern;
- b) localisation of PDs.

The PD signals, ignited during one or more oscillating voltage waves, are detected and processed by the system for two purposes:

1. A phase-resolved PD pattern can be obtained from multiple DAC sequences. In this way, patterns can be obtained which are similar to those recognised under 50(60) Hz conditions, as shown in figure 8.7a;
2. Single PD pulses can be analysed for original location by using time domain reflectometry. Statistical evaluation of PD signals obtained after several voltage waves can be used to evaluate the discharge sites in the power cable, as described for distribution cables in chapter 4.

8.4 PARTIAL DISCHARGE PROPERTIES

Considering the life-time expectancy also for transmission power cables, the determination of the insulation condition by several PD properties is of importance. A new HV test system has been brought into the development stage on the bases of the investigations in this thesis. The PD properties as described for lower voltage class power cable have been shown to be measurable with the system for HV testing too. The quality of the PD properties requires further investigations during measurements in field.

9

CONCLUSIONS & RECOMMENDATIONS

In this thesis, the feasibility of PD diagnostic methodologies at damped AC voltages for the early recognition of insulation defects in distribution power cable networks has been evaluated, in view of long term preventive maintenance. Based on the on-site detection and localisation of defects, the development of knowledge rules for condition assessment of the different insulation systems in the cable network has been the final objective of these investigations.

9.1 CONCLUSIONS

The cable network under investigation is directly buried, whereas the only physical access to the cable system is possible at one of the terminations and electrical detection is mainly the only possibility. Due to the propagation of EM waves through cable systems, the PD detection is possible at these terminations. In this thesis, we came to the following insights. The conclusions can be subdivided in cable insulation, diagnostics and condition assessment.

INSULATION DEGRADATION

- (1) The local insulation degradation mechanisms emanate from various defects occurring in the cable components. In particular for four different types of mechanisms we have found major impact on the performance: degradation in cavities or fissures, degradation on surfaces, degradation by treeing and degradation by discharges in oil.

- (2) Partial discharge phenomena are indicated as the most important symptoms for local degradation processes in power cable systems (section 2.4). As a result, partial discharges provide sensitive diagnostic parameters to recognise the presence of local insulation defects. Therefore, on-site PD diagnostics are suitable methods for condition assessment, as the defects can be pinpointed along the cable length.

PD DETECTION AND LOCALISATION

Using PD diagnostics for field applications, the following aspects can be concluded:

- (3) To localise PD in mixed power cable systems, detailed information is required on the insulation types and lengths of the different cable parts. Systematic deviations in the PD locations occur using the single velocity approximation for the localisation. Due to the different propagation velocities in different insulating materials, a deviation up to a few percent of the cable system length occurs, dependent on the ratios of the lengths and velocities of the different insulation lengths. A correction can be calculated by separating the time interval into the individual propagation times of the cable parts. After the origin of the PD event has been attributed to a specific cable part, the location can be determined with the different propagation velocities and lengths in the cable system.
- (4) For the PD diagnostic tool, based on damped AC voltages, this thesis shows that it is an effective method for PD detection and localisation in the power cable network. PD ignition is excited at high voltage and low power as a loaded cable system is off-line and discharged over an air-core coil. A temporarily damped AC voltage with frequencies in the range of 100 – 500Hz activates within 100-200ms the ignition of the PD sources in a cable system. A compact measuring system has been build, by which we showed that a low noise level and high sensitivity for discharging defects in polymeric and impregnated paper cable insulation are feasible in practice.
- (5) For damped AC voltages and 50Hz continuous AC stressing, we concluded that the values for the relevant PD parameters characterise different defect models very accurately. Between the different energising methods minor differences are found. In particular the relation between the ignition delay time, the voltage level and the frequency of the test voltage leads to a slightly decreasing PD magnitude at higher frequencies for dielectric bounded cavities.

- (6) For a full evaluation of PD occurrence in a cable system, we concluded that the following information should be included in standard test procedures:
- (a) PD activity as a function of voltage;
 - (b) PD localisation of different discharge sources in the cable system;
 - (c) Multiple PD properties to describe a PD process, e.g. PD inception voltage, PD magnitudes and PD pattern.

CONDITION ASSESSMENT

An important part of the condition assessment is devoted to the probability that an outage results from the insulation defects. The technical qualification of the cable system's condition can be useful for further decision processes by an asset manager to prevent such outages.

- (7) The experience norms for PD properties that we have derived are independent of individuals. The norms are obtained by statistical analysis of the series of measurements of the measured PD properties (section 6.2) per cable component.
- (8) A specific type of distribution is allocated to each PD property. With the obtained measured data, the distribution of a PD property can be quantified for a specific cable component, for which we calculate 95% norm levels.
- (9) A method of adding up weighted deviations of PD properties from the norm levels is introduced. Using these levels, successful estimation of the risk of failure by discrimination between different categories of criticality is obtained. Different PD properties describe different aspects of the condition of a cable system and its components. The most critical category occurs when multiple PD properties are outside the norm.
- (10) A diagnostic tool based on damped AC voltages developed for transmission cables analogous to the one for distribution voltage levels will give insight in the near future ageing behaviour at higher system voltage levels.

9.2 RECOMMENDATIONS FOR FURTHER RESEARCH

- (i) The larger the amount of diagnostic information the more validated results from statistical analyses of the PD parameters for the different cable components are obtained. Therefore, it is recommended to keep collecting measurement data from different components for continuous adjustment of the key experience norms. The experience norms are now determined on cable component level, while a deeper analysis on defect type level provides a better criticality analysis. If the defect type(s) in one component is (are) identified and distinguished, the probability of failure can be better estimated.
- (ii) For better performance of the condition assessment, knowledge-sharing on an international level is recommended. In case of newly introduced diagnostic tools, the collection of relevant data for the determination of experience norms is time and costs consuming. In order to be able to define these norms more quickly, knowledge-sharing on an international level would be effective, discerned for different types of cable components. Furthermore, the knowledge-sharing will lead to more reliable experience norms.
- (iii) Not all degradation can be spotted by partial discharges, e.g. moisture penetration in resin insulation, or the time-period of the final degradation stage with PD activity may be too short to provide a warning signal, e.g. watertreeing in XLPE insulation. To diagnose power cable systems on these types of defects bulk measurements may provide an alternative. New detection techniques should be developed which are able to detect the warning signal for these defect types in particular if these techniques can pinpoint these defect along the cable system length.
- (iv) Different diagnostic tools based on PD detection and localisation are developed for the distribution power cables. However, for the transmission power cables, these kinds of applications are not available, while also the first generation of transmission power cables is reaching its expected life-time. Condition assessment on these cable types would bring a lot of knowledge to the present unknown condition state of these network connections.



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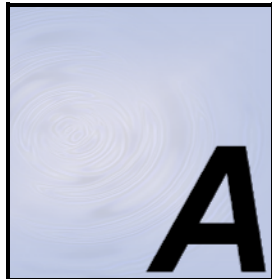
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FAILURE STATISTICS

In this appendix, failure statistics in the Dutch power network are described. The reflected numbers are averaged for the period between the years 1991 and 2001. As a result, a representative view of the outage causes is described.

A.1 FAILURE STATISTICS OF THE POWER NETWORK

The failure rates in the power network may be registered in system voltages categories, high voltage (HV), medium voltage (MV) and low voltage (LV). Figure A.1 shows an example of an outcome of the registration, showing the outage probability per year and the average outage time as a result of failures in the three categories.

In the Netherlands, customers may be confronted with a power interruption caused by failures in the MV network once per every 3.75 years. The probability of an outage resulting from the HV and LV network are once per 12.5 and 77 years respectively. On contrary, analysis of the

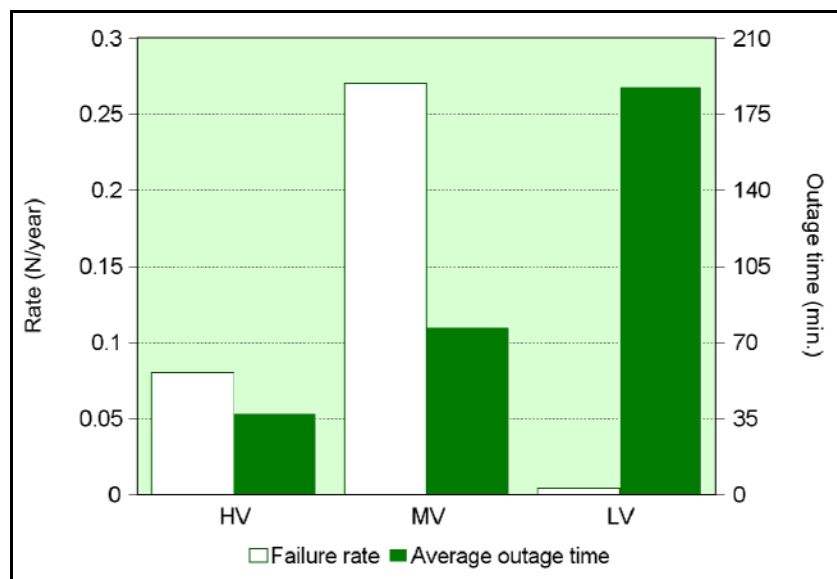


Figure A.1: Example of the failure rate and the average outage time per interruption electricity customers in the Netherlands, as result of failures in the HV, MV and LV network. The reflected numbers are averages for the ten years [27].

average outage time shows another distribution, where the outages in the LV network show highest results (187 min), followed by the MV (78 min) and the HV network (37 min) [27].

The differences in the outage probability and the outage time between the different network levels can be explained by four main influencing factors, as are shown in table A-1. Failures in the HV network are not occurring as often as a result of the relative small number of components and the historical good quality and property of maintenance in this part of the network. Due to the high redundancy (ring networks, “N-1” criterion) and the possibility of remote switching actions from operation centres, the outage probability and time are relatively low.

The LV network is much wider spread out, but the number of customers connected is limited as compared to the HV and MV network. However, if a failure occurs, the time to restore the energy supply is long in relation to MV and HV networks, due to the radial network principle (no “N-1” criterion). The redundancy is generally low in the LV network. The failure needs to be repaired before the energy supply can be restored.

Table A-1: Influencing factors of the outage probability and outage time for the three power network categories.

	Relative number of components	Historical maintenance level	Number of customers involved	Energy supply restore
HV	Small	High	High	Remotely (often no outage)
MV	Medium	Medium	Medium	Switching by hand in the field
LV	Large	Medium	Low	After repair

The outage probability from the MV network is much higher than the HV network because the network is more distributed and historically seen less well maintained. If a failure occurs, a part of the mostly meshed network is switched down, affecting numerous numbers of customers. Furthermore, switching activities to restore the energy supply have to be carried out by hand. Hence the outage time is longer as compared to HV and shorter than LV network.

Multiplying the failure rate and the average outage time per interruption, as reflected in figure A.1, the average outage time per year for a customer is the highest for MV network (21 minutes per year) as compared to the outages from

the HV (3 minutes per year)¹⁴ and the LV network (0.75 minutes per year). From this comparison, it can be concluded that the MV network needs attention to reduce the minutes of outage.

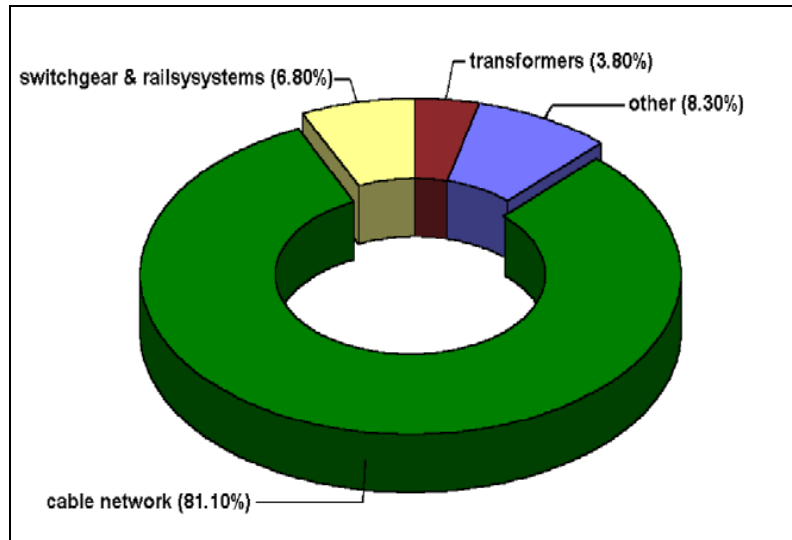


Figure A.2: Outages related to the MV network, divided into four categories. Outages as a result of e.g. wrong switching actions are reflected under the term “Other” [23].

Outages as described above have their origin in a number of components: switchgear, rail systems, transformers or the cable network. Figure A.2 shows the relative number of outage causes related to these categories. Under the term ‘other’, outage related to wrong switching actions and badly tuned protection relays are reflected.

This investigation shows that the cable network is associated to 80% of the outage in the MV power network. This is partly related to the higher probability of failure due to external influencing of non-electrical nature, such as digging activities for other types of underground networks, like communication cables, gas and water pipes, or foundations construction for new buildings. Although these external factors are causing almost 36% of the outages in the cable network, cable insulation degradation is still responsible for the major part of the outages in the distribution network.

¹⁴ The spreading in the HV outage expectations is bigger than for MV and LV, due to the combination of relative low failures and the external influence, like weather.

A.2 FAILURE STATISTICS OF DISTRIBUTION CABLE NETWORK

From the failure statistics example in figure a.3, it is shown that external damages by third parties are causing 36% of the failures in the MV power cable network [23]. The external damages are related to the cable parts, due to the extensive lengths of the cable components. Cable joints are confined components, for which the probability of external damages are much smaller.

Apart from the external damages, still more than 60% of the breakdowns in the cable network are caused by internal defects in the insulation systems of the cable network. These failures from internal insulation degradation will be prevented by using the right diagnostic tools. The majority of the failures caused by internal defects occur in the cable joints: 46%. The remaining breakdowns occur in the cable terminations (1%) and the insulation of the cable parts itself (16%), see figure A.3.

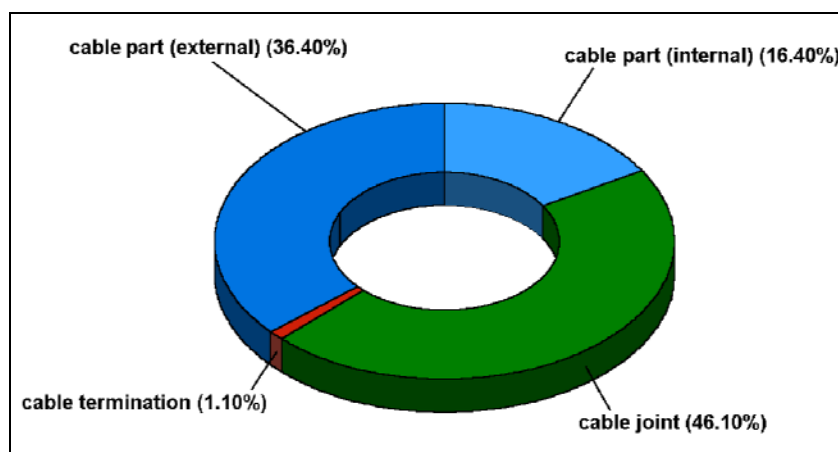


Figure A.3: Example of the failure distribution in a distribution cable network. More than half of the failures are related to the cable parts, but the major part of these failures is caused by external damages (due to e.g. digging activities).

CABLE

In the power network nowadays, two different main types of power cable are used, namely paper insulated lead sheathed cable (PILC) and cross-linked polyethylene insulated (XLPE) cable. From the statistics of figure a.3, it follows that the major part, 68.6% (36% of 53%), of the outages of cable parts is caused by direct external damages, both in PILC and XLPE cable parts. Furthermore, more than 93% of the outages in cable parts are related to damages of the PILC parts and only 7% to XLPE insulated cable parts, whereas the population of PILC is 8 times as high as XLPE (see numbers in parenthesis). These can be internal damages or indirect external damages, e.g. small damages due to digging or laying activities to the outer screen of the cables, which will not result in immediate failures.

The differences between the number of PILC related and XLPE cable related outages is mainly caused by the fact that still almost 90% of the cable systems

used in the statistical analysis figure A.4 are paper/oil insulated. The average age of the PILC systems is higher than the XLPE systems.

CABLE JOINTS

In the failure distribution, the joint types are divided into three categories based on the principle of insulation used; mass (liquid mixture of oil and resin), oil or synthetic (shrink or resin) insulation. The mass and the synthetic insulated joints both have more or less an equal part of the joint related outages. A lot of the

failures of synthetic joints are related to resin insulated joints.

As a result of water penetration (water diffusion) in the resin material, the insulation quality of the resin materials decreases tremendously. As the groundwater level is very high in the Netherlands, the power cables are almost always situated in the groundwater.

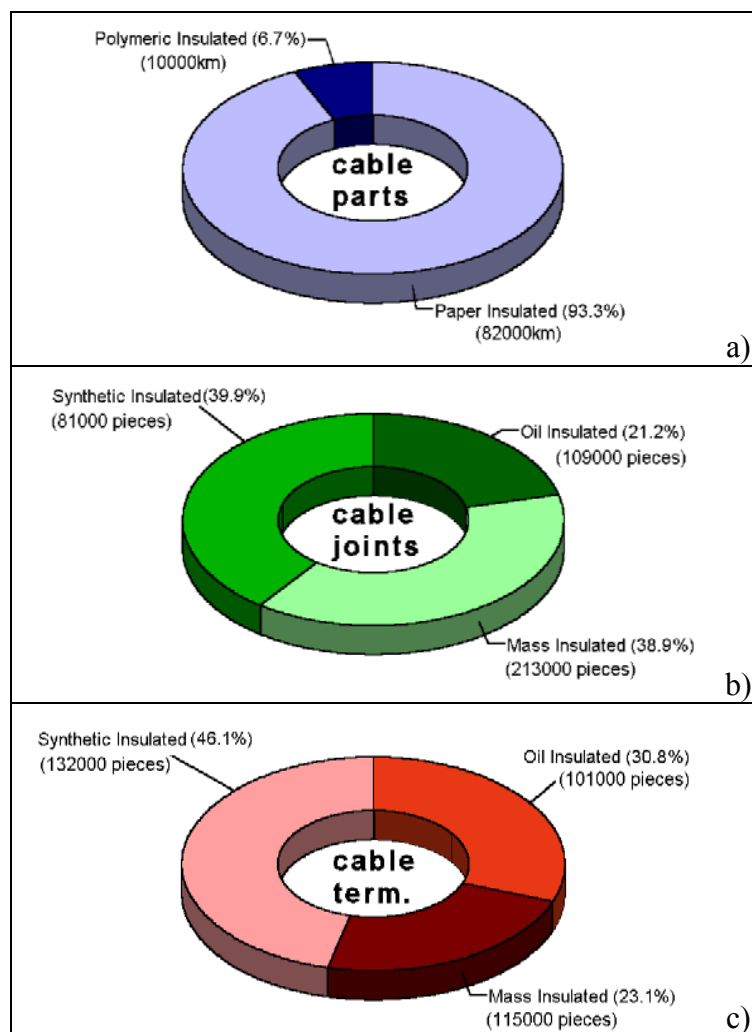


Figure A.4: Statistical overview of the registered outages related to the different components (insulation / construction) in the distribution cable network:

- a) cable, categorised in paper/oil and XLPE insulation
- b) cable joints, categorised in oil-filled, mass-filled and synthetic insulated;
- c) cable terminations, categorised in oil-filled, mass-filled and synthetic insulated.

The population of the components types used for the analysis are given in parenthesis.

CABLE TERMINATIONS

Dividing the cable terminations types into the same categories as the joints, it is clear from the graph of figure A.4 that most outages occur in synthetic insulated terminations, mostly constructed with shrink materials on PIL cables. Cable terminations are the cause of only one percent of the total number of outage. This is partly related to the fact that they are accessible and therefore visual inspection can be carried out, e.g. the oil level in the termination can be checked.

From the previous statistical analysis, it can be concluded that the MV cable joints are related to 37% (46% of 81%), the major part, of the total number of outages in the power network. The MV cable insulation is related to 13% of the outages and the MV cable terminations to only less than 1%. Furthermore, the external causes in the MV network are related to 29% of the outages in the power network.



ON-LINE PD DIAGNOSTIC - VHF PD DETECTION METHOD

The on-line PD diagnostic tool as investigated is based on the application of an external VHF PD sensor at the cable circuit's end, at the neutral, the cable earth connection to the substation earth. By using spectral analysis, PD activity in a cable circuit can be detected. Similar on-line PD diagnostics are applied for generators, GIS and transformers. The available on-line PD diagnostics [1,33,105,121] use different sensor types, dependent on the measuring location along a cable circuit.

B.1 MEASUREMENT SET-UP

On-line PD detection systems use the line voltage for the excitation of PD in the cable circuits. Active defects will discharge, and the resulting PD pulses will propagate as TEM waves through the cable [87]. At the end of a cable system, in a substation, the earth screen is stopped just before the cable is connected to the switchgear. At this point the earth screen is connected to the substation earth, whereas the PD pulses will couple out through this neutral.

In order to detect PD sources in power cable systems on-line, a VHF detection circuit can be used [13,43]. The PD sensor, a high frequency split-core current transformer is attached around the earth connection of the cable system, figure B.1. This 5 MHz HFCT is connected to a spectrum analyser (SA), which is connected to a computer for controlling and data processing. If PD is active in the diagnosed cable, PD pulses pass the HF sensor and are detected by the SA.

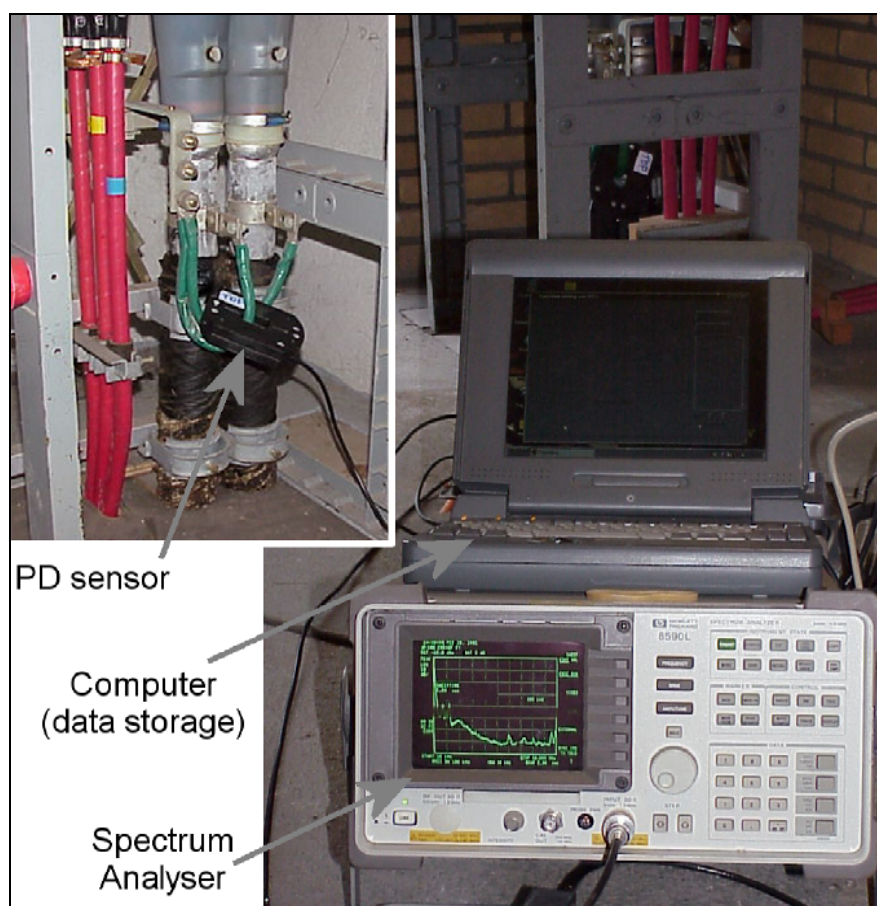


Figure B.1: The VHF on-line PD detection system; the PD sensor is attached to the earth connection of the cable circuit, whereas PD are detected by the spectrum analyser. The computer is used for storage of measurements results and the spectrum analyser set-up.

Due to the on-line situation, the background noise of the specific location cannot be detected at the cable system by switching it out of service. Therefore, the background noise is measured at the central earth location of the substation. As a result, a general background noise is detected, which may be a little different than the actual background noise of the cable circuit.

Using spectrum analysis [86], the distinction between external disturbances and internal PD from cables is obtained. In particular, by tuning the SA to frequency ranges with a high signal to noise ratio, typical phase-resolved PD pattern are measured and analysed for the presence of internal discharges, see figure B.2.

The same measurement circuit can be applied for those power cable circuits, which are directly accessible from the outside [86]. In this way, the PD signals are detected without propagation and can be detected at higher frequencies. For these power cables, the localisation is also possible by measuring that spot with the highest amplitude (at one fixed frequency).

B.2 PD PROPERTIES

The on-line diagnosis of the presence of PD in power cable circuits with the VHF detection method is based on two main properties:

- PD signal spectrum;
- Phase-resolved PD pattern.

PD SIGNAL SPECTRUM

From the obtained signal spectrum of a cable circuit, one can analyse the detected frequency spectrum for PD activity. Generally, an increase of the signal spectrum in the frequency range from 1 - 4MHz, as compared to the background noise spectrum, indicates the probability of PD activity in the cable sample, as shown in figure B.3. At those frequencies with high S/N ratios, the SA may detect possible PD patterns.

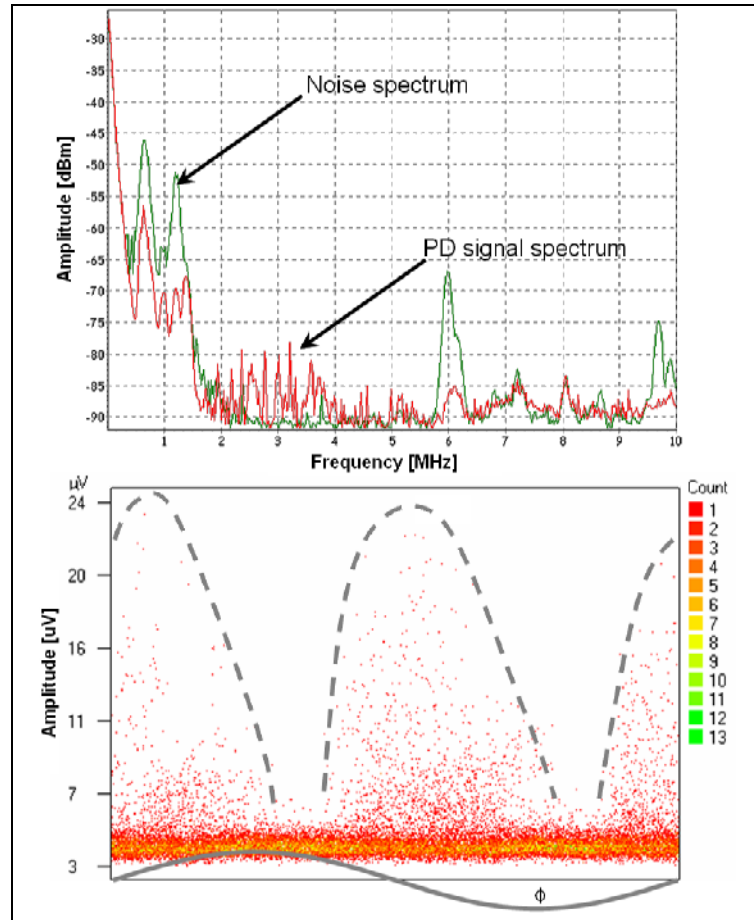


Figure B.2: Example of on-line measuring result using VHF PD detection on a 571m long 3-core belted paper insulated power cable. The background noise is detected at the substation's central earth and the signal spectrum at the cable neutral. By tuning to a centre frequency with high signal to noise ratio (between the noise and the signal spectrum above), a phase resolved PD pattern can be obtained. In this case, a clear 50Hz related PD pattern is detected.

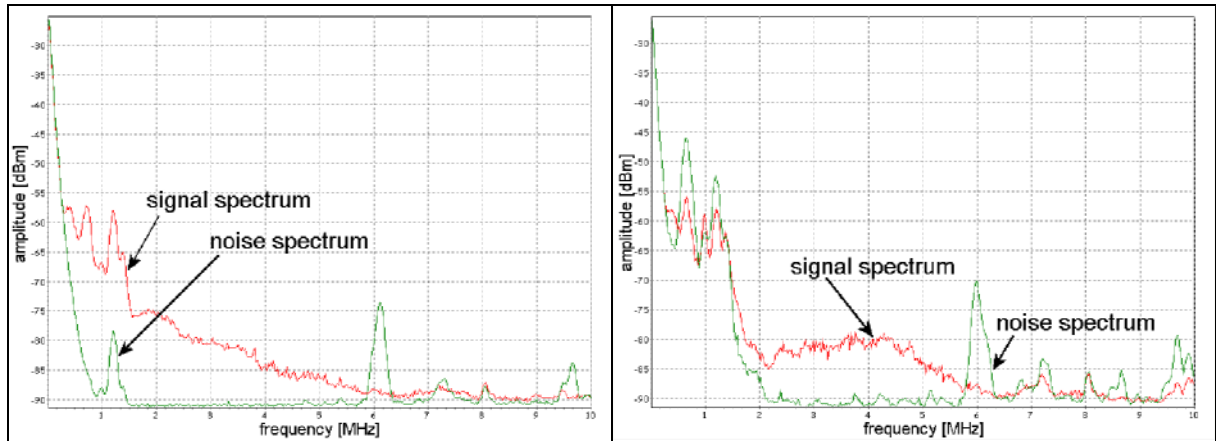


Figure B.3: Examples of typical PD spectra, as obtained from the VHF on-line PD detection system. Generally, an increase of the signal spectrum in the frequency range of 1-5MHz indicates the probability of PD activity.

PHASE-RESOLVED PD PATTERN

Tuning the SA to frequencies with high S/N, phase-resolved PD patterns may be obtained. For this purpose, the SA is set to the ‘zero-span’ mode on a certain centre frequency (CF) and triggered to the 50 Hz voltage wave making sweeps of 20ms. The result is a phase-resolved PD pattern, known from off-line PD detection and recognition, see figure B.4. If a clear phase-resolved pattern is obtained, this means that PD sources are active under the normal operation of the cable circuit. Due to the fact that the power cables in the distribution network are mostly three-phase circuits, it cannot be derived from a PD pattern from which phase it is coming.

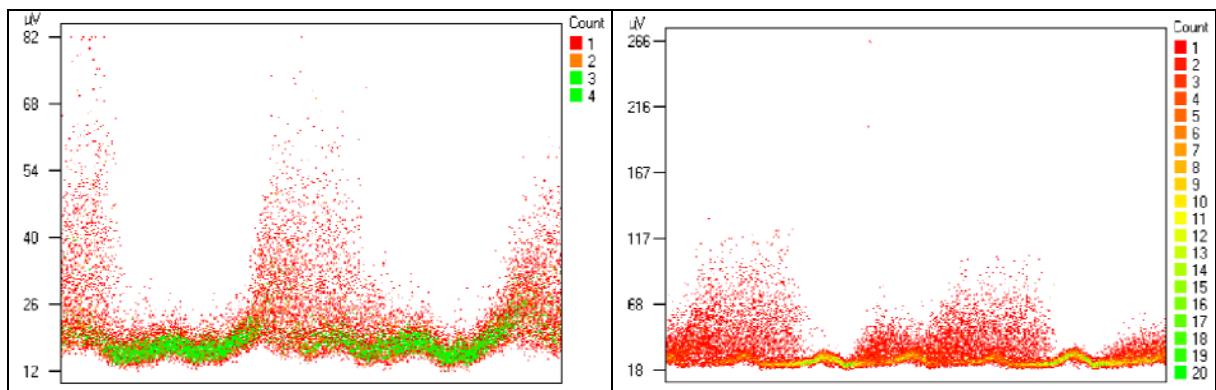


Figure B.4: Examples of typical phase-resolved PD patterns, as obtained from the VHF on-line PD detection system, after tuning to a frequency with high S/N ratios. The phase angle of the pattern is related to mains voltage of the SA, and not directly to the cable’s voltage.

Furthermore, the SA is triggered to the line frequency of the power supply in the substation. The phase shift between the power supply and the cables phases is not known. Therefore, advanced pattern analysis by statistics and classification tools [36,74] as known from off-line PD detection, is not applicable for the on-

line PD detection in the field. The PD patterns are only used to determine if PD is active in the power cable. If necessary, an in-depth analysis can additionally be performed by off-line diagnostics.

PD INTENSITY

For on-line PD testing with the VHF method, the repetition rate of PD can be obtained from the obtained PD pattern, as shown in figure B.4. The PD intensity can be obtained when measuring the PD pattern at a fixed time interval. The detection of the PD pattern is performed in sweeps of 20ms. If a PD pattern is collected in e.g. standard 200 sweeps, at least the distinction between high and low PD intensity can be made. However, measuring the PD pattern on all phases together, the intensity gives just a general impression on the PD activity.

B.3 PRACTICAL APPLICATION

An on-line PD detection system does not fulfil the IEC 60270 recommendations about PD detection, amplification and calibration, which is necessary to detect discharges in pC. Furthermore, using the VHF detection method, the system is set to only one frequency for pattern analysis. This frequency contains only a part of the energy content of a PD wave. Due to the fact that the frequency spectrum is not the same in the measured frequency range, the detected values in the PD pattern are relative. As a result, the amplitude of measured PD activity by the on-line system is represented in a μV -value. This implies that the usual interpretation of PD amplitudes in $[\text{pC/nC}]$ cannot be performed during the field application of on-line PD diagnosis.

Using on-line VHF method in the field, several practical sensitivity aspects have to be taken into account. The result of an on-line PD measurement can be strongly influenced by [123]:

- Influence of cable load: The moment of on-line measurements can be of great influence. Depending on the load of the power cable, different results can be obtained as PD activity may change with the power load.
- Influence of installation type: For optimal measurements with the applied on-line PD detection method, the HF sensor should be attached as close as possible to the neutral of the power cable. For some of the switchgear types, this is not possible. Furthermore, the neutral should be safely accessible.
- Influence of on-line disturbances: On-line energising may be accompanied by external disturbances which are 50Hz related. The phase resolved pattern may be hard to interpret due to these signals.
- Influence of signal attenuation: Signal attenuation effects in case of VHF detection on power cables are visible in the field, as shown in figure B.5.

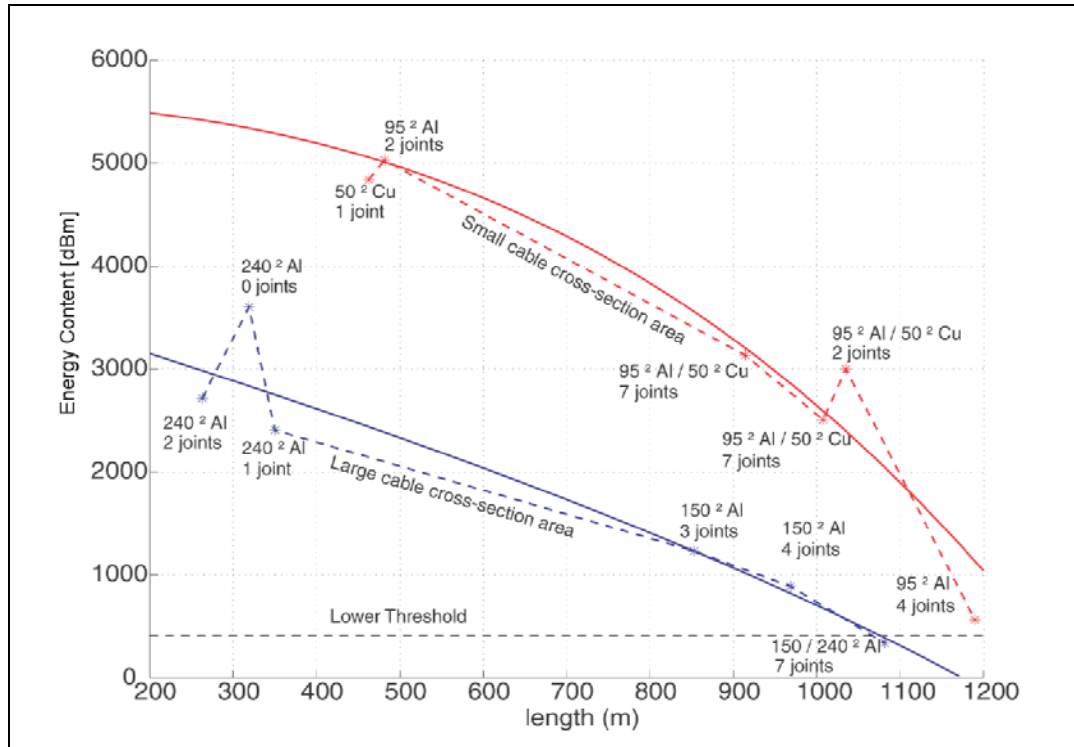


Figure B.5: Measurement results for signal attenuation for power cables of different lengths and larger cross sections. The energy content of the different S/N spectra, after injection of artificial PD pulses of different amplitudes, is calculated for determination of the on-line detectable cable lengths.

More than 70 on-line measurements are performed, to prove the effectiveness of this diagnostic as a pre-selective tool for off-line diagnosis. The VHF on-line PD detection results are categorized in three groups, as reflected in figure B.6:

- I. clear PD pattern; presence of PD source in cable sample;
- II. doubtful PD pattern; presence of PD source is not clear as a result of high disturbances or multiple PD sources;
- III. no PD pattern; no PD activity in the cable sample, the noise level is low.

In case of clear PD patterns, PD sources are active under operation voltage of the cable, which means a degradation of the insulation materials. More accurate diagnosis is required by off-line PD measurements. Doubtful PD patterns indicate that PD related defect might be active in the cable insulation. The patterns can be influenced by external disturbances or by the presence of PD related to multiple phases. Off-line measurements are recommended. If the noise level is low, and there is no detectable PD pattern, this indicates that no PD source is active during service of the power cable.

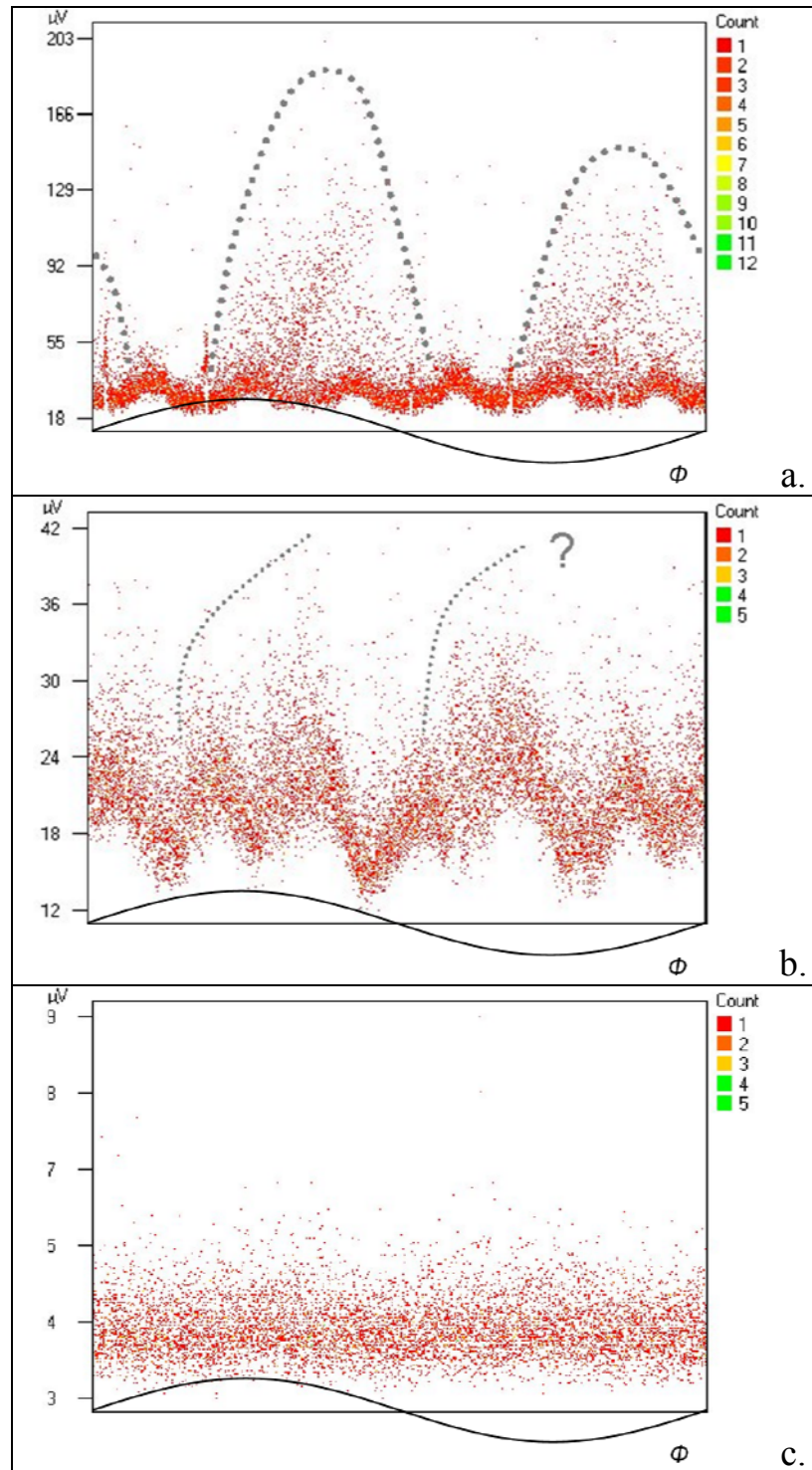


Figure B.6: Categorisation of on-line PD diagnostics for field application. For category I and II, off-line PD diagnostics is recommended for in dept analysis of the insulation condition of the cable system;

- Cat I: clear PD pattern, active PD source;
- Cat II: doubtful PD pattern (due to external noise or the propagation distance), possible active PD source;
- Cat III: no PD pattern, if the cable is within the length limitations [122], no active PD sources.

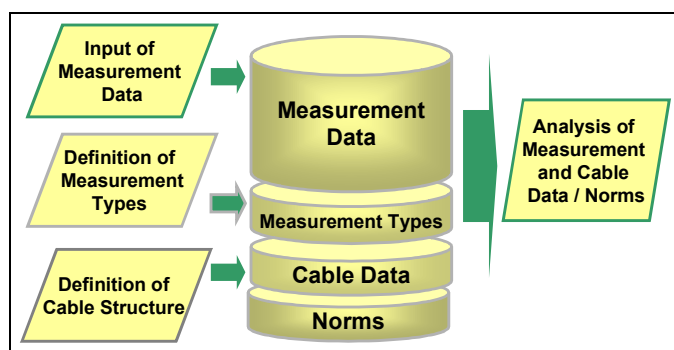


DATABASE FOR CONDITION ASSESSMENT SUPPORT

To support condition assessment of distribution power cables, database systems are needed to manage the data from measurements and inspections. The database for management of measurement data is also used to perform statistical analysis from which knowledge rules and norms can be set. The system as applied for the data collection and analysis in this thesis consists of the following components:

- I. module to input or define the cable data (structure, component types);
- II. module to input measurements;
- III. module for the analysis of the data;
- IV. database to store the data;

Separating the functionality of the system in these four blocks has the advantage that extra modules can be added to store data in or to use data from the database.



The database system should be able to interact with its environment to be functional. To do so, four modules will be implemented as separate software programs, called respectively Definition, Input, Measure and Analyse, as shown in figure C.1.

Figure C.1: Schematic structure of a diagnostics database to support condition assessment of power cables.

To use the system with the diagnostic tool in this thesis, a suitable measurement type has to be defined. From chapter 4 it's known that the diagnostic tool system gives a number of properties. Because the measurement sessions consist of multiple shots at different test voltages, the amount of data to store is very large. The

choice has been made to store only properties at the nominal voltage and at twice the nominal voltage.

Also in the database, the different cable component types can be defined. To each of the cable component types, norms can be assigned for different PD properties. From the different components, the diagnosed cable systems can be added to the database, as shown in figure C.2. All the required information on the cable system can be added. The obtained measurement data are assigned to the individual cable components or to the full cable system.

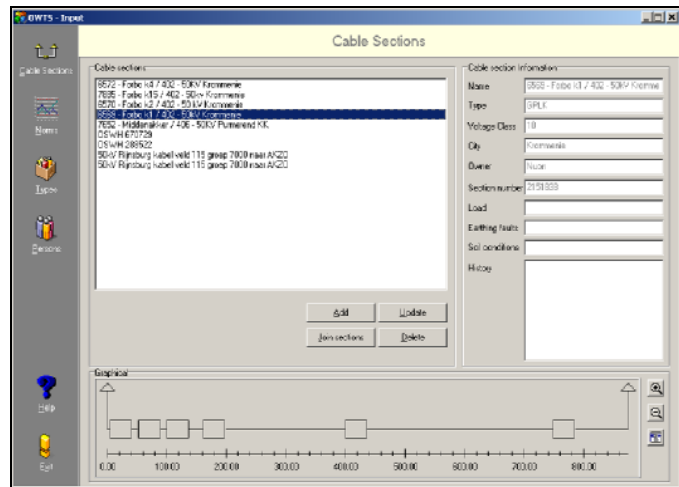


Figure C.2: Screenshot of 'Cable Sections' screen of the application input. The bottom shows a graphical reflection of the selected cable system.

After selection of one of the in the database available cable systems measurements result can be added, removed or updated for the cable system, or for the individual components, as can be seen in figure C.3. On the left, an overview of a cable system is shown where after selection the measurement input can be filled. The analysis of the inserted measurement data is applied for time analysis or type analysis of the measurement data. Because the database can contain a large amount of data, filters can be used to restrict the amount of data for analysis purposes. The analysis can be performed on three different levels: component level, type level and group level. The component view is used to view and analyse the measurement data per component. The type view enables statistical analysis on components of the same type. The group view is used to view and analyse the measurement data on groups of components.

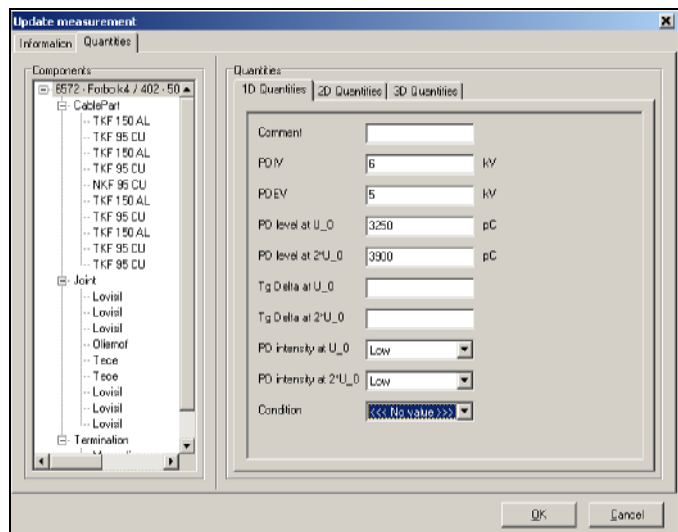


Figure C.3: Measurement add and update screen. On the left an overview of the components in the selected cable system. On the right is the applicable properties and their values are reflected.

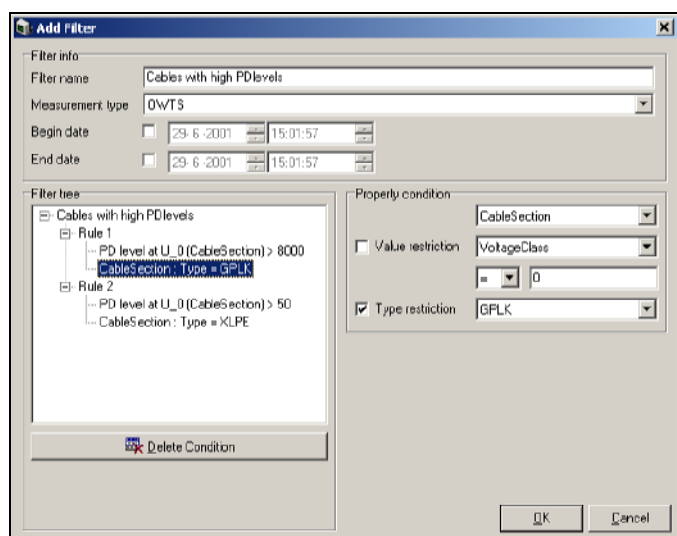


Figure C.4: The dialog for adding and updating a filter. At the top the general filter information is presented, bottom left a tree overview of the filter is shown. Bottom right the selected condition is shown; in this case the condition is a type restriction on cable systems, namely PILC.

A filter is constructed of rules, and rules are constructed of conditions. After selection of the root of the tree, controls appear for adding rules. When a rule is selected, conditions can be added to this rule, or the rule can be removed. One can use the restriction of the value of a property of a component (joint, termination, cable part or cable system), see figure C.4. Expressions can be composed by one or two properties and an operator to restrict the data amount. By combining these data restriction, certain data amounts can be used for analysis purposes. E.g. all cable joint of type A situated in paper oil insulated joints with a PDIV below service voltage.

The analysis on the component level shows the properties which are relevant to the selected component for the different measurement sessions. An output matrix shows the different PD properties of the different measurements. When norms are in use, the elements of the component tree will colour red if they are outside a norm and green if they are inside a norm. This colouring is recursive, so a cable system will colour red, if one of its components is red.

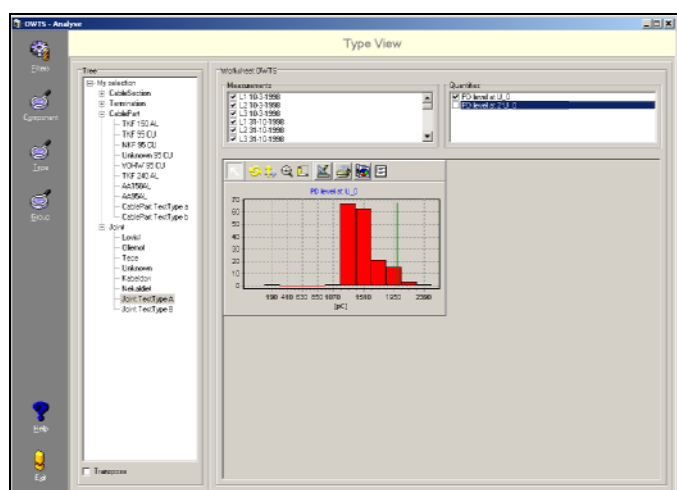


Figure C.5: Histograms created in the type view.

The analysis on type level is used to display statistical analysis of measurement data, as shown in figure C.5. The tree on the left displays the different types of components. Selecting a component type and a PD property will display the histogram of the measurement results that satisfied the filter and are performed on the selected component type. The histogram of the measurement data can also be displayed and exported as a table.

Analysis on group level is used to analyse properties by group. In case of the PD measurement with DAC voltages on cables, the only group available is the cable system. For example, a table can be analysed that shows property values for all the joints in cable system, for one measurement and property.

By using a database as described, the integrity of the collected data is an important issue. What if measurement data in one file or from one measurement session contains information about a cable system and its components? The situation can occur that one of the sub-components will be replaced. Now the measurement data is no longer valid for the new combination of the component and sub-components. If this data stays in the database, it is no longer valid. If this data is deleted, information about the non-replaced components will be lost.

The cable system changes when components are replaced or when the cable system is enlarged with another cable system or divided into two parts. The new cable system is no longer the same cable system as the old one. A new cable system should be entered in the database and the old cable system will be marked as a ‘historic’ and remains in the database. In this way, cable parts, joints or terminations can belong to multiple cable systems in the database. Only one of these cable systems can be the ‘current’ cable system. The other older cable systems must all be ‘historic’.

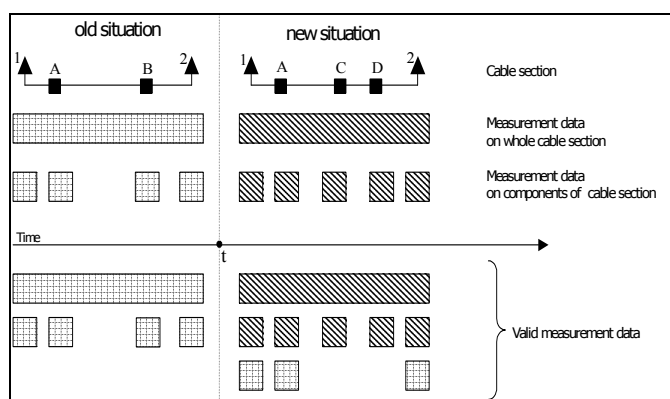


Figure C.6: A cable system in original (left) and modified (right) form, along with its diagnostics data, and the resulting valid diagnostics data. The cable system is modified at time t ; two joints C and D replace joint B, after which not all data on the cable system is still valid. The diagnostic data from cable parts are not shown for simplicity.

By using a reference to its former cable system(s), the history of cable system can be maintained. Because PD property values are linked to the components themselves, the historic data from the components themselves is still accessible from the new ‘current’ cable system. An example of this is shown in figure C.6. At time t , two joints C and D and a short cable part replace joint B. The measurement data on terminations 1 and 2, and joint A is the only that remains valid in the new situation. The date when a cable system became historic should remain stored inside the database to facilitate the ability to view measurement data that only applies to the historic cable.



ECONOMIC ANALYSIS OF CM VERSUS CBM FOR CABLES

Although condition assessment is always interesting from a technical point of view, in modern electricity business the application of diagnostic tools in the practice should be cost effective. Therefore in this paragraph, a comparison of the benefit between corrective maintenance and condition based maintenance, based on PD diagnostics at damped AC voltages is investigated. A description of the diagnostic tool is given in chapter 4.

For corrective maintenance policy, the costs of one failure (C_{CM}) can be calculated by multiplying the power loss due to the failure ($P_{failure}$), the outage time due to the failure ($t_{failure}$) and the claim costs of all customers' connections for non-delivered energy (C_{CC}). Furthermore, the costs for repair of the disturbed component (C_{repair}) should be added:

$$C_{CM} = P_{failure} * t_{failure} * C_{CC} + C_{repair} \quad (D.1)$$

The indicative penalties for non-delivered energy are dependent on the different types of connection to the power network. In most countries, there are standard penalties, determined by the government (as the example in table D-1). Furthermore, liability claims can in most countries be submitted in case of disturbances, where the indicative compensations are for industries is €10 per non-delivered kWh and for households is €1 per non-delivered kWh.

Table D-1: Customer compensation in case of an electricity disturbance of more than 4 hours. This compensation is independent from possible liability claims.

Connection	Customer type	Compensation per connection
$U < 1\text{kV}$	Household	€ 35
$1\text{kV} \leq U < 25\text{kV}$	Small Industry	€ 900
$U \geq 25\text{kV}$	Large Industry	€ 90.000

Condition based maintenance costs (C_{CBM}) can be calculated by summing the costs for switching operation (driving and switching actions) to put the cable system out of service ($C_{switching}$), the cost of the diagnostic measurement ($C_{measurement}$), the writing-off of the diagnostic instrument per measurement ($C_{instrument}$), and the costs of the preventive correction (C_{corr}). Where,

$$C_{switching} = C_{man-hour} * t_{switching}; \quad (D.2)$$

$$C_{measurement} = C_{man-hour} * t_{measurement}; \quad (D.3)$$

and

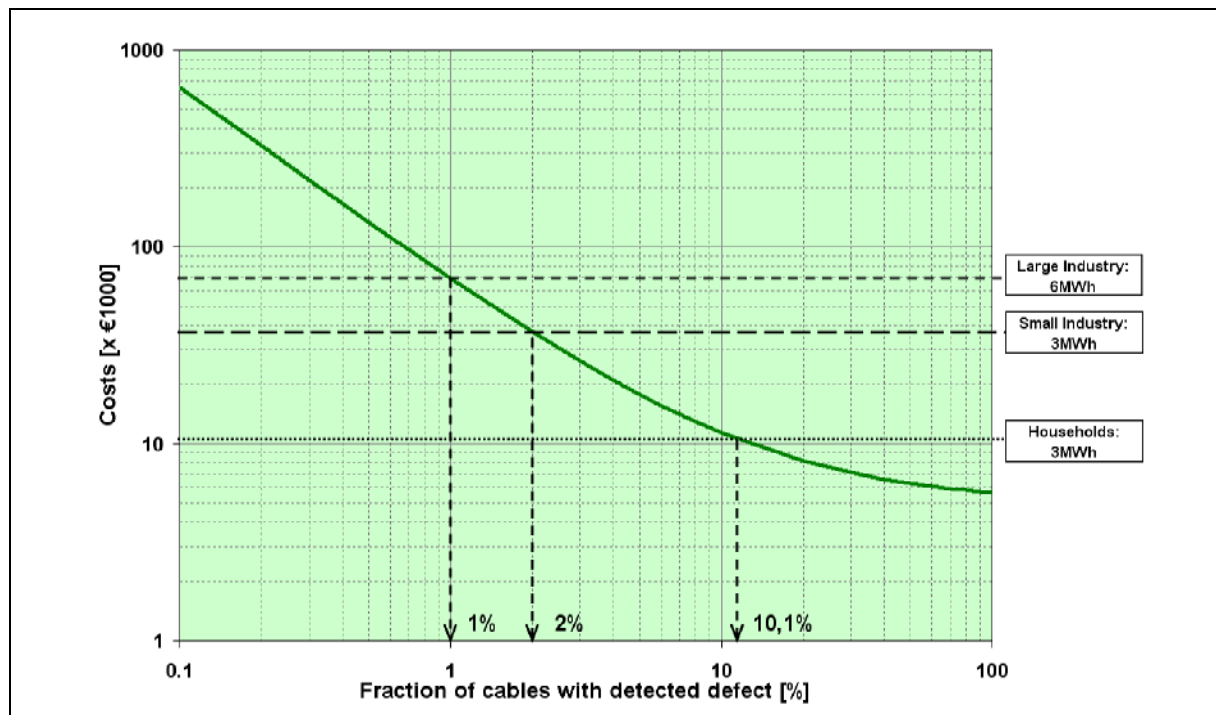
$$C_{instrument} = \frac{C_{purchase}}{T_{amortisation}} * \frac{1}{N_{meas/year}}. \quad (D.4)$$

The effectiveness of a diagnostic tool is dependent on the fraction of (serious) defects to be detected and to be prevented. Therefore, the CBM costs are expressed as a function of the fraction of detected defects (E_{tool}) by the diagnostic tool:

$$C_{CBM}(E_{tool}) = \left(\frac{C_{switching} + C_{measurement} + C_{instrument}}{E_{tool}} \right) + C_{corr} \quad (D.5)$$

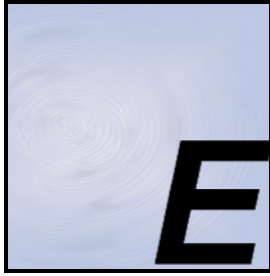
The comparison of the costs of the two maintenance strategies as a function of the number of detected defects is shown in figure D.1. In this example, the costs of corrective maintenance are split into three different connections sizes, for which the typical cable load and time duration of failure are already known on average (non-delivered energy for large industry = 6000 kWh; small industry = 3000 kWh and group of households = 3000kWh). The input data for the equations above are reflected in figure D.1, next to the graph.

The break-even points of the effectiveness of the diagnostic tool can be determined for the different connections. For large industries, the usefulness of strategic application of CBM for power cables is high as compared to the other connections. The break-even point for large industries holds that if in more than 1 out of 100 tested cable systems, a possible failure is detected and prevented, than the diagnostic tool will be cost effective. It is also economically interesting to apply diagnosis in case of smaller industry and households, where the break-even points are respectively 2 and 10%. This shows that for the average cable connection, condition based maintenance is profitable.



$C_{man-hour}$	$t_{switching}$	$t_{measurement}$	$C_{purchase}$	$t_{amortisation}$	$N_{meas/year}$	C_{repair}	$C_{correction}$
€ 70	2 hours	4 hours	€ 65000	5 years	150	€ 7000	€ 2000

Figure D.1: Maintenance costs for CM and CBM as a function of the fraction of cables with detected defects. CM costs are reflected for three types of connection to the network. Break-even points reflect the number of detectable cable defects each 100 diagnosed cables. Input data for the calculations are given.



LABORATORY INVESTIGATION ON REPLACED CABLE JOINT

To find out the origin of the PD activity in the replaced joint of example 2 in chapter 8, and for knowledge collection of the probable cause of the PD activity, the joint was put under further investigation in the laboratory. The removed joint was diagnosed with DAC voltages, and measured in different configurations of the three phases, as is shown in the measurement results of figure E.1. All the measurements in the different configuration showed PD activity around 5000pC in the first cycle of the DAC test voltage. This PD activity is caused by the few meters of cable at both sides of the joint, which were necessary to install terminations for the measurement purposes.

When phase L3 is part of the configuration, another PD activity is detected as well. A re-ignition of the PD occurs at other periods of the voltage cycles. The re-ignition is occurring at test voltage of $1.3 * U_0$. This inception voltage is higher than the PDIV, which occurred during the measurements in the field. The PDEV of the PD source in phase L3 is around U_0 , as is shown in figure E.2. The obtained PD amplitude level in the laboratory is in the same order as those obtained in the field, much more than 10000pC. The PD pattern is asymmetric, and present in the 1st and 3rd quadrant, which tells us that either internal PD in electrode bounded cavities or surface discharges are related to the defect [69].

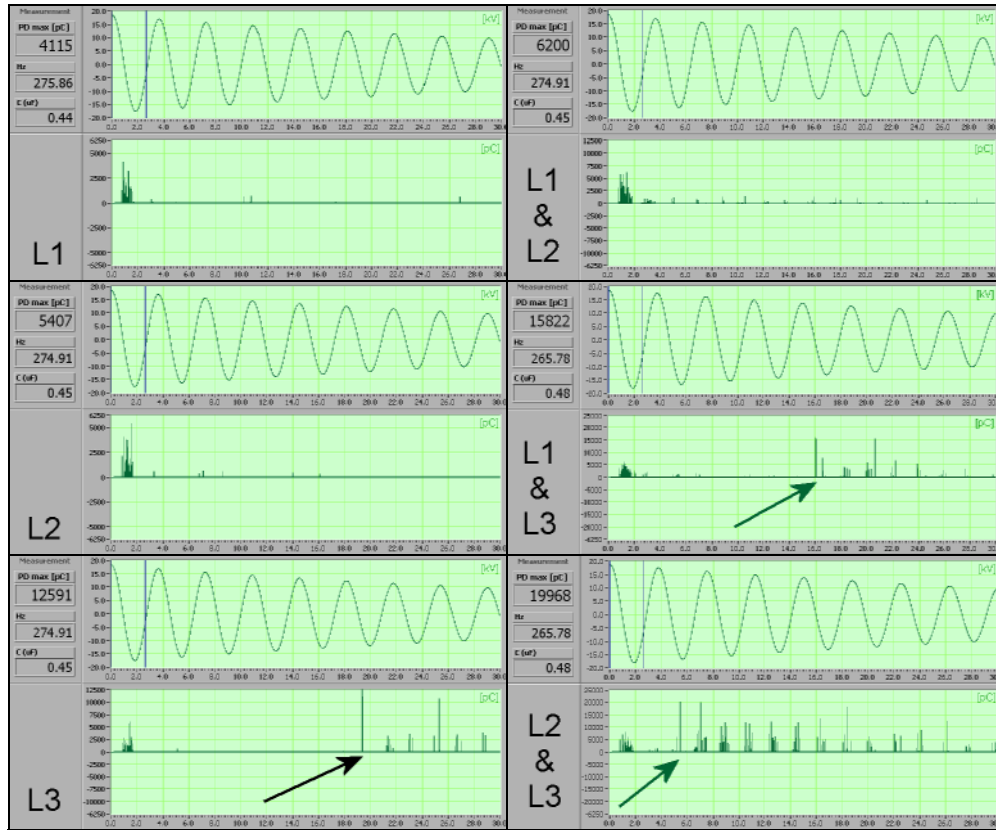


Figure E.1: Measurement results, obtained from joint 7 at test voltages of 18kV. When phase L3 is part of the measurement configuration, a re-ignition of PD takes place in a later voltage cycle of the DAC voltage. It can be concluded that a PD source is located in phase L3.

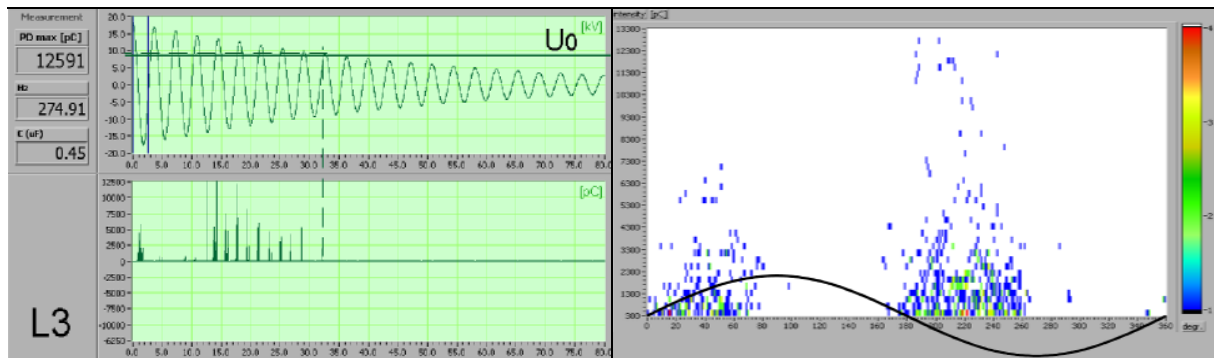


Figure E.2: Phase resolved PD patterns obtained from the measurement result of joint 7.

As a result of the result from the measurements on the joint, the sample was opened for investigation. The analysis for forensic evidence showed that the oil level in the joint was decreased. An under-pressure, as a result of the oil diminution by the cable parts in the field, was not present at the opening. This is most probably the reason that the inception voltage of the joint has increased as compared to the field measurement. After the dismantlement of the joint's

housing, it showed that in the upper phase PD activity has occurred between the conductor connection and the lead sheath, as shown in figure E.3.

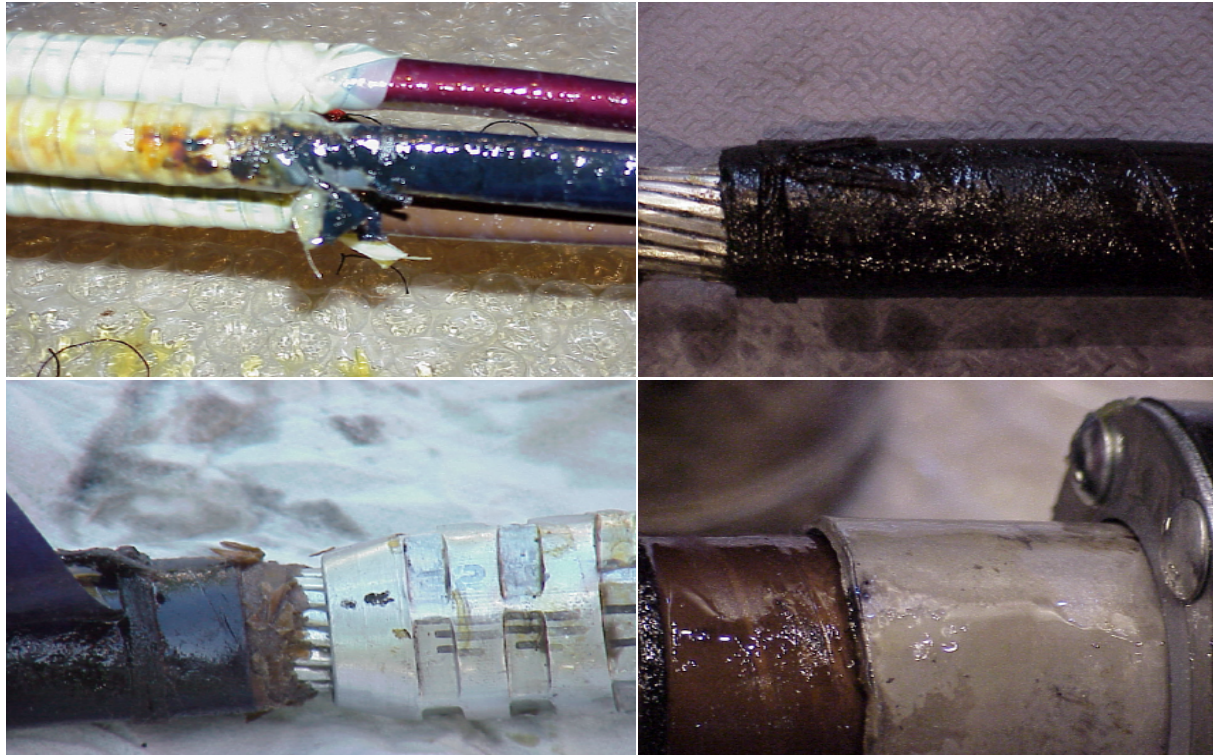
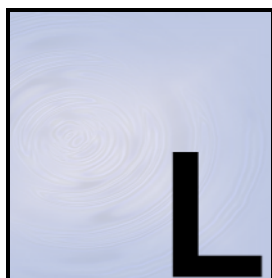


Figure E.3: Forensic evidence of the PD activity in the investigated cable joint. Carbonised parts are found on the surface of the paper insulation of the upper situated phase, as a result of surface discharges between the conductor and the earth sheath due to decreased oil level.

Clear carbonised oil parts are visible on the surface of the paper insulation. As a result of the fibre sheets around the different conductor connections, the carbonised oil parts are concentrated on the conductor insulation.



LISTS

LIST OF ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
AC	Alternating Current
AM	Asset Management
CBM	Condition Based Maintenance
CDF	Cumulative Distribution Function
CIGRÉ	Conseil International des Grands Réseaux Électriques International Council on Large Electric Systems
CM	Corrective Maintenance
DAC	Damped Alternating Current
DC	Direct Current
EM	Electromagnetic
HF	High Frequency
HV	High Voltage (transmission level)
IEC	Commission Electrotechnique Internationale International Electrotechnical Commission
LV	Low Voltage
mrd	Maximum Relative Deviation
MV	Medium Voltage (distribution)
OWTS	Oscillating Wave Test System
PD	Partial Discharge
PDEV	Partial Discharge Extinction Voltage
PDF	Probability Density Function
PDIV	Partial Discharge Inception Voltage
PDLav	Average PD level
PDLmax	Maximum PD level

PDOF	Partial Discharge Occurrence Frequency
PILC	Paper Insulated Lead-sheathed Cable
ppm	Parts Per Million
PVC	Poly Vinyl Carbonide
S/N	Signal to Noise
SA	Spectrum Analyser
SI	Switching Impulse
TBM	Time Based Maintenance
TDR	Time Domain Reflectometry
TEM	Transverse ElectroMagnetic
TF	Task Force
VHF	Very High Frequency
VLf	Very Low Frequency
WG	Working Group
XLPE	Cross-Linked PolyEthylene

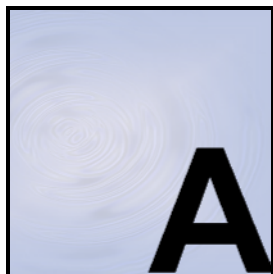
LIST OF SYMBOLS

C	Capacitance
D_b	Cavity diameter
DL	Dielectric Losses
E	Electric field
f	Frequency
G	Dielectric conductivity
kV_{peak}	Peak value of the voltage in kV
kV_{rms}	RMS value of the voltage in kV
l	Length of cable system
l_N	Length of cable part N
L	Inductance
m_n	Mean of a distribution
q	Discharge magnitude
Q	Quality factor
q_0	Weibull scale parameter
q_i	Magnitude of discharge i
R	Resistance
t_{ch}	Charging time
U_0	Nominal phase-to-earth voltage
U_N	Nominal phase-to-phase voltage
U_{inc}	Relative inception voltage
u_{pd}	PD voltage pulse
v	Propagation velocity for PD waves
v_{AV}	Average propagation velocity
x_i	Location of PD event i

Z	Impedance
Z_0	Characteristic impedance
α	Attenuation factor for PD wave
α_{DAC}	Quality factor of DAC system
β	Phase constant for PD wave
β_{DAC}	Damping factor of DAC voltage
γ	Propagation constant
Δt	Time difference (between incident and reflected pulse)
Δt_{cal}	Propagation time of twice the cable system length
Δt_N	Propagation time of twice the length of cable part N
ΔV	Voltage drop as a result of a discharge
ε_0	Permittivity of vacuum
ε_r	Relative permittivity
η	Weibull shape parameter
λ	Wave length
μ_r	Relative permeability
ξ	Average number of events in a Poisson distribution
σ_s	Surface conductivity
τ_{cd}	Deposited surface charge time constant
Φ_i	Phase angle

LIST OF UNITS

C	Coulomb
eV	Electronvolt
F	Farad
H	Henry
Hz	Hertz
kWh	Kilowatt-hours
m	Meter
N	Newton
s	Second
S	Siemens
V	Volt
Ω	Ohm



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SAMENVATTING

CONDITIEBEPALING VAN ENERGIEKABELS DOOR ONTLADINGSDIAGNOSE MET GEDEMPTE WISSELSpanningen

Dit proefschrift focust op de conditiebepaling van één van de meest uitgebreide delen van het energievoorzieningsstelsel: het distributiekabelnetwerk. Distributiekabels hebben een kritische functie in de regionale verspreiding van elektrische energie. De meerderheid van de energieonderbrekingen vindt plaats in dit distributiekabelnetwerk. De faaloorzaken in kabelsystemen zijn voor meer dan 60% gerelateerd aan interne defecten, terwijl het overige deel is gerelateerd aan externe invloeden.

Aan de hand van de analyse van veel voorkomende defecttypen in de verschillende isolatiematerialen en hun degradatieprocessen kan de materiaalveroudering in kabelsystemen worden gecategoriseerd in vier lokale degradatieprocessen, die allen gerelateerd zijn aan deelontladingen. Daarmee is aangetoond dat de ontladingskenmerken gevoelige parameters verschaffen over degradatieprocessen, waarvan de waarden kunnen worden toegepast in preventieve metingen.

Distributiekabelnetwerken zijn ondergronds, waardoor de enig mogelijke rechtstreeks fysieke toegang tot een kabelstelsel via de eindsluitingen in de onderstations is. Elektrische detectie is daarom praktisch gezien de belangrijkste mogelijkheid voor het toepassen van diagnostiek, bijvoorbeeld ontladingsdetectie. Met behulp van ontladingsdiagnostiek kunnen de defecten worden gelokaliseerd in een bepaalde component van het kabelstelsel. De locaties van de ontladingsbronnen in een kabellengte kunnen worden geanalyseerd met behulp van “time domain reflectometry”, waarbij gecompliceerde signaalinterpretaties noodzakelijk kunnen zijn.

Voor kabelsystemen, opgebouwd uit meerdere isolatietypen, kan de standaard lokalisatieprocedure resulteren in een systematische afwijking in de correcte locatie

van ontladingsbronnen. Tengevolge van de verschillende voortplantingssnelheden in de verschillende isolatiematerialen kan deze afwijking enkele procenten van de totale kabellengte zijn. De afwijking in de ontladingslocatie is sterk afhankelijk van de verhoudingen in lengtes van en voortplantingssnelheden in de verschillende kabeldelen. Dit proefschrift geeft oplossingen voor het maken van de correcte lokalisatieanalyse in deze gemengde kabelsystemen en voor het corrigeren van een foute locatieanalyse.

De haalbaarheid van een laagbelastende ontladingsdiagnostiek, gebaseerd op gedempte wisselspanningen (tijdelijke geleidelijk dalende wisselspanning t.g.v. een spanningsoscillatie in een resonant circuit) is in dit proefschrift onderzocht. De ontladingsdetectie kan worden uitgevoerd gedurende de tijdelijke, dempende wisselspanningen met een duur van 100-200ms en met spanningsfrequenties in het bereik van 100-500Hz. In dit proefschrift is aangetoond dat dit een effectieve belastingsmethode is voor kabelisolatie ten behoeve van ontladingsdetectie. Het compacte en lichtgewicht meetstelsel resulteert in het veld in een laag ruisniveau en een hoge detectiegevoeligheid voor ontladende defecten, zowel voor papier als polymeer geïsoleerde kabelsystemen.

De effecten van verschillende testspanningen op ontladingsactiviteiten zijn onderzocht. Verscheidene defectmodellen zijn met 50Hz wisselspanning, gedempte wisselspanningen met verschillende frequenties en 0,1Hz spanningen gemeten om de ontladingsactiviteit te bestuderen. De invloed van vorm en frequenties van testspanningen zijn mede op distributiekabels in het veld geëvalueerd. Aangetoond is dat de grootte van de ontladingsparameters bij gedempte wisselspanningen in overeenstemming zijn met degenen verkregen bij conventionele continue wisselspanning voor verschillende typen defecten.

Kennisregels zijn ontwikkeld voor de conditiebepaling van de verschillende isolatiesystemen. Vastgesteld is dat statistische analyses van grote hoeveelheden van meetgegevens een doeltreffende en betrouwbare methode is om ervaringsnormen voor conditiebepaling af te leiden. De verschillende eigenschappen van ontladingen hebben betrekking op verschillende aspecten van de conditie van een kabelstelsel en zijn garnituren. De gewogen combinatie van de meerdere kennisregels resulteert in een methodologie voor het maken van beslissingen om kabelsystemen optimaal in stand te houden. Praktische toepassingen van het beslissingscriteria-model zijn geëvalueerd op basis van kwaliteitscontrole, reductie van risico en betrouwbaarheidsverbetering.

Ten slotte, als spin-off van dit onderzoek aan gedempte wisselspanningen, is geparticipeerd in de industriële ontwikkeling van een nieuwe gedempte wisselspanningsgenerator voor ontladingsdetectie en lokalisatie aan hoogspanning transmissiekabelsystemen.

F.J. WESTER



ZUSAMMENFASSUNG

ZUSTANDSBESTIMMUNG VON ENERGIEKABELN DURCH TEILENTLADUNGSDIAGNOSE MIT GEDÄMPFTEN WECHSELSPANNUNGEN

Diese Dissertation konzentriert sich auf die Zustandsbeurteilung eines der dezentralisiertesten Teile des Spannungsversorgungssystems: dem weitverzweigten Energiekabelnetz. Die Kabel haben eine sehr wichtige Funktion in der regionalen Verteilung der elektrischen Energie. Die Mehrheit der Störungen im Energienetz hängen mit dem weitverzweigten Kabelnetz zusammen. Die Gründe für die Ausfälle in den Kabelsystemen sind zu über 60% auf interne Defekte zurückzuführen, während die restliche Fehlerrate im Zusammenhang mit externen Einflüssen steht.

Wenn man die am häufigsten auftretenden Fehlerarten und die Degradationsprozesse unterschiedlicher Isolierungen analysiert, kann die Materialalterung des Kabelnetzes in vier lokale Degradationsprozesse unterteilt werden, welche alle mit Teilentladungen zusammenhängen. Daraus resultiert, daß die Teilentladungscharakteristiken sensitive Parameter reichen über die Alterungsprozesse und es somit möglich ist, präventive Messungen zu machen.

Da die Kabelnetze unter der Erde verlegt sind, liegt der einzige direkte physikalische Zugang zum Kabelsystem an den Endpunkten der Strecke. Die elektrische Ortung ist deshalb die einfachste Möglichkeit für eine Diagnose, z.B. Teilentladungsmessung. Mit dieser Diagnose (TE) können die Isolationsfehler punktgenau spezifischen Komponenten des Kabelsystems zugeordnet werden. Die Ortung der Teilentladungen entlang der Kabellänge kann durch Zeitbereich Reflektometrie analysiert werden. Die genaue Interpretation dieser TE-Signale ist teilweise sehr komplex.

Für stromführende Kabelsysteme, bestehend aus unterschiedlichen Isolierungen, kann ein standardmäßiges Auswertungsverfahren systematische Abweichungen der

korrekten TE-Ortung ergeben. Wegen der unterschiedlichen Ausbreitungsgeschwindigkeiten in den Isolationsmaterialien, kann diese Abweichung mehrere Prozente betragen und ist von den Verhältnissen der Längen und der Laufzeitgeschwindigkeiten der verschiedenen Kabelteile abhängig. Diese Dissertation zeigt einen Weg auf, wie bei Kabelsystemen mit unterschiedlicher Isolation diese Lokalisationsfehler mit einer korrekten Analyse behoben werden können.

Die Machbarkeit von energiearmer Teilentladungsdiagnostik mit Hilfe von gedämpften LC-Schwingkreisen wurde erforscht. Spezifische Meßsysteme sind bereits entwickelt worden welche die Teilentladungen detektieren während der gedämpften Sinusschwingung von 100-500Hz während 100-200ms. Es ist in dieser Dissertation aufgezeigt, daß die Methode mittels erregtem Schwingkreis sehr effizient ist und sich sehr gut für die Teilentladungsmessung eignet. Das kompakte und leichte Meßsystem weist einen tiefen Meßgeräuschpegel und eine hohe Empfindlichkeit auf, im Bereich von Entladungsdefekten bei imprägnierten Papier- und Polymer-Kabeln.

Die Einflüsse von unterschiedlichen Testspannungen auf das Teilentladungsverhalten sind erforscht. Mit der 50Hz AC Methode, gedämpften Sinusschwingungen mit unterschiedlichen Frequenzen und der 0.1Hz Methode wurden verschiedene Prüflinge mit Fehlern auf das Teilentladungsverhalten untersucht. Auch wurde der Einfluss der Testspannungsform und der Frequenz an Kabeln im Feld verifiziert. Diese Dissertation zeigt auf, daß die Meßwerte der Teilentladungen mit der Methode der gedämpften Schwingung in hohem Grade vergleichbar sind mit den herkömmlichen Wechselspannungsmethoden bei unterschiedlichen Prüflingen.

Außerdem sind Richtlinien für die Zustandseinschätzung der unterschiedlichen Isolations-Systeme entwickelt. Resultierend aus statistischer Analyse großer Mengen von Meßdaten, ist eine wirkungsvolle und zuverlässige Methode zum bestimmen der Zustandseinschätzung abgeleitet worden. Die verschiedenen Teilentladungseigenschaften beziehen sich auf unterschiedliche Aspekte des Zustandes eines Kabelsystems und seiner Garnituren. Die gewichtete Kombination der verschiedenen Wissensregeln, resultiert in einer Methodenlehre zur Entscheidungsfindung für die Instandhaltung der Kabelsysteme. Auf Basis der Entscheidungskriterienmethode, wurden unterschiedliche praktische Anwendungen auf Qualitätskontrolle, Risikoverringung und Zuverlässigkeit hin überprüft.

Als Resultat dieser Arbeit auf dem Gebiet der gedämpften Wechselspannungen, ist als Spin-Off die industrielle Entwicklung eines neuen auf dieser Basis funktionierenden Spannungsgenerators zur Messung von Teilentladung und der Fehlerortung an Hochspannungskabeln in Auftrag gegeben worden.

F.J. WESTER

FRANK J. WESTER WAS BORN ON MAY 18TH, 1972 IN THE NETHERLANDS. HE STUDIED ELECTRICAL ENGINEERING AT THE 'HOGESCHOOL ALKMAAR' FROM 1991 UNTIL 1995. IN 1998, HE RECEIVED HIS MASTERS DEGREE IN ELECTRICAL ENGINEERING AT DELFT UNIVERSITY OF TECHNOLOGY. SINCE 1998 HE IS EMPLOYED AT NUON NV, AN ENERGY UTILITY IN THE NETHERLANDS, AS A DIAGNOSTIC ENGINEER AND LATER AS A CONSULTANT, PERFORMING RESEARCH IN THE FIELD OF ON-SITE CABLE DIAGNOSTICS IN COOPERATION WITH THE DEPARTMENT OF HIGH VOLTAGE TECHNOLOGY & MANAGEMENT AT THE DELFT UNIVERSITY OF TECHNOLOGY, FROM WHICH THIS PH.D. THESIS IS THE RESULT.

