OPTIMIZATION OF ON-SITE PD MEASUREMENTS AND EVALUATION OF DIAGNOSTIC PARAMETERS FOR ASSESSING CONDITION OF DISTRIBUTION CABLE SYSTEM

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ABSTRACT

Distribution power network is one of the largest assets in the power network. Distribution power network can be established in two ways: with overhead lines (or overhead cables) and with underground power cables. Nowadays the tendency of construction distribution power network is more to underground cables, especially in big city like Jakarta where 85 % of the total distribution power networks are underground power cables.

Reliability and availability of a power network is determined by the condition of all components in that power network. Distribution power as one of its components is also involved to determine the reliability and ability of the power networks. Due to the fact that more than half of the breakdowns in distribution power network are caused by internal fault in the insulation systems or accessories, diagnostics of distribution power cable are very important to prevent such breakdowns and get knowledge about actual condition of particular system. By knowing the condition of the cable, the early action can be done before the breakdown occur during operation.

One of the most popular PD diagnostic for distribution power cable is off-line PD diagnostic using Oscillating Wave Test System (OWTS). This system is very powerful measurement and very sensitive measurement. Many parameters can influence the quality of the measurement and several problems can occur during performing PD measurement.

In this study, several parameters which can influence the quality of the measurement are presented. This study also presents several problems that are obtained during performing PD measurements based on experiences obtained by PT PLN (Persero) Distibusi Jakarta Raya & Tangerang and the experiences of PD measurement in German. Guidelines procedures are proposed in order to minimize the problem and to provide an optimal use of OWTS system for condition assessment of distribution power cables.

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CHAPTER 1

Introduction

1.1. Distribution Power Cable Network

Distribution power network is one of the largest assets in power network. The main purpose of distribution power network is to distribute the energy from the sub-station to the customers. In figure 1.1 an example of power network can be seen where distribution network is one of important part. Distribution power networks can be provided in several voltage levels in the range of 1 kV up to 36 kV.

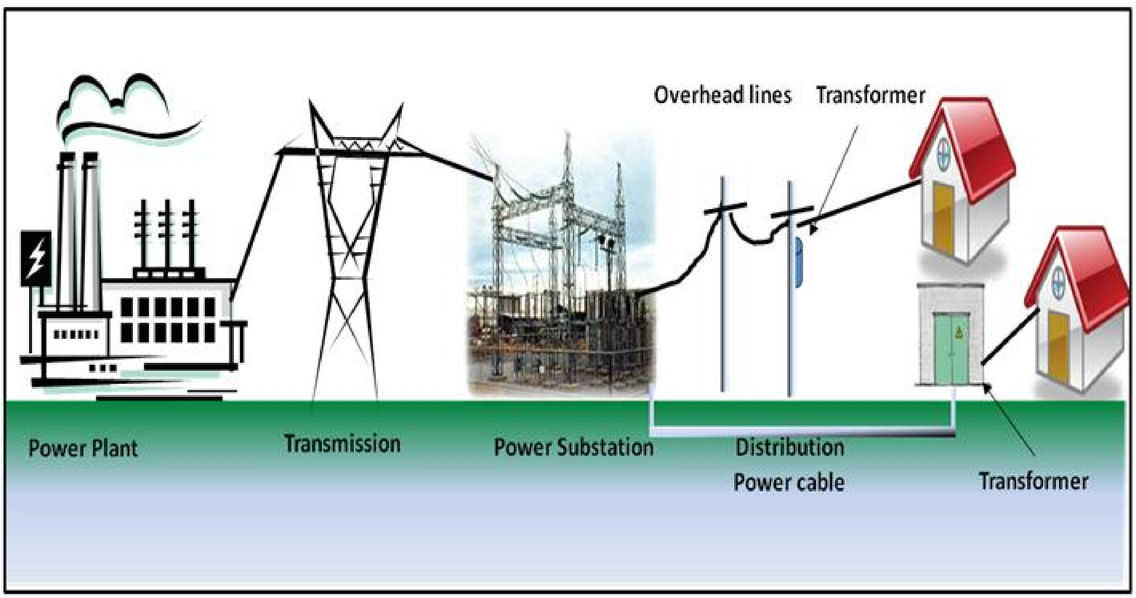


Figure 1.1: Distribution lines as one part of power network.

There are two ways to construct the distribution power network: with overhead lines (or overhead cables) and underground power cables. The distribution networks with overhead lines were mainly used in the early days of electrification. Nowadays underground power cables usually used in big city whereas overhead lines are preferred in electrification of rural area.

From an investment-cost point of view, overhead lines are favourable. However, regarding urbane space availability, aesthetical and environmental considerations, safety issues, regulation and technical matter underground power cables can have the advantages [1]. In contrast to investment cost from an operation-cost point of view, underground power cables more competitive because maintenance-cost for underground power cables are relatively low compare to overhead lines.

In Jakarta, Indonesia, the electricity is provided by PT PLN (Persero) Jakarta Raya & Tangerang. The distribution power networks in Jakarta are installed in 20 kV voltage level. PT PLN (Persero) Jakarta Raya & Tangerang has 10,056 kilometers length underground cables and it is about 85 % of the total length of the distribution networks in Jakarta [2]. The major part of the distribution cable network consists of XLPE insulation, but during the past period, belted-type paper insulated lead cable was commonly used.
Table-1.1 describes the total length of the medium voltage distribution network in Jakarta in 2004.

Table 1.1: Total length of medium voltage distribution power network in 2004 [2]

Distribution Network Area	Underground Cables [km]	Overhead lines [km]	Total Length [km]
Gambir	2,879	46	2,925
Kebayoran	1,794	105	1,899
Kramatjati	2,653	65	2,718
Tangerang	2,731	1,569	4,300
Total Length	10,056	1,785	11,842

Several regulations issued by Regional Government of Jakarta which stated that PT PLN (Persero) Jakarta Raya & Tangerang is not allowed to build new distribution network with overhead lines. The only way to build new distribution network is by constructing medium voltage network using underground cable. From this condition it can be concluded that the need of the underground cable network will increase in the future.

The reliability and availability of the total power network are strongly influenced by the distribution power cables. In general, the distribution power cable is responsible for the major part of the outage in a power network. Table 1.2 represents the failure statistics of power network in Jakarta in 2004. It shows from table 1.2 that more than 70 % of the frequent interruption in power network was contributed by failures in the distribution power lines and 53 % of the duration outage was contributed by the distribution power lines. From number of failure, it can be seen that overhead lines contribute more than underground cable, while from the duration outage the underground cables contributed more than overhead lines. It can be conclude that failure in the underground cables need longer times to recovery than failure in overhead lines.

Table 1.2: Failure statistics of power network in Jakarta 2004 [2]

	Description	SAIFI*) (times/cust/year)	(%)	SAIDI**) (Minutes/cust/year)	(%)
A.	**Interruption caused by failure**				
1	Customer connection	0,07	1,12	10,52	3,16
2	Low voltage lines	0,11	1,86	7,37	2,22
3	Transformer	0,39	6,40	37,71	11,34
4	Medium voltage lines (Overhead)	3,02	49,64	85,21	25,62
5	Medium voltage lines (underground)	1,40	23,10	92,81	27,91
6	Transmission system	0,58	9,57	27,99	8,42
7	Disasters	0,02	0,25	6,37	1,92
B	**Planned Interruption (Maintenance)**	0,49	8,06	64,55	19,41
	Total	**6,08**	**100**	**332,54**	**100**

**) SAIFI = System average interruption frequency index (times per customer)*
***) SAIDI = System average interruption duration index (minute per customer)*

1.2. Partial Discharge Diagnostic for Power Cables

As described in the previous section, the failure in underground cables is responsible for the major part of interruption in power network in Jakarta. In general, failure in underground cables can be influenced by external and internal failure. External failure is caused by external influences of non electrical nature such as digging activities or by the movement of the soft wet soil. External failure can be reduced by further optimization of communication between companies with underground network and regulator for network-laying registration.

Internal failure is related to defect in the cable insulation or in the accessories of the cable system. Internal failure contributed the major part of interruption in underground cables. Strategic maintenances have to be implemented in medium voltage lines especially in underground cables to reduce interruption in power system. The strategy is focus more to the internal failure as a major part of causes in interruption in power cables.

Partial discharges (PD) are considered as one of indication of possible discharging weak spots in cable insulation that may eventually lead to failure in the cable system. The detection, location and recognition of partial discharges at an early stage of possible insulation failure are great importance for maintenance purposes [1]. Maintenance can be planned based on result from PD diagnostics to prevent interruption caused by breakdown failure in underground cables.

PD diagnostics can be performed in two ways: on-line and off-line PD diagnostics. In on-line PD diagnostics, the cable system remains in service during measurements.

In this way active PD sources which are active and detectable under the service condition can be recorded.

In off-line PD diagnostics, measurements are performed after the cable system is disconnected from the voltage network. An external supply voltage is used to energize the cable system at different voltage levels e.g. up to 1.7Uo and in this way the PD sources related defects ignited and recorded.

In this thesis the PD diagnostic data used for analysis was obtained from off-line PD measurements with DAC (damped AC voltages) performed by PT PLN (Persero) Distribusi Jakarta Raya & Tangerang and the experiences of PD diagnostics in Germany.

This PD diagnostics provides most powerful information about diagnostics data as obtained from on-site inspections. More than 100 utilities around the world also use this method, so called OWTS method (Oscillating Wave Test System), to determine the condition of medium voltage distribution networks. PT PLN (Persero) Jakarta Raya &

Tangerang is one of company which used this method to determine the condition of their medium voltage distribution networks.

1.3. The Problem Definition

The quality of the information as obtained by on-site PD diagnosis of power cables depends on several factors. As compared to other on-site tests e.g. voltage withstand tests the application of PD diagnosis is more complex. In particular due to complexity of PD processes on one hand and diversity of on-site conditions several aspects have to be taken in to account to provide high quality of the diagnostic results.

Based on experiences which obtained by PT PLN (Persero) Distribusi Jakarta Raya & Tangerang and the experiences of measurements in German, several problems have been observed during performing measurements.

In addition to manufacturer information as given in the user manual and referring to international literature about 70 positions have been published about the analysis of measuring data there is no practical guideline available till now.

In order to minimize the problems in performing PD measurement on the one hand and to provide an optimal use of OWTS MV technology for condition assessment of MV power cables PD diagnosis a practical guideline is needed.

Such guidelines are developed to sup port the users to perform a good PD measurement in the following procedures:

1. Object definition

   Completeness of relevant information about object test strongly influences the accuracy of interpretation of PD data. Lack of information about components will result in difficulty and ambiguity in interpretation of PD data. To increase the accuracy of interpretation of PD data, relevant information about object test should be clearly defined.

2. Calibration

   Prior to measurement test, calibration performed to calibrate PD reading and PD propagation velocity. Several problems may be obtained during performing calibration (e.g. poor reflection, high background noise, wrong connection, etc).

Performing one range calibration is also one of problem that may influence the quality of the whole measurement.

3. Measurement test procedure

   During performing measurement several voltage level and numbers of measurement should be applied to the system. Selection of test voltage levels in combination of the number of voltage excitations is always an issue in getting sufficient and representative measuring data. Appropriate PD range has to be selected in order to ensure the system can detect maximum PD level. Problems are found when PD range selected is lower than PD maximum level or PD range selected is extremely higher than maximum PD level.

4. Data Collection and Analysis

   Data obtained from measurement are collected and stored in the measurement tool. Based on these data, to describe the PD processes in a cable section several parameters can be evaluated. The selection of the most important ones is very crucial to obtain optimal information.

   To present the PD occurrence along the length of cable, PD mapping is performed by using TDR (Time Domain Reflectometry) analysis. The quality of the PD mapping is determined by the accuracy in selection of the matching original pulse and reflected pulse. Problems may be found in matching original pulse and reflected pulse.

5. Condition assessment

   Based ion the analysis as given in point 4 test report has to be generated. Moreover using such a report has to provide a good basis for conclusions about the actual condition of tested power cable section. Also this information has to be able to be used in further asset management related decision processes.

1.4. Objective of this study

The objective of this study is to observe the effects of the problems which obtained during performing PD measurement on the quality of measurement. Guidelines are proposed to improve the quality of PD measurement. The Guidelines is developed to support the users to perform a good PD measurement in the following procedures:

- Object definition

- Calibration test procedure
- Measurement test procedure
- Data Collection and Analysis
- Condition assessment

1.5. Thesis Layout

This thesis is described in several chapters; Chapter 2 presents Partial Discharges Occurrence, different types of PD sources in the power, measurement methods and the advantages of using OWTS system cable. Chapter 3 explained the importance of object definition, cable system and its accessories to obtained good measurement. Chapter 4 describes the problem in performing calibration test. Chapter 5 presents measurement test procedures. Problems during performing PD measurement and its proposed solution are provided in this chapter. In Chapter 6, Data collection and analysis from measurement test and performing PD mapping is describes. The problem and proposed during performing PD mapping and its solution are presented in this chapter. Chapter 7 represent condition assessment PD. Chapter 8 provides the conclusions of this study and recommendation for future research is made.

CHAPTER 2

Partial Discharges Occurrence in Power Cable

Partial discharges defined in IEEE Standard 400.3™ 2006 as small electric sparks or discharges that occur in defects in the insulation, or at interfaces or surfaces, or between a conductor and a floating metal component (not connected electrically to the high voltage conductor nor to the ground conductor), or between floating metal components if the electric field is high enough to cause ionization of the gaseous medium in which the components are located. The discharges do not completely bridge the insulation between conductors, and the defects may be entirely within the insulation, along interfaces between insulating materials (e.g. at accessories) or along surfaces (terminations) [3].

2.1 Ageing mechanism in power cable

Partial discharges in a power cable mostly occur in defect in the insulation or in the accessories of the cable system. Defect in the insulation cable system or in accessories of cable system can occur due to influence of several ageing factors. These ageing factor divided into four basic ageing factors; thermal, electrical, mechanical and environmental factor [4]. These factors generate ageing process/mechanism in a cable system and these mechanisms may eventually lead to a cable failure.
Figure 2.1 shows the basic factor and ageing mechanisms of power cable system. An aging process/mechanism could be generated by different factors and an aging factor can also generate difference mechanisms [5].

During ageing, influences of stresses, which initially do not affect the insulation system can become ageing factor and result in further degradation. These stresses can be differentiated in three categories; operational stresses, environmental stresses and human handling.

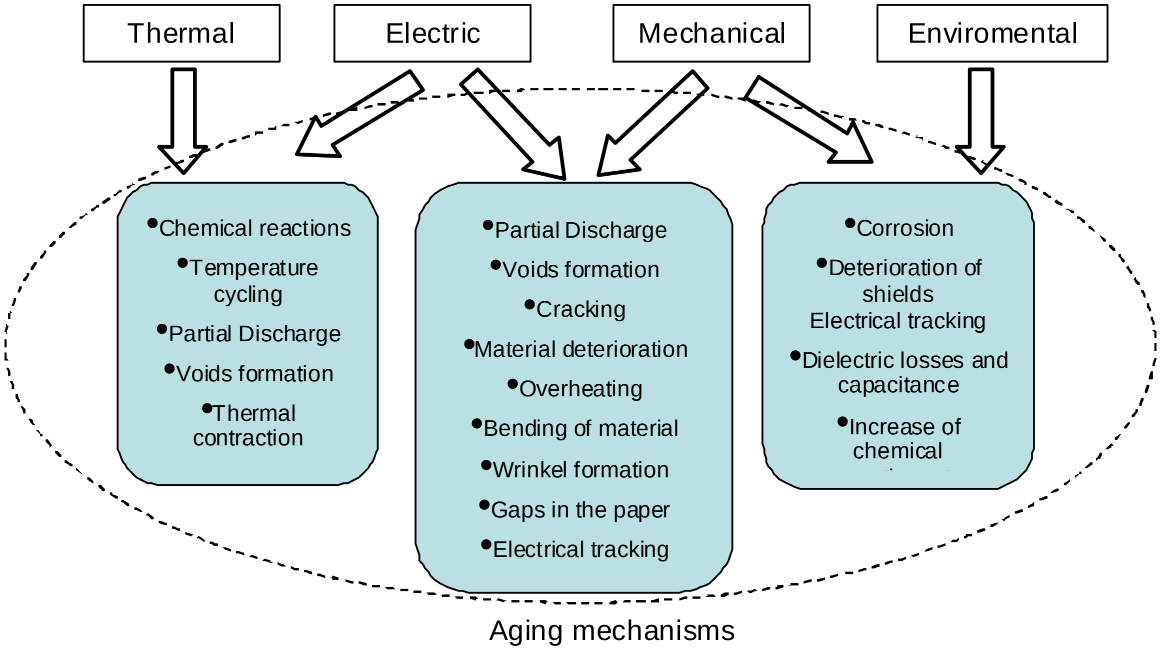


Figure 2.1: basic factor and aging mechanisms of power cable system [5]

Operational stresses occur during normal or extensive service condition such as load cycle or e.g. high temperature. Environmental stresses are produced by acting of such medium as: water, gases, acids, chemicals etc. It has large influence on introduction of defects in the insulation. The example of environmental stresses are; water/humidity, ground pollution and mechanical stresses. Human handlings result from inaccuracy during installation of new cable system or during fixing a cable accessory of the cable system. Small defects during installation or assembling procedure 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 workmanship [6].

2.2 PD Occurrence in Power cable

In general, partial discharges can be classified in four types: internal discharges, surface discharges, corona discharges and electrical trees [7,8,9]. Figure 2.1 shows four types of partial discharge.

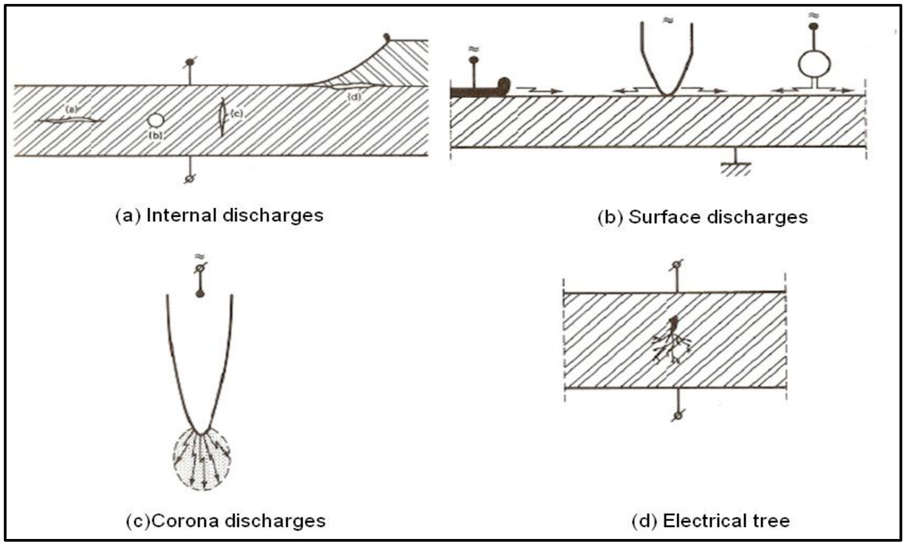


Figure 2.2: Types of partial discharges [7].

Internal discharges occur in the cavity bounded by insulating material as can be seen in figure 2.2 (a). Usually the cavity is filled by gas or oil which has lower dielectric strength than insulation material. There are four examples of internal discharges:

- Flat (or disc-shape) cavity parallel to the electrodes
- Spherical cavity
- Fissure perpendicular to the electrodes
- Fissure perpendicular to the electrodes

The breakdown strength in the cavity depends on its dimension and governed by the type of gas and the gas pressure in the cavity [7].

Surface discharges occur along dielectric interface where a substantial tangential field is present. Examples of surface discharge are shown in figure 2.2(b). Surface discharges can occur in bushings, ends of cables, overhang of generator where the discharge from outside touches the surface.

Corona dischargers are discharges in gases (or liquid) caused by locally enhanced field from the sharp point of electrodes. Corona discharges may be found at the high voltage electrode, but they can also be found at the earthed side or half-way between electrodes. Figure 2.2 (c) depicts the occurrence of corona discharges. Corona discharge does not depend on the distance between electrodes because discharges occur by the field concentration at a sharp edge.

The process of electrical tree (treeing) occurrence is started by erosion of the cavity, forming a pit. The pit grows deeper and deeper. The electrical field at the tip of the pit approaches the intrinsic breakdown strength of the dielectric. The dielectric breaks down over a short distance and causing a narrow channel. At the top of this channel the intrinsic breakdown strength is reached again and the channel grows in steps. After a while, the channel widens and further growth takes place, but now zigzag and with branches, similar with lightning [7]. In figure 2.2 (d) presents a sample of electrical treeing in insulation.

PD occurrence in power cable can be described using the equivalent circuit which is well known as a-b-c model. In figure 2.3, a-b-c model is depicted where the defect (cavity) in the dielectric is represented by capacitance c, the sound part of the insulation configuration is represented by capacitance a, b represent the capacitance of dielectric in series with the cavity.

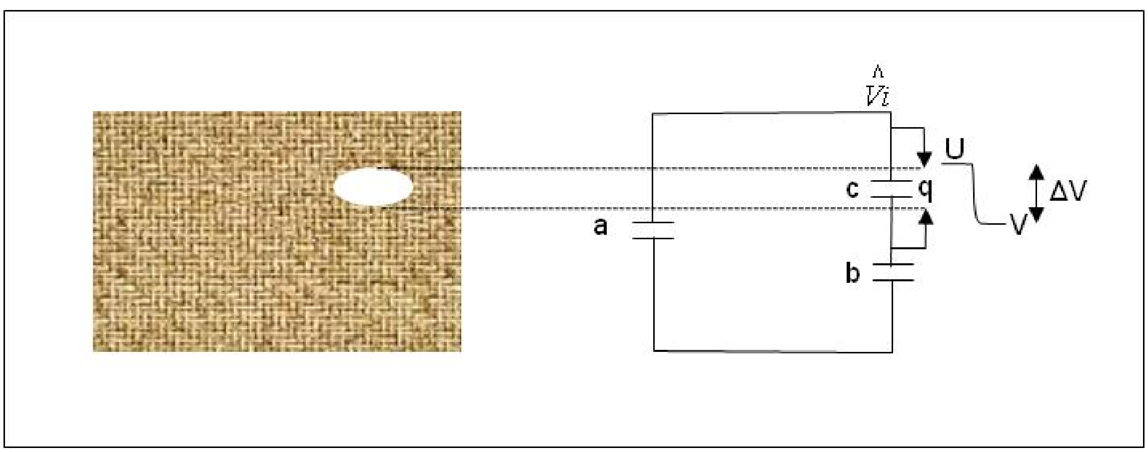


Figure 2.3: the equivalent circuit for PDs [6].

A discharge occurs in the when *Vc* reaches the breakdown voltage U^+, where U^+ follows from the Paschen curve. After breakdown, the voltage over the cavity drops to the residual voltage *V+* and gap is partially discharged. This happen takes place in a time of just a few nanoseconds. After the discharge has been extinguished, the voltage *Vc* increase again, when the voltage *Vc* reaches *U+*, a new discharge occurs and *Vc* drops to

V+. This happens several times, in this way groups of recurrent discharges occur during positive half of voltage cycle, and the negative half of the voltage cycle will be found. In figure 2.4 the principle of the recurrent of partial discharges in a defect is shown.

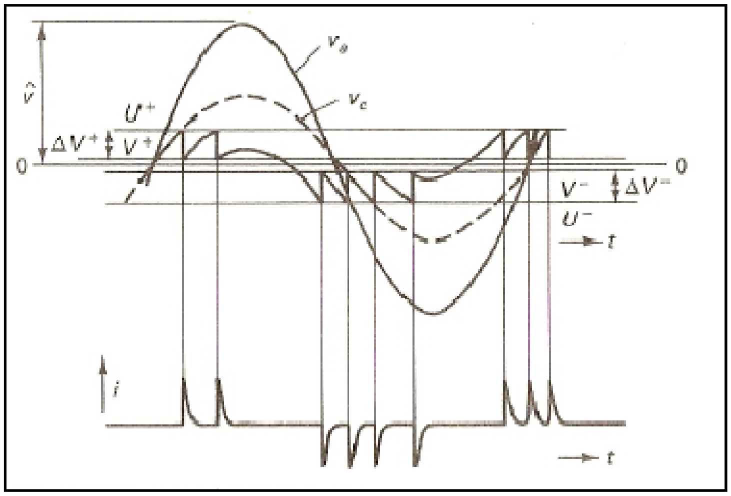


Figure 2.4: The principle of the recurrent of partial discharge in a defect during one AC power cycle [6].

The amount of charge, which is displaced by the discharge current in the leads of the sample, is equal to [7]:

$$q = b.\Delta V \tag{2.1}$$

This equation shows that PD magnitude is related to the capacitance *b* and voltage ΔV. The capacitance of *b* is related to the defect size as derived in equation 2.2 and Figure 2.6 illustrates the relation of the capacitance b and the defect size [7].

$$b \simeq \varepsilon_0 \varepsilon \,.\, (\frac{A}{d}) \tag{2.2}$$

where *A* is the area of the defect in the insulation, and *d* is the insulation thickness and consequently [7]:

$$q = \varepsilon_0 \varepsilon \,.\, (\frac{A}{d}) \Delta V \tag{2.3}$$

Equation 2.3 shows that the PD magnitude increases with the area *A* of the discharge site and the applied voltage ΔV *[7]*.

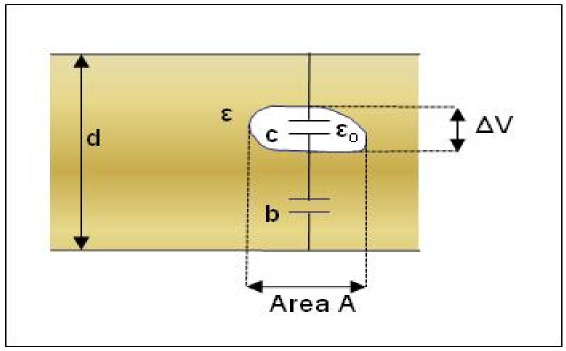


Figure 2.5: the relation between defect size and PD magnitude.[7]

2.3 Measuring Methods

PD detection in power cable system can be performed in two ways, off-line or on-line.

1. In the off-line PD detection, the cable system is disconnected from the network. To energize the cable system and to ignite the discharge related defects an external power supply is used. The location of PD source is determined by using the time domain reflectrometry (TDR).
2. On-line PD measurement is performed while the cable system remains in service. In this case the cable system is still energized by network. PD activities under the service condition in all phases are detected, but the distinction between the phases is difficult.

2.3.1. Different types of measuring methods

For off-line PD measurement, several standard methods have been developed. In table 2.1 an overview of off-line PD measurement and its energizing methods are described.

Table 2-1: Standard off-line methods for PD diagnostic testing of distribution power cables [10]

No.	Voltage Type	Voltage source
1	AC 50/60 HZ	Inductively tuned resonant circuits
2	AC 15-300 HZ	Frequency tuned resonant circuit
3	VL 0.1 HZ	0.1Hz sine wave generator and amplifier
4	DAC 50-500 HZ	Damped oscillating voltage wave excitation sources

Evaluating technical and economical aspects of a method is needed by utility for decision process in setting up diagnostic facilities. A number of technical and economical aspects have to be considered for those processes are [10]:

a. Voltage type: equivalence in PD inception processes among different voltage stresses for solid insulating materials.
b. Non-destructiveness: non-destructiveness of voltage stress during the diagnosis.
c. IEC 60270 conformity: in the case of measuring the PD quantity apparent charge of PD pulses in [pC] and [nC] the PD detection methods applied has to fulfill the recommendation of IEC 60270.
d. Sensitivity: immunity for on-site interferences and the level of system background noise.
e. Analysis: possibility to generate a broad spectrum of PD diagnostic information to support diagnostic knowledge rules.
f. Efficiency: investment costs, maintenance costs, transportability and operation of the method in different field circumstances.

Figure 2.6 shows evaluation of different PD diagnostics based on the Nuon utility approach. It shows that in this particular case, the DAC 50-500 Hz methods show the best fitting to aspects as defined above.

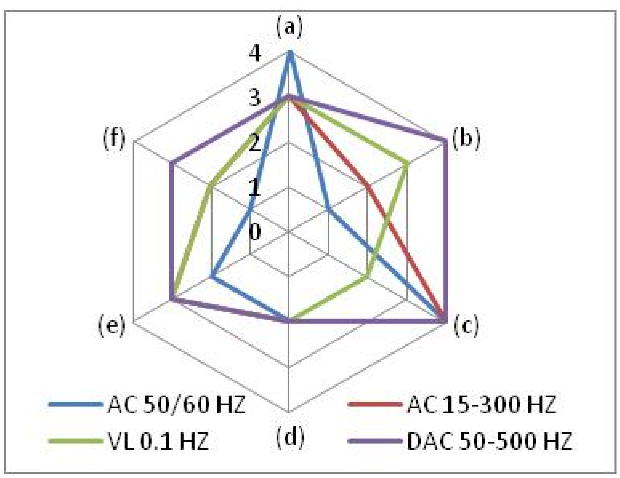
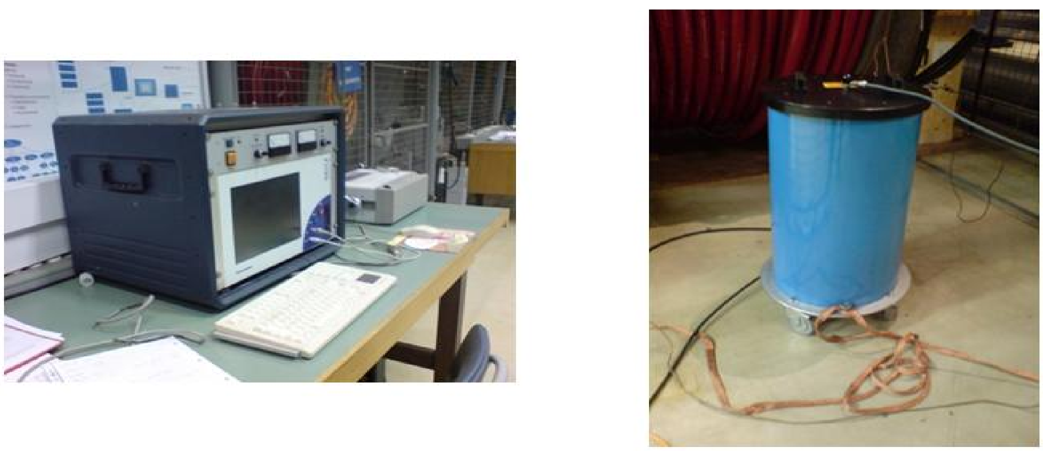


Figure 2.6: An overall evaluation of different PD diagnostics for different power cables [10].

2.3.2. PD measurements with DAC (Damped AC voltage)

Oscillating wave test system (OWTS) is one of methods of off-line PD diagnostic. This system is used to energize, to measure and to localize the position of PD source in the cable. In this method, damped AC (DAC) voltage is used to energize a cable system in frequency range 50 Hz-1.5 kHZ. OWTS system consists of two main units; OWTS analyzer unit and OWTS coil unit (figure 2.7).

OWTS analyzer unit consists of HV supply and data processing & control unit. HV supply is used to energize a cable system by damped AC (DAC) voltage. Data processing & control unit is used to process data measurement and to control overall measurement processes. OWTS coil unit consists of the HV coil, HV divider, and coupling capacitor. HV coil functions as an external inductor, HV divider is used for voltage measurement purposes and coupling capacitor is used to provide a closed circuit for the displacement q.



(a) (b)

Figure 2.7: Application of the Oscillating Wave Test System (OWTS)

a. *OWTS analyser consists of HV supply and data processing & control unit*
b. *OWTS coil unit consists of the HV coil, HV divider, and coupling capacitor.*

Figure 2.8 the shows schematic view of the (OWTS) diagnostic tool. For generating DAC voltages, the cable system under test is charged linearly with DC power supply (current) in a few seconds until the voltage reaches the selected test voltage level. The time charging time depends on the capacitance of the cable system and applied voltage as derived in equation 2.4 [6].

$$t_{ch} = \frac{U_{test}.C}{I_{load}} \tag{2.4}$$

Where I_{load} is the maximum load current of DC supply.

In this case the power demand remains low because the cable is charged with a DC power supply and the charging time is relatively small. After cable is charged the DC power supply is disconnected and then the cable sample is connected to an air core inductor in less than 1 µs. In this way, an RLC loop is created and an oscillating voltage (damped AC voltage) wave is generated. This DAC voltage is used to ignite PD related defect in the cable system.

The test frequency of the oscillating voltage wave is approximately the resonant frequency of losses circuit [6].

$$f = \frac{1}{2\pi\sqrt{L.C}} \tag{2.5}$$

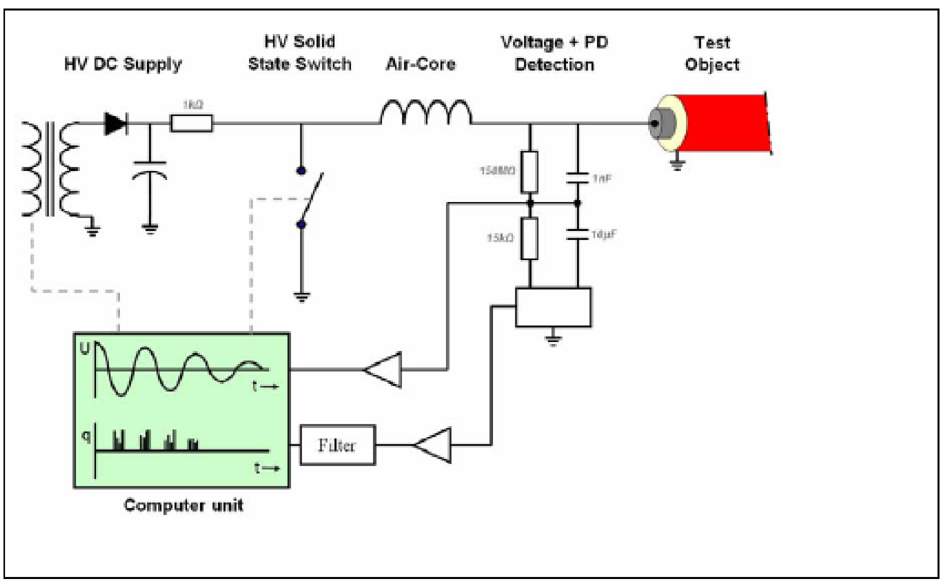


Figure 2.8: Schematic view of the (OWTS) diagnostic tool [10].

2.4 PD Localisation

2.4.1 Principle of PD Localisation Analysis

Time-domain reflectometry (TDR) is used in off-line PD measurement to determine the location of PD sources in a power cable system. Figure 2.9 shows the principle of PD wave propagation and localisation in a cable system. PD in a power cable system generates PD waves. PD waves will propagate from the source towards both directions of the cable. One pulse will propagate directly to the PD detector which connected to one end of the cable. Another pulse will propagate to the other end of the cable which left open. Full reflection of the PD waves will occur at the open end of the cable and the reflected PD waves will travel to the direction of PD detector.

The location of the PD activity can be determined by calculation the distance x_i with measuring the time difference between the incident PD wave (the first arriving PD wave from a PD event to the detector) and the reflected PD wave (the second arriving PD wave from a PD event to the detector) [6], as expressed in equation 2.6.

$$\begin{cases} t_1 = \dfrac{x_i}{v} \\ t_2 = \dfrac{(l - x_i) + l}{v} \end{cases} \xrightarrow{\Delta t = t_2 - t_1} x_i = l - \frac{v.\Delta t}{2} \qquad (2.6)$$

l is 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.

If detection is performed at the both sides of the cable system at the same time, both PD waves are detected at one of the cable ends. The PD event location at the distance x_i can be determined by [6]:

$$\begin{cases} t_1 = \dfrac{x_i}{v} \\ t_2 = \dfrac{(l - x_i)}{vv} \end{cases} \xrightarrow{\Delta t = t_2 - t_1} x_i = \frac{l - v.\Delta t}{2} \qquad (2.7)$$

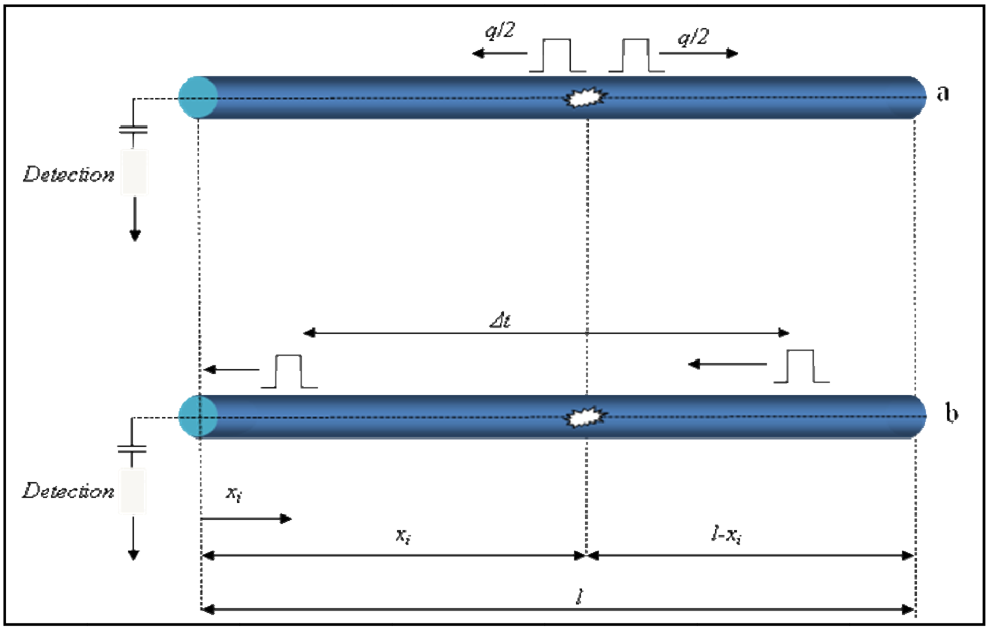


Figure 2.9: Principle of PD wave propagation and location in cables [6]:

a. Just after ignition two PD waves travel in both direction

b. After reflection the PD waves travels in the same direction.

The velocity of the propagation wave v for a particular cable is usually obtained from calibration. The standard calibration pulse is injected into one end of the cable system. The pulses travel through the length of the cable twice in a certain time interval. The propagation velocity calculated by [6]:

$$v = \frac{2.l}{\Delta t_{cal}} \tag{2.8}$$

Figure 2.10 shows a practical example of the calculation velocity of propagation waves obtained from measurement on 20 kV XLPE cable system from station PK 181 to station PK 180 in Jakarta. The length of the cable is 255 meter and the time difference between the incident PD wave and the reflected PD pulse (Δt) is 3.23 µs. The propagation velocity is 157.41 m/ µs.

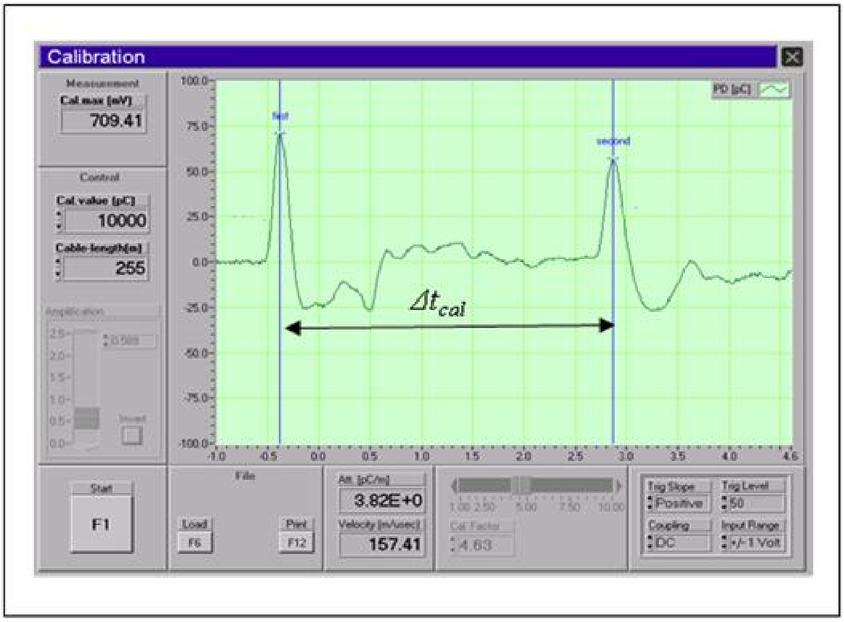


Figure 2.10: Example of the calibration of the propagation velocity in PILC cable

Figure 2.11 shows a practical example of analysing PD location in a cable system by using TDR. Measurements tool detects the incident PD pulse (*A*) as the first pulse, after which the reflected PD pulse (*B*) is detected. The time difference between incident PD pulse (*A*) and the reflected PD pulse (*B*) is then calculated as Δt. This Δt together with velocity propagation (v) are used to calculate location of the PD event using equation 2.6.

PD pulse *A'* is the reflection of the incident PD pulse *A* at the detection side, it travel along the length of the cable and it is reflected again at the cable end. The time difference between PD pulse *(A')* and the incident PD pulse (*A*) will be equal to Δt_{cal}.

Figure 2.11: Example of the location of a PD source by analysing the PD wave time difference

2.4.2 PD Localisation Analysis in Cable System with Multiple Insulation Types

Cable system can be constructed by multiple insulation types due to maintenance and tendency to change insulation from impregnated paper insulation to polymeric insulation. These cables systems are called mixed insulated cable. Due to the fact that propagation wave velocity for impregnated paper insulation and polymeric insulation is different, an error in the analysis of PD site location occurs.

The analysis of PD site location as expressed in equation 2.13 can be used, where the calibrated velocity is the average propagation of the applied insulation material. In this case the influence of cable joint is negligible due to their short length. The location error occurs up to several percent of the total cable length depending on the combination of practical length and material. Therefore another approach for Localisation of PD source in multiple cable system is required.

Schematic view of propagation of PD waves in mixed power cable system is shown in figure 2.12. The propagation velocity for mixed power cable system depends on the ratio between the lengths l_n of different types of cable part and their characteristic propagation velocity v_n. The averaged propagation velocity v_n that is obtained by calibration, as can be derived from equation 2.9 [6]:

$$v_{AN} = \frac{(l_A+l_B).v_A.v_B}{l_A.v_B+l_A.v_A} \qquad (2.9)$$

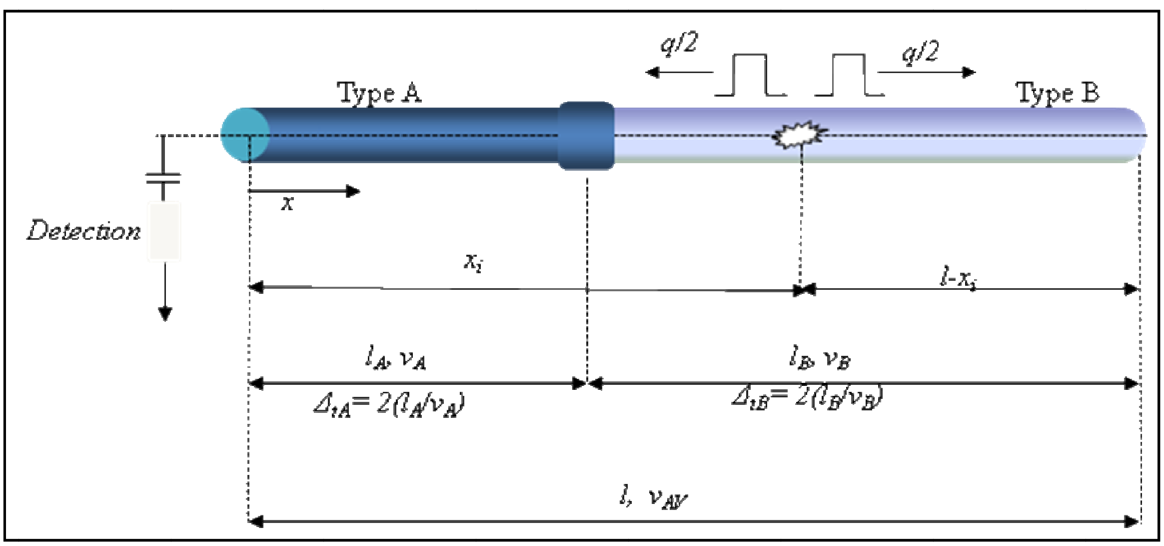


Figure 2.12: Schematic view of propagation of PD wave in mixed power cable system [6].

The position of PD origin location in mixed cable can be analyzed by following steps:

1. Measuring the time different between the incident and the reflected PD wave Δt_x.
2. Finding out from which part of the cable the PD wave is originating. In this case, it can be determined by comparing the Δt_x to Δt_B (see figure 2.13). Δt_B is the (expected) travel time of the cable most distant from the detection side. If $\Delta t_x > \Delta t_B$, the PD is located in the nearer cable part (cable part type A). If $\Delta t_x = \Delta t_B$, the PD is located exactly in the transition between two cable insulation (joint). If $\Delta t_x < \Delta t_B$, the PD is located in cable part type B.
3. Last step is calculation the position of the PD source location. For the PD origin in cable part B ($\Delta t_x < \Delta t_B$), the location of PD source is:

$$x_i = l - \frac{(v_B.\Delta t_x)}{2} \quad (2.10)$$

For the PD in origin cable part A ($\Delta t_x > \Delta t_B$), the location of PD source is:

$$x_i = l_A - \frac{v_A(\Delta t_x - \Delta t_B)}{2} \quad (2.11)$$

2.5 The importance of PD parameter for diagnostics purposes

The goal of PD diagnostic in the power cable system is to determine the condition of the cable system. Determination of this condition is based on parameters that obtained from the PD diagnostics. Several parameters (PD properties) are obtained from PD diagnostic using OWTS system for the total cable system and derived after location analysis for individual cable components are shown in table 2.2.

Table 2.2: PD properties as obtained from DAC measurement [6]

Cable System	Cable component
PD inception Voltage (PDIV)	
PD extinction Voltage (PDEV)	
PD magnitude at ~ V	
PD Pattern	
PD intensity	
PD Mapping	PD inception Voltage (PDIV)
	PD magnitude at ~ V
	PD occurrence frequency

2.5.1 PD inception voltage (PDIV) and PD extinction voltage (PDEV)

PD inception voltage (PDIV) is the applied voltage at which repetitive partial discharges are first observed in the test object, when the voltage applied to the test object gradually increased from a lower value at which no PD occurs [11].

In measurement by using OWTS system, PDIV is obtained by increasing the test voltage step by step until PDs are observed in the cable. The voltage at which the internal PDs occur for the first time is identified as the inception voltage (PDIV).

PD extinction voltage (PDEV) is the applied voltage at which repetitive partial discharges is cease to occur in the test object, when the voltage applied to the test object gradually decreased from a higher value at which PD pulse observed [11].

In measurement by using OWTS system, PDEV is obtained from the voltage cycle above the PDIV. The voltage at which the internal PDs stop occurring is identified as the extinction voltage (PDEV) [6].

PDIV and PDEV are the most important PD parameters for condition assessment of the power cable. By knowing the PDIV and PDEV, it can be determined whether PDs occur during normal condition (at Uo) or PDs occur at voltage higher than nominal voltage. If PDIV is lower than the operation voltage, means that PD occurrence is continuously active during operation [10]. For condition PDIV higher than Uo, PD can occur ignited by over-voltage such as switching operation. Once PDs ignite it will remain active at normal voltage condition for the next cycle if the PDEV lower than Uo. This is also the reason why the cable system should always be tested with higher stress than nominal.

2.5.2 PD Magnitude

The specific magnitude of the apparent charge q according to [11] is the largest repeatedly occurring PD magnitude. Depend on the type of component and age, certain PD magnitude can be accepted in the cable system. PD magnitude parameter is used to determine whether the PD occurrence in the component can be accepted or not.

2.5.3 PD Pattern

PD pattern is representation of the appearing partial discharge as a function of the phase angle Φ_i of the applied voltage test. PD patterns that are obtained from PD measurement at DAC voltage can be different in different phase. The analyzing of the phase resolved PD patterns is used to determine the type of defect in the cable [6].

2.5.4 PD Occurrence Frequency

PD occurrence frequency is number of PD events in the specific location in the mapping at one DAC voltage. This parameter is used to determine whether a cable system has PD concentration in the component.

2.5.5 PD Mapping

After analyzing the location of PD event by using time domain reflectometry (TDR), the location of PD events are represented along the length of the cable in PD mapping. The concentrations of PD events at one location represent a PD related defect. Figure 2.13 shows PD mappings from PD measurement on PILC cable system.

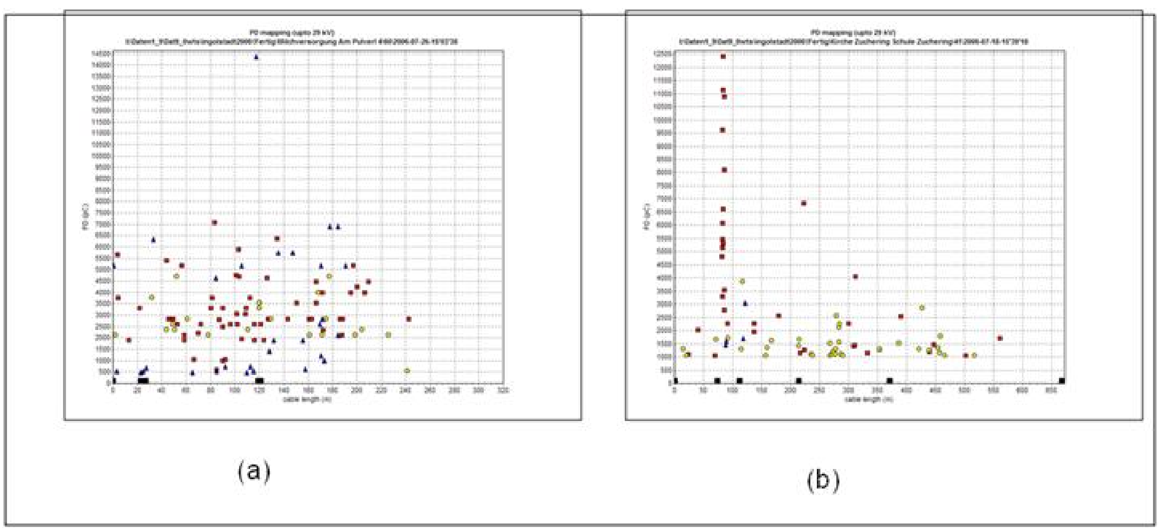


Figure 2.13: PD mapping performed on PILC cable system
(a) Partial discharges are scattered along the length of the cable.
(b) Partial discharges are concentrated in cable-part.

CHAPTER 3

Object Definition

The purpose of PD diagnostic is to assess the current conditions of cable system. To obtain a good assessment, the accuracy of interpretation of PD data is very important. Generally, a good accuracy in interpretation of PD data is obtained when testing a very good cable system or a very bad cable system [3]. In a very good cable, there is no PD activity at service condition and PDIV is typically higher than 2 Uo, whereas a very bad cable will typically exhibit a low PDIV and high level of PD activity will be obtained.

The accuracy of interpretation of PD data in the cable system at condition between very good and very bad is not easy. Providing all information about the component of the cable system convinced can increase the accuracy of interpretation the PD data. Wrong interpretation of PD data sometimes occurs because of the lack information of the component in the cable system.

This chapter presents the important definition of the test object to obtain an accurate interpretation of PD data.

3.1 Characteristics of power cables

In general underground power cables can be characterized by [6]:

1. Underground power cables are buried so that the physical access to the cable only in the two terminations.
2. One or more cable joints are present in a cable system if the lengths of the cable system more than the length of one cable drum (500 m).
3. Due to repair/replacement or topological change a cable system often consists of mixed insulation type and different types of accessories.
4. Operational and maintenance history may have different influences on the insulation condition during the service life.

Due to these characteristics, a cable system generally consists of:

- two terminations at both ends of the cable system which used to make connection to another part of the power system,

- N cable parts (insulation parts).
- N-1 joints which used as connections between cable parts.

The physical access to the cable is only possible at terminations, hence the most effective way to perform on-site PD diagnoses on underground power cable is at one of the terminations [6].

Figure 3.1 shows the representation of a cable system consists of two terminations, five cable parts and four joints which can be built by different types.

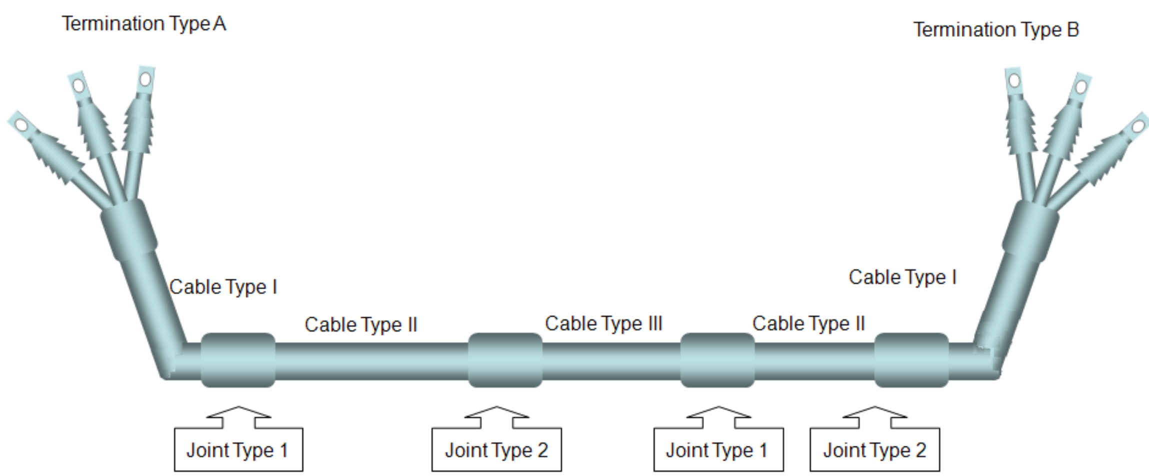


Figure 3.1: Representation of a cable system [6].

3.2 Partial discharge data interpretation

During performing PD measurement several PD parameters which indicate component health collected and stored. The characteristic of the PD parameters depend on [3]:

- Type and location of defects in the cable system
- Insulation material
- Operations conditions of such as applied voltage, load and time.
- Type of PD measurement

Due these facts, to interpret the existence of PD in the cable system, relevant information about test object is needed. This information together with PD parameters and interpretation rules are combined to achieve a good interpretation of PD data. Interpretation rules are made by giving categories to each PD parameter which indicate harmfulness of the existence of PD in the cable system.

Table 3.1 Interpretation rules for PD diagnostics on power cables [10]

Parameters	Categories	
PDIV and PDEV	< operation voltage	> operation voltage
PD magnitude	> typical value	< typical value
PD Pattern	harmful fault type	less harmful fault type
PD intensity	high	low
PD location	cable insulation	cable accessories
PD Mapping	PD Concentrated	Scattered PD location

The existence of PD in the cable system cannot be interpreted as indicate the likelihood of the PD to cause failure, additional information concerning the source of the PD is required to determine its severity. For instance, PD activities were observed with maximum PD magnitude 550 pC cannot be determined whether it is harmful or not to the insulation material without additional information about types and age of this insulation. If this the insulation type is XLPE, this value is not acceptable anymore while for an aged PILC insulation, the 550 pC PD magnitude is still in the range of acceptable value.

Looking at experience of PD measurements that performed by PT PLN (Persero) in Jakarta, problems have been in interpretation PD data due to lack of information of the object test. Figure 3.2 shows an example of OWTS measurement report from PD measurement that performed on a 255 meter cable system from station PK 39B to station PK 198 in Jakarta. The information of the components of the cable system is not clearly defined:

- Insulation types are not clearly defined (XLPE-PILC).
- Installation year is not defined.
- Type and position of the joints are not clear. It can be seen that there are two joints in the same position.

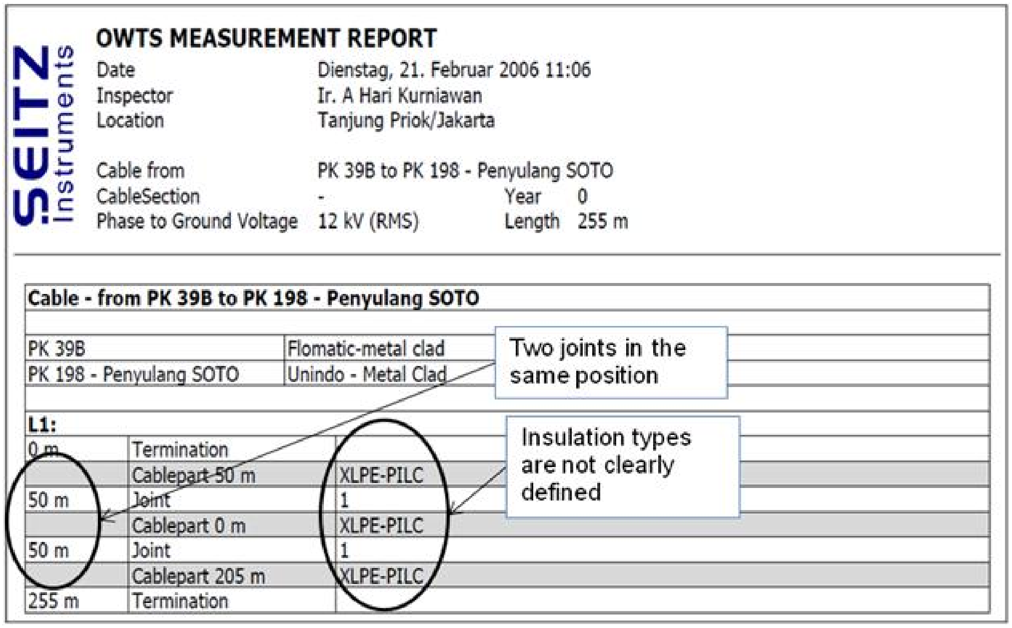


Figure 3.2: OWTS measurement report of cable system from station PK 39B to station PK 198 – Feeder Soto in Indonesia

Moreover, in the PD mapping of this measurement (see figure 3.3), the numbers and the position of the joints were changed after performing PD mapping based on the measurement result. The position of the first joint was changed from 50 meters to 45 meters. Additional joints added at the position of 120 meters, 160 meters and 215 meters.

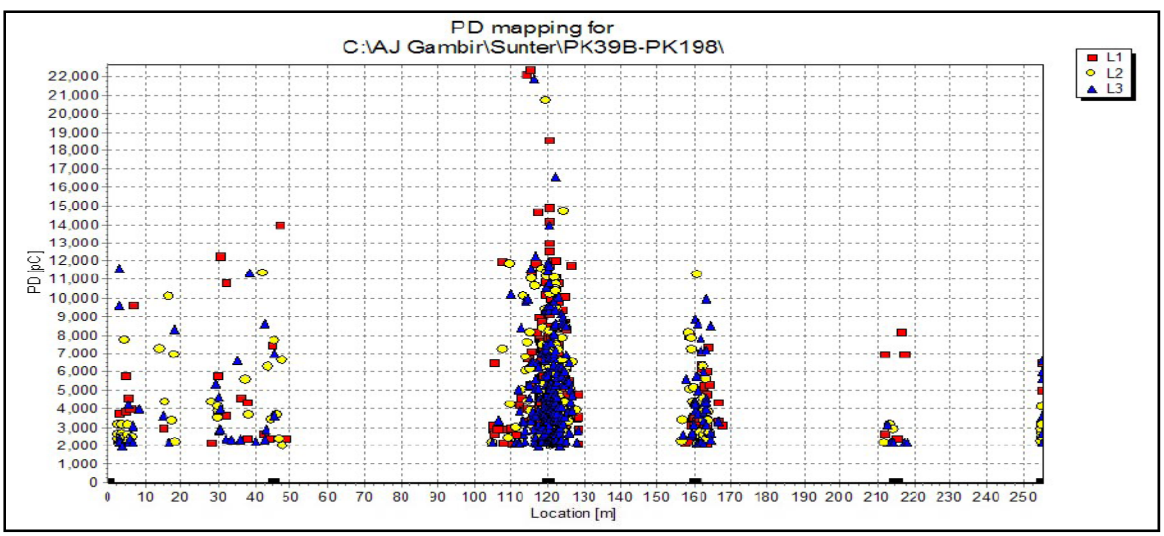


Figure 3.3:PD mapping of measurement of cable system from station PK 39B to station PK 198 – Feeder Soto in Indonesia

The lack of relevant information about the test object and differences number of joints in the OWTS measurement report and in the PD mapping will result in difficulty and ambiguity in interpretation of PD data. The result of this PD measurement cannot be used as an input to make maintenance decision.

3.2.1 PD interpretation in Cable Insulation

Two different types of cable insulation are considered in this study; XLPE and PILC. Typical partial discharge sources and interpretation of PD occurrence are different for both of this cable insulation type. In this section, typical sources and PD interpretation in both types of cable insulation type will be discussed.

3.2.1.1 PD interpretation in PILC

Paper-insulated lead covered cables (PILC) are impregnated with oil that does not flow easily at ambient temperature [12]. Temperature cycling or oil leaks can cause void which can be sites for PD in the PILC cable. PD occurs in this voids, therefore it is not uncommon PD in the range of some hundreds picocoloumbs can occur in PILC cable. In general the existence of PD in PILC cable is cause by oil leaks, water ingress and local field as shown in table 3.2.

Table 3.2 typical insulation degradation processes of the cable insulation [10]

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

PILC cables are considered more resistant to PD than XLPE cables. In the PILC cable a certain PD magnitude and intensity is acceptable. For new PILC cable PD magnitude < 500 pC is accepted and for aged PILC cable PD magnitude up to 2000 PC is accepted [12]. Due to the differences accepted PD magnitude for new PILC cable system and for aged PILC cable system therefore information about the installation year of cable system is necessary to obtain a good PD interpretation.

In general the following rules are used in interpretation of existence of PD in PILC cable system:

- If PD activities are scattered along the length of the PILC cable system can be considered as good and reliable, even if large distributed discharges appear.
- Partial discharges with high density in a confined area e.g. 10 m to 30 m are considered as discharge concentrations. This PD concentration may indicate a faulty joint.
- PD concentrations with value of 8000 up to 10000 pc to be considered as suspicious.
- PD concentrations with value higher than 10000 pc to be considered as very suspicious.

Figure 3.4 is an example of PD measurement performed on PILC cable system in Alkmaar. It follows from this figure that PD mapping contains a complicated view of PD activities in a cable system. Scattered PD activities in the layered insulation can be affected by pressure and temperature changes in the paper oil insulation caused by switching off the cable system and short cooling process [6].

In this PD mapping PD activities are scattered along the length of the cable.

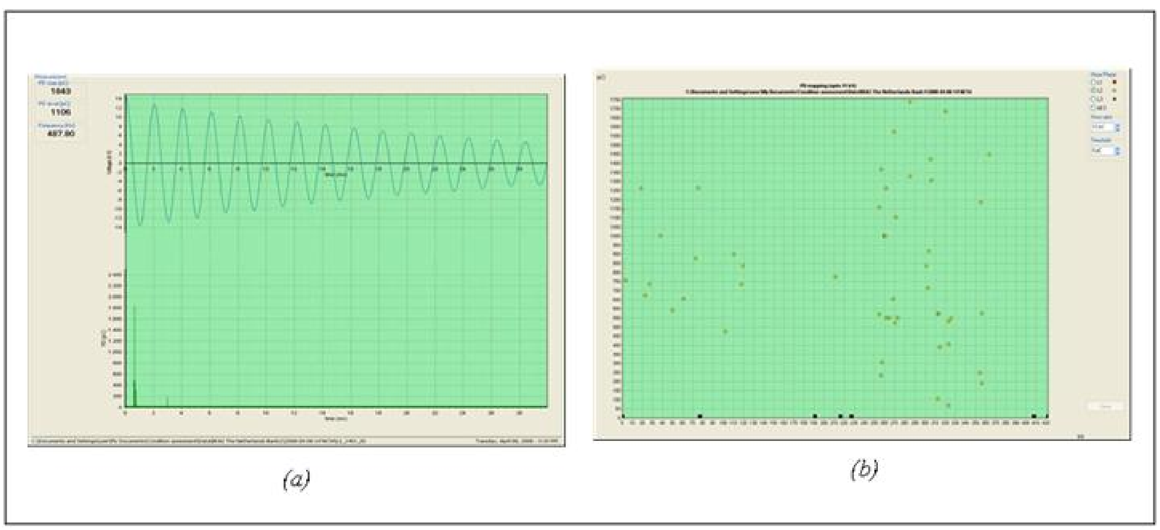


Figure 3.4: PD mapping of a 450 m, 5.8 kV PILC Cable system from BKA2 to De Nederland's Bank in Alkmaar.

3.2.1.2 PD interpretation in XLPE

In general the existence of PD in XLPE cable system caused by water tree, insulation voids and local field concentrations (see table 3.2). In contrary to the PILC cable, in XLPE cable no PD activity is allowed [10]. Therefore, in XLPE cable system at measurement up to 1.7 Uo should be PD free. PD concentration with value higher than 10 PC is to be considered as suspicious.

Figure 3.5 shows an example of PD mapping of measurement of a 1100 m XLPE cable in German. There are 4 joints in this cable system and PD concentrations are observed in the 2^{nd} and the 3^{rd} joint.

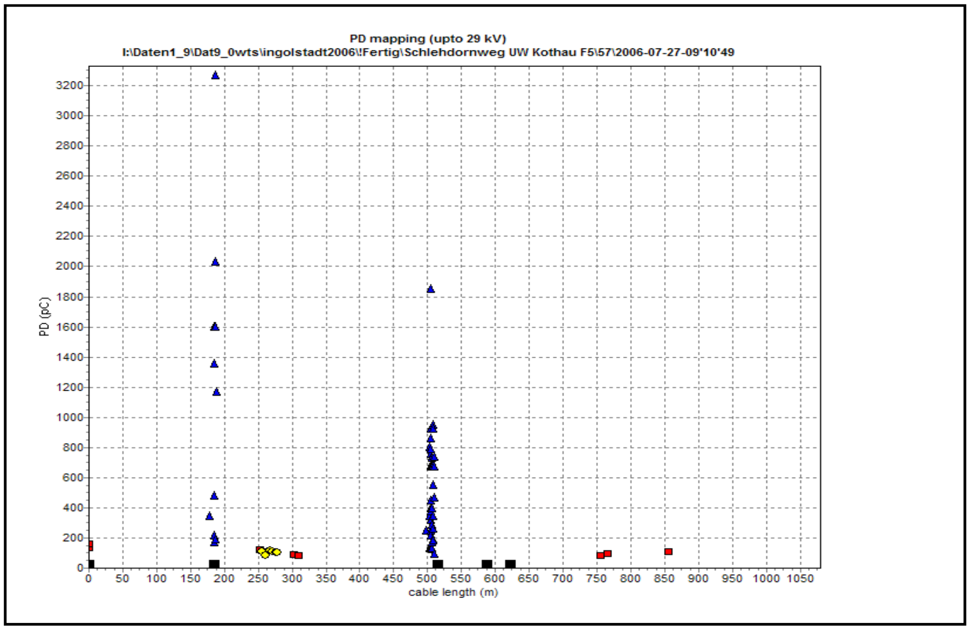


Figure 3.5: Measurement result of a 1100 m XLPE Cable system in German.

3.2.2 PD interpretation in Accessories

Accessories of the cable system are used as connection between cable parts and cable system to another part of power system. Joints are used as connection between cable parts, while terminations are used as connection to another part of power system. Unlike the insulation cable, accessories must be assembled in the site. The inclusion of defect in accessories can be occurred during installation. In general PD occurrences in accessories cause by interface problem, bad hardening, conductor problem and local field enhancement (see table 3.2). Depending on the type of the accessories, a certain PD level is allowed in the accessories.

3.3 Component Information

Prior to performing PD diagnostic, is necessary to collect all relevant information about the component of the cable system. Information is classified in four groups: cable system, insulation cable, accessories and measurement information. According to [4], prior to performing the PD diagnostic, information of cable system, insulation cable, accessories and measurement information are recommended as shown in table 3.2.

Table 3.2 Recommended data component prior to performing PD measurement

Components	Information data
Cable System	• Cable section identification (i.e., substation name, from switch No. to switch No.) • Operating voltage • Type of construction • Installation year
Insulation Cable	• Name of cable manufacturer • Cable insulation • Conductor type and size • Cable length. • year placed in service
Accessories	• Type of accessories • Name of cable manufacturer • Location of the accessories • year placed in service • Cable voltage class.
Inspection Information	• Test date,time • Inspector • Comment

In the PD diagnostics by using OWTS system, prior to performing measurement, these data should be filled in the test object input screen as shown in figure 3.6.

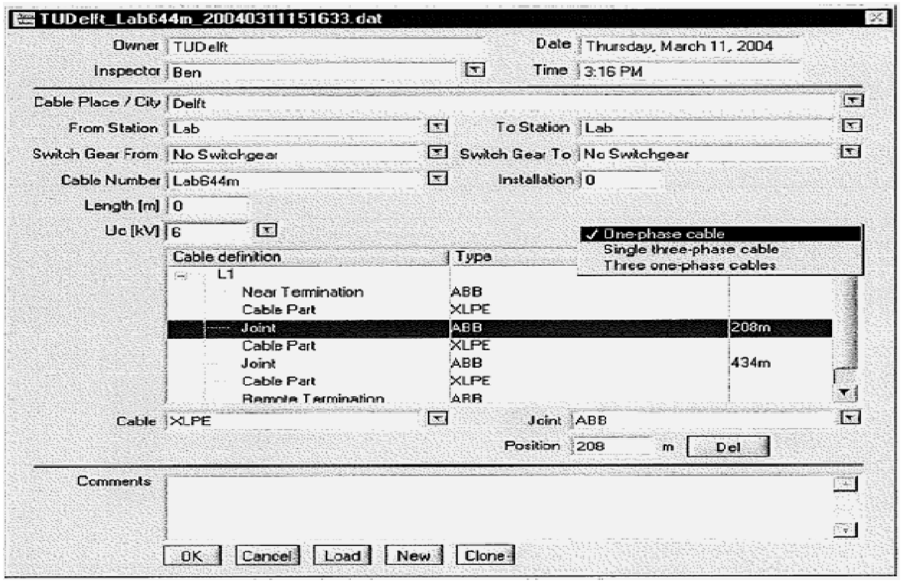


Figure 3.6: Test object input screen.

3.4 Conclusions

1. From PD measurements performed by PT PLN (Persero) Distribusi Jakarta Raya dan Tangerang, it has been observed that most of measurements were performed without clear definition of the test object. As result the severity of the existence of partial discharges in the cable system cannot be interpreted.
2. The purpose of the condition assessment is to assess the current condition of cable system. An accurate interpretation of PD is necessary to achieve a good assessment.
3. The severity of existence of PD in the cable system cannot be interpreted if all relevant information about cable system is clearly defined. The lack of relevant information about the cable system will result in difficulty and ambiguity in interpretation of PD data.
4. PD parameters, object definition together with PD interpretation rules can be used in interpretation of PD data. Interpretation is done by giving categories to each PD parameter of component based on interpretation rules. In this way the severity of the existence of PD in the component can be determined.

CHAPTER 4

Calibration Test Procedure

4.1 General

Prior to performing measurement test, the measurement system has to be calibrated. PD calibration is performed to calibrate PD reading and PD propagation velocity. Calibration is very essential because this is a single method to verify the measurement system is functioning correctly and to check the sensitivity of the measurement system to detect PD. Due to its essentiality, it can be said that measurement can be skipped if the calibration is not correct.

PD occurrence is stochastic processes, it means that PD magnitude in the cable system can not be predicted precisely, moreover PD occurrence in all range should be measured in proper range, therefore it is necessary to perform calibration in several range from the lowest range up to the maximum expected PD range during measurement. Two possible consequences of applying one range calibration are the PD range is too high or PD range is too low. If PD range is too high, the sensitivity of the cable system to measure low PD magnitude is minimal. The impact of using too high PD range to the test result is that the cable system with low PD magnitude will be observed as a PD free cable, but actually the cable is not PD free. Observation of PD inception voltage may also be shifted to the higher value if too high PD range is used. The actual PDIV cannot be observed using too high PD range.

If PD range is too low, the real PD level in the cable system cannot be measured. The measurement system cannot measure the PD level higher than PD range. As result the real picture of PD occurrence in the cable system cannot be obtained and this result cannot be used for condition assessment of cable system.

Wrong calibration can also occur if the pulse reflection is poor which can affect the pulse propagation velocity. Wrong propagation pulse velocity can not be used in localisation of PD sources in the cable system.

In PD diagnostics using OTWS system, the calibration is performed in two procedures:

1. Calibration of the PD reading;

   Calibration of PD reading is performed according to [13]. This calibration is made by injecting current pulse to the termination of the cable system. A certain PD pulse (e.g. 100pC) is injected to the cable system. The recorded PD pulse at the near end is evaluated by integrating it with respect to time as explain in equation 4.1[14].

   $$q = k \int v \, dt \tag{4.1}$$

   The constant k in equation 4.1 is adjusted until the PD magnitude read in the measurement tool is same with the injected PD pulse.

2. Calibration of the PD pulse propagation velocity reading;

   In this calibration, PD pulse is injected to the cable system, original pulse and reflected pulse are detected by measuring system. The propagation velocity of the pulse in the cable system is calculated by the time different between the original PD pulse which recorded in at the near end and the reflection pulse. The velocity propagation pulse is calculated as following [6]:

   $$v = \frac{2\,l}{\Delta t_{cal}} \tag{4.2}$$

   where $\Delta t_{cal} = t_{reflection} - t_{original}$

Performing calibration test is crucial because the quality of PD measurement and PD localisation are strongly affected by the quality of calibration. During performing calibration test the following problems have been several which can influence quality of calibration:

- poor reflection pulse
- one range calibration
- Imperfect connection

In this chapter, procedure to perform a good calibration is discussed. Impact of problems during performing calibration on PD measurement are also discusses in this chapter.

4.2 Calibration test procedure

4.2.1 Connection setup of OWTS System

As have been described in the first chapter, OWTS system consists of two main units: OWTS analyzer unit and OWTS coil. During the PD measurement using OWTS system, the cable system disconnected from the network. Before performing measurement, OWTS analyzer, OWTS coil and test object have to be connected properly in order to avoid unexpected effect that can influence the quality of measurement.

The OWTS coil and OWTS analyzer are connected through two cables; the HV system cable that used to energize the cable system and system control cable that used for transmission of the measurement signal from OWTS coil to the OWTS analyzer.

The test object (cable system) is connected to the OWTS coil by using HV cable connection. Earth connector in OWTS coil and sheath grounding of the cable are earthed using grounding cable. Figure 4.1 shows the test circuit of the PD measurement using OWTS system that is performed in the laboratory. Figure 4.2 shows the test circuit of PD measurement that is performed in the site to PILC cable system in Alkmaar.

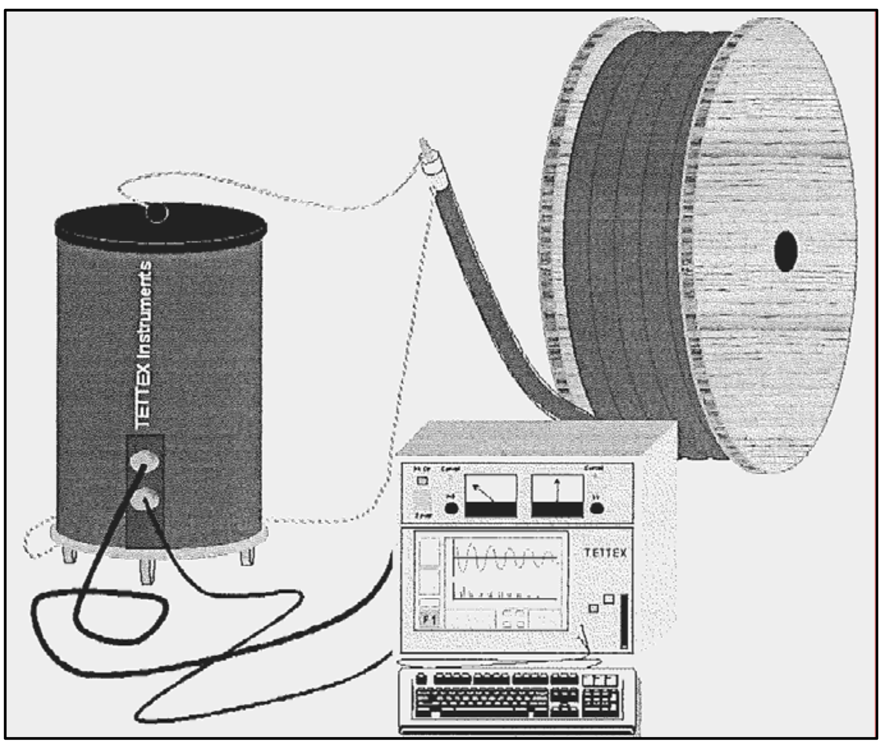


Figure 4.1: OWTS test circuit component of OWTS system [15]

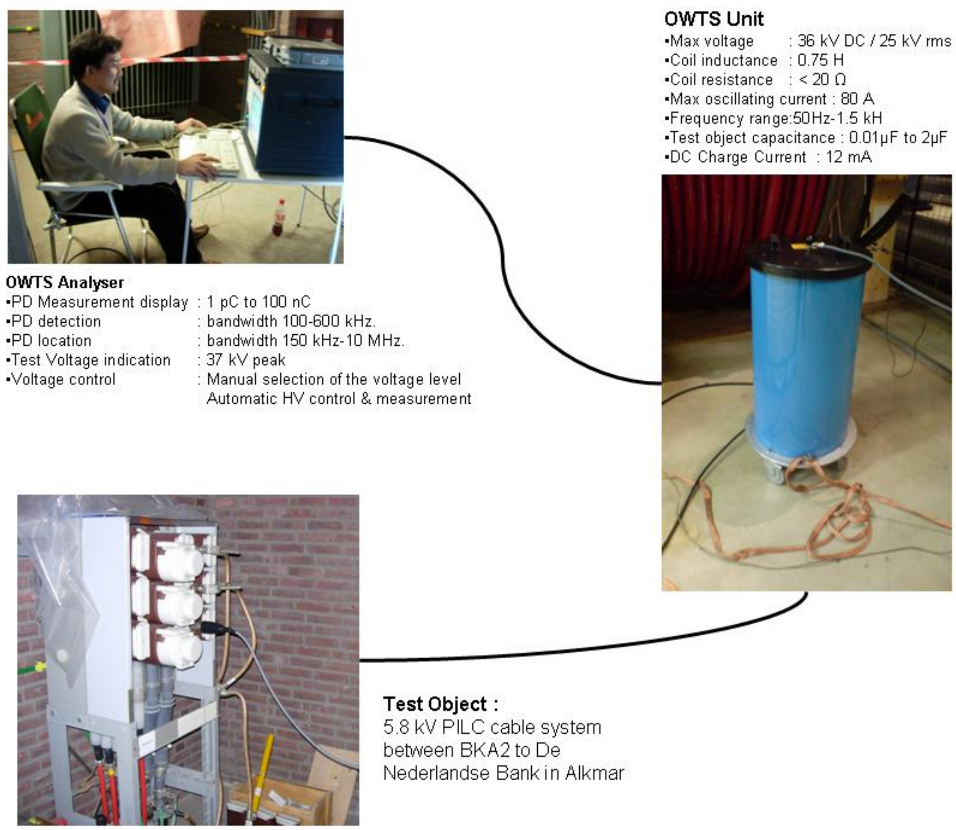


Figure 4.2: Connection setup of PD measurement in the PILC cable system in Alkmaar.

During performing calibration, the calibration is connecting to the system. The calibrator connector (+) is connected directly to the termination or connected on the top of the OWTS coil. The calibrator connector (-) is connected on a grounded part of the termination or on earth connection of OWTS coil. Figure 4.3 (a) represent the connection of calibrator to the cable system.

4.2.2. Calibration of Pulse propagation velocity

To perform calibration, defined pulse (e.g. 100pC, 1 nC) is injected from the calibrator to the cable system. Injected pulse will travel along the length of the cable. Due to the remote end is left open the pulse is fully reflected at the remote end. The first peak pulse and the second peak (reflected) pulse are recorded in time domain at measurement tool as illustrated in figure 4.3 (b). Time domain reflectometry (TDR) is used to analyse the propagation pulse in the cable system. Time difference between the first and the second pulse is measured to calculate the propagation velocity of pulse using equation 4.2.

In the case that 2nd pulse (reflected pulse) is not detected, the trig level should be changed. If pulse is not detected after changing trig level, the calibration should be changed into higher PD pulse magnitude. Figure 4.4 shows an example of calibration where peak pulses are clearly displayed. This step is very crucial because the propagation velocity pulse is used to determine the location of PD occurrence in the cable system. The correctness of PD localisation in PD mapping depends on this step.

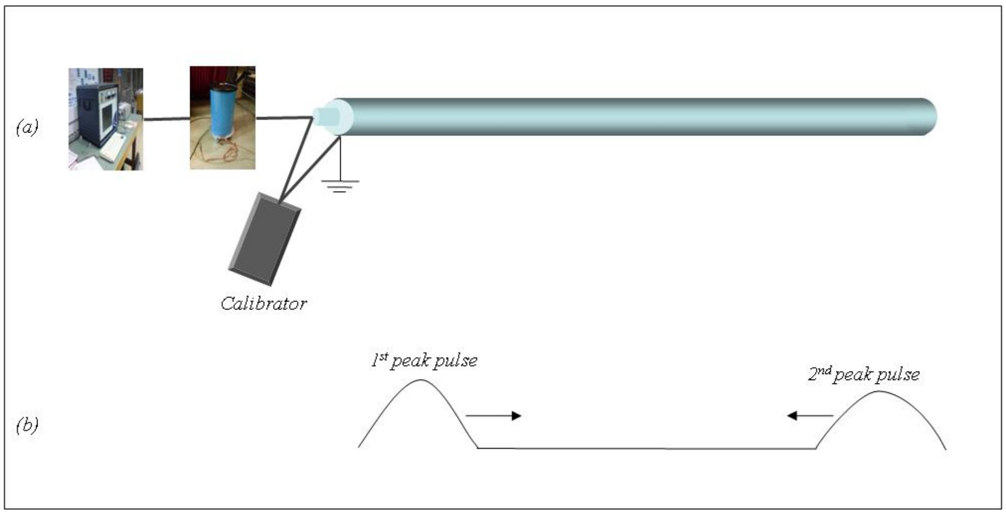


Figure 4.3: Connection setup of PD calibration test.

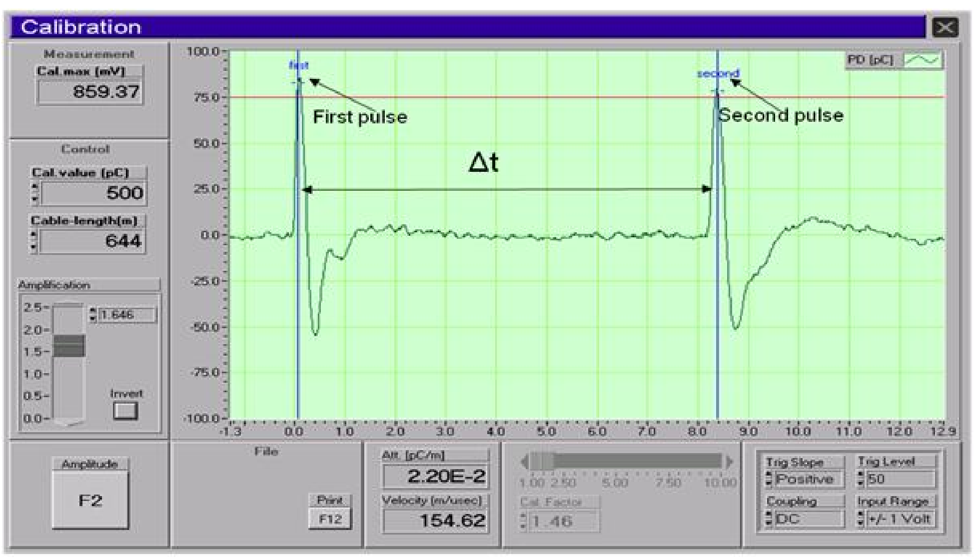


Figure 4.4: Calibration of pulse propagation velocity using OWTS System version 4.0

4.2.3. Calibration of PD reading

The next step is to calibrate PD reading. In this case the calibration factor is adjusted so that the measurement tool read the same PD magnitude as calibration pulse. Figure 4.5 shows an example of adjustment calibration factor. The calibration is stored and it will be used during performing PD measurement. Due to the fact that PD occurrence is stochastic process and the expected PD magnitude cannot be predicted precisely, performing calibration in several ranges is necessary.

Due to the differences capacitance and the length between the phases in three phases cable system are minimal, performing calibrations on one phase is sufficient.

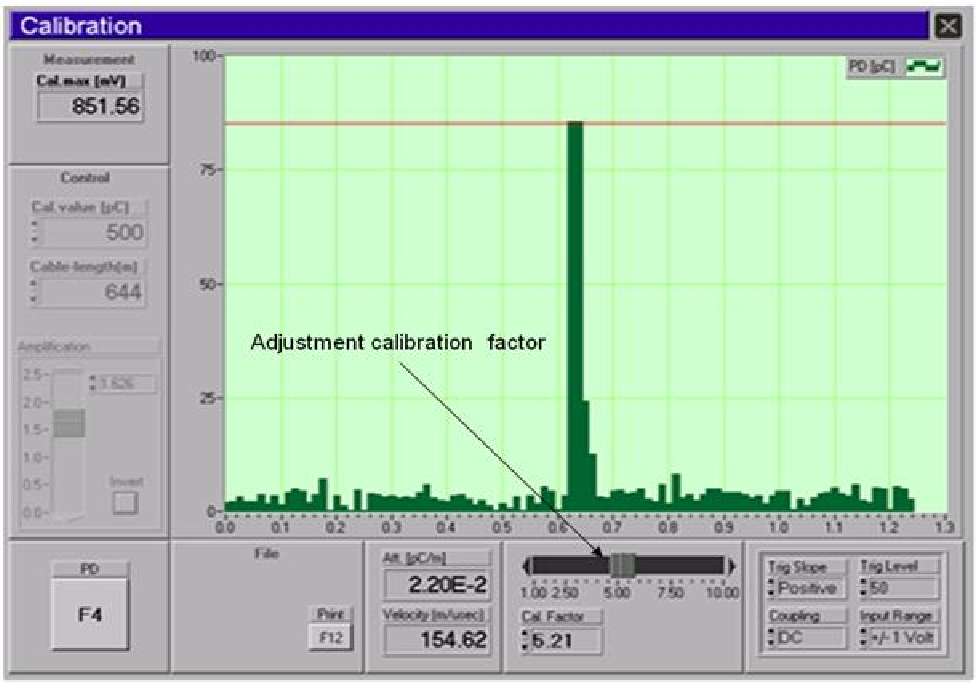


Figure 4.5: Calibration of PD reading using OWTS System version 4.0

4.2.4. Joint location detection

Due to the difference impedance of cable system and joint, additional reflection pulse may occur on each joint position domain during calibration. This phenomenon can be used in detection of position of the joint in the cable system. Figure 4.6 shows the phenomena of additional reflection from joint in the cable system.

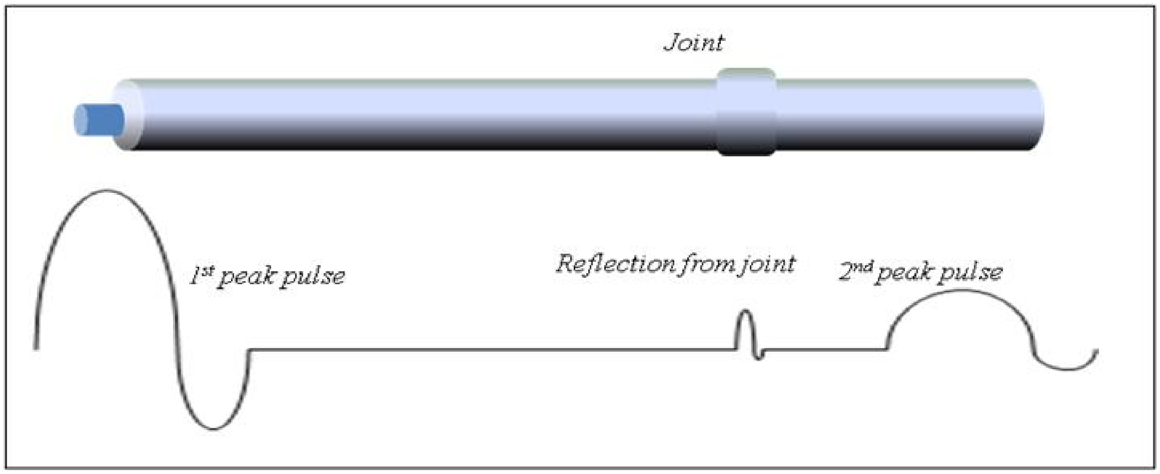


Figure 4.6: Detection of joint position using calibration.

Using time domain reflectometry (TDR), time difference between the first pulse and additional reflection from joint can be measured. The position of the joint is calculated by using time difference between the first pulse and additional reflection from joint and pulse propagation velocity as shown in equation 4.3.

$$l = \frac{\Delta t_{cal} \; x \; v}{2} \tag{4.3}$$

Figure 4.7 shows an example calibration where additional pulse was observed during calibration. Time different between the first pulse and reflection from joint, Δt =0.7 µs and the pulse propagation velocity v ==146.17 m/µs. The position of the joint is obtained by using equation 4.3 is 51 m.

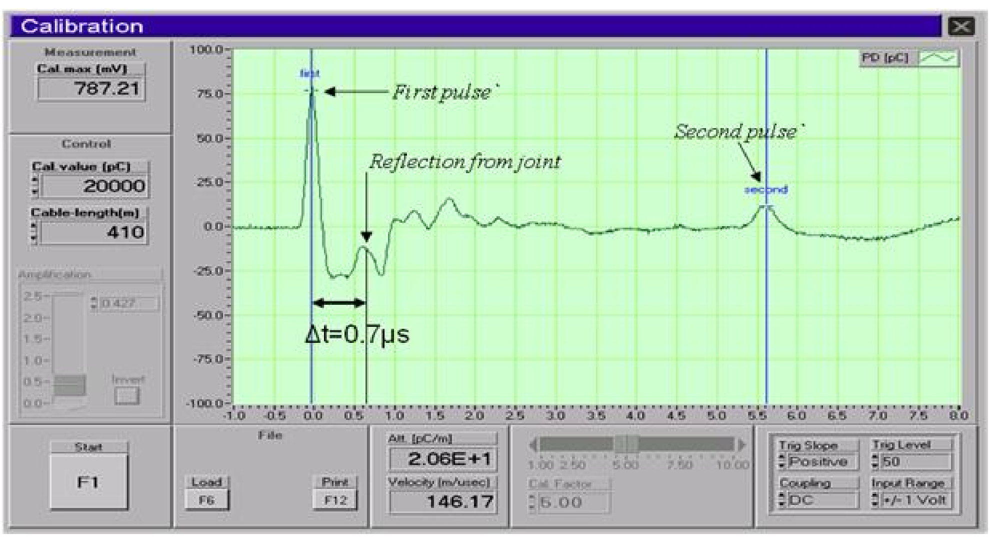


Figure 4.7: Additional pulse observed during calibration

In order to obtain a good result of calibration that can be used in performing PD measurement, flowchart calibration test procedure is proposed in figure 4.8.

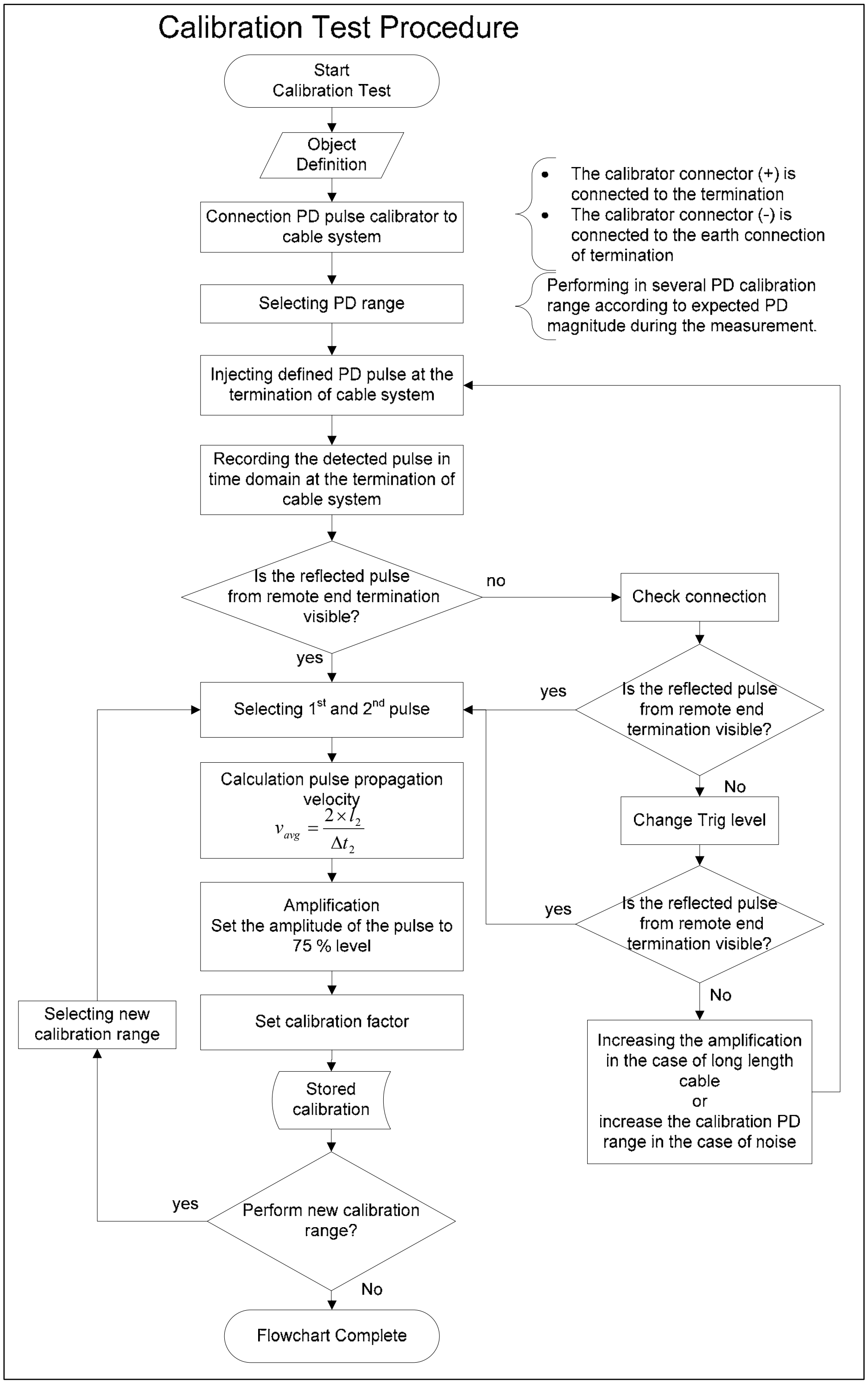


Figure 4.8: Flowchart calibration test procedure.

4.3 Problems in performing calibration

Based on experiences which obtained by PT PLN (Persero) Distribusi Jakarta Raya & Tangerang and the experiment in the laboratory, several problems have been observed during performing calibration.

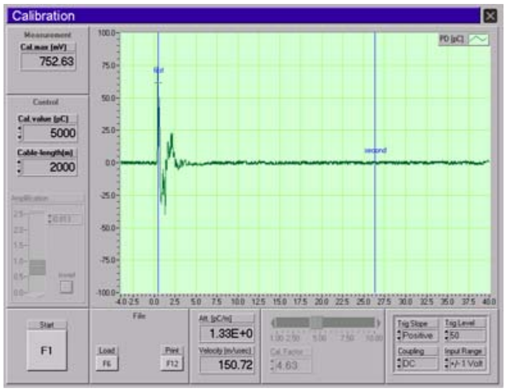
4.3.1 Poor reflection pulse

As has been explained in the beginning of this chapter one of the purposes of the calibration is to obtain the propagation velocity of the pulse in the cable system. For that reason the original and the reflection pulses should be clearly displayed and selected. In a calibration with poor reflection as shown in figure 4.9, the reflection pulse cannot be selected correctly. In this case the correct propagation pulse velocity cannot be obtained. The impact of using wrong propagation pulse velocity is PD activities in the cable system cannot be localised correctly, as result good PD mapping cannot be obtained.

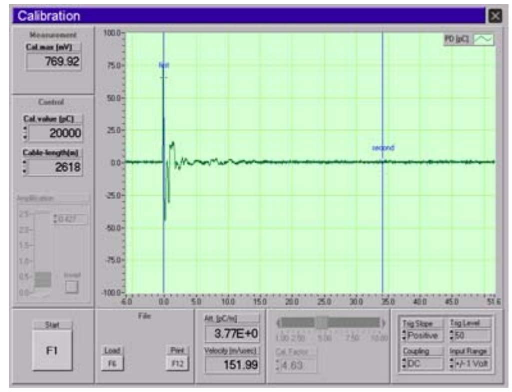
Figure 4.9 shows four calibrations that were performed in Indonesia which indicated as calibrations with poor reflection pulse. In general these poor reflection pulse calibrations are observed in performing calibration on long length cable system. Poor reflection pulse in the case of long length cable can be reduced by amplifying the pulse until reflection pulse is visible.

4.3.2 One range calibration.

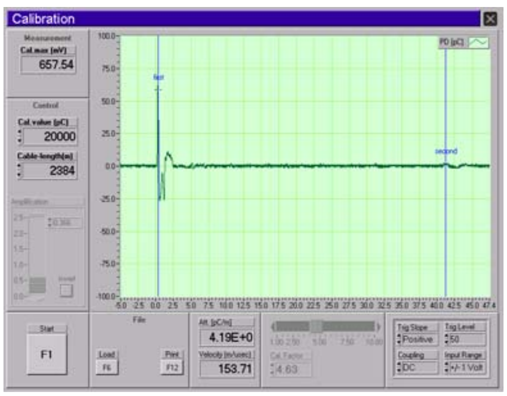
One range calibration in PD measurement is measurement performed in several voltage levels using only one calibration range. Due to PD occurrence is a stochastic process and the PD magnitude is applied voltage dependent moreover for all PD range that can occur in the cable system have to be measured in proper PD range, it is necessary to perform calibration in several ranges. The PD calibration ranges have to be selected higher than the PD magnitude which could be expected during the PD measurement. The expected PD magnitude in the power cable system depends on the type and the condition of the cable system. For instance, for PD measurement of service aged PILC cable system or on service aged XLPE cable system, the expected PD magnitudes are in the range of 100 C up to 100 nC, therefore for these two types of cable system, PD calibration range in the range of 100C up to 100 nC should be provided.



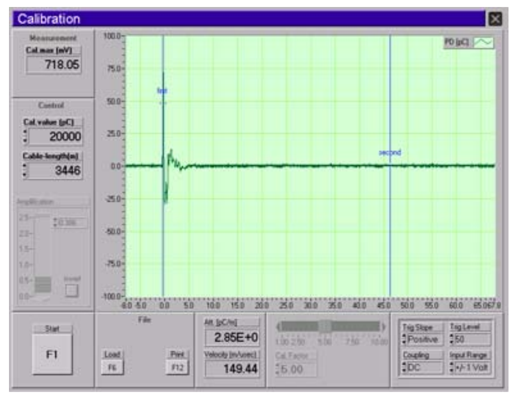
a. *Cable system from station 68 A to GI*



b. *Cable system from GI to station 24*



c. *Cable system from station K66 to GI*



d. *Cable system from station GH 24 to GI*

Figure 4.9: the calibrations that were performed in several cable systems in Indonesia

Following are two possible consequences of applying one range PD calibration in the PD measurement:

a. The calibration value is too low;

   The effect of this condition is the maximum PD magnitude cannot be recorded. The maximum PD magnitude which can be recorded by the system is in the range of PD calibration Value. Figure 4.10 is an example of PD measurement which performed using calibration range lower than maximum PD magnitude. It can be seen that PD pulses higher than calibration range are clipped. The maximum PD magnitude recoded in this measurement might be lower than the actual maximum PD magnitude. This means that PD measurement using too low PD range is not a good picture about the real PD levels and the result can not be used in condition assessment of the cable system.

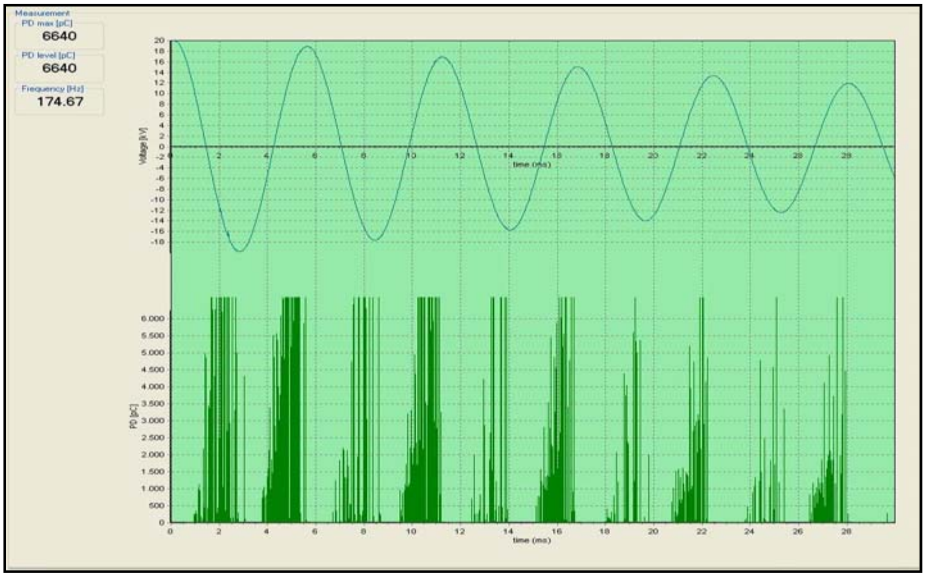


Figure 4.10: PD measurement that was performed with PD calibration value lower than maximum PD magnitude.

b. The calibration value is too high;

In the case of calibration value is too high, the sensitivity of the measurement to measure low PD magnitude is minimal. Only the PDs with magnitude close to the calibration value are clearly detected. In some cases, the result of PD measurement using high PD range is that cable system is PD free even there are some PDs with lower PD magnitude in the cable system.

4.3.3 Imperfect Connection

High background noise can affect the quality of the calibration due to a lot of pulses are observed in the time domain during calibration. The pulses will affect the selection of the reflection pulse. Imperfect connection of the earth connection is a common source of the background noise in performing calibration. The sheath neutral of the cable that is not earthed properly may induce a lot of noise to the measurement system. The noise resulted because the potential of the sheath neutral is floating above the earth. The effect of this imperfectly earthed cable may exhibit in time domain during calibration. More pulses observed or background noise is very high which influence the selection of peak pulse. Figure 4.11 shows the calibration that performed on a 644 meter XLPE cable in the laboratory, where the sheath neutral of the cable was not grounded.

This high background noise may affect the correctness in selecting peak pulse which can affect the quality of calibration of pulse propagation velocity and calibration of PD reading. This effect can be eliminated by repairing or improving the connection of measurement system.

In the case of high background noise originated from external sources and cannot be eliminated by repairing the connection, the calibration should be performed with higher PD range.

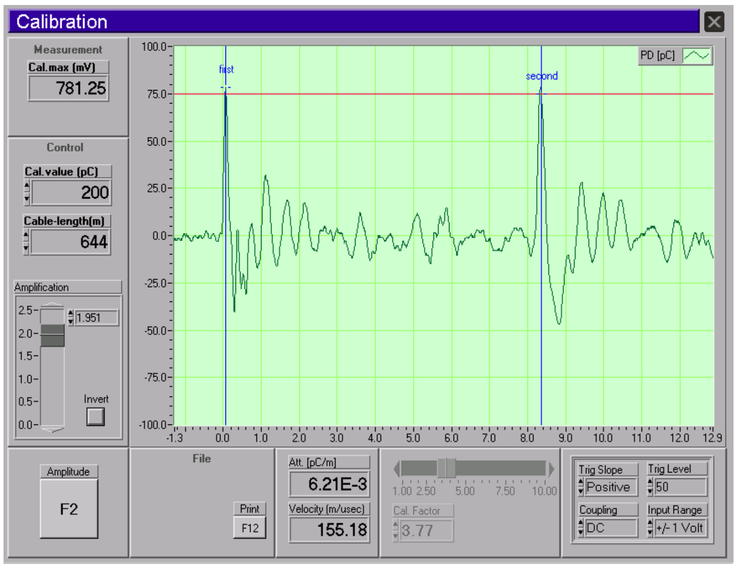


Figure 4.11: Calibration perform without connecting sheath neutral to grounding.

4.4 Conclusions

1. Performing calibration test is very crucial because the quality of calibration affects the whole quality of PD measurement.
2. Calibration is performed to calibrate PD reading and PD propagation velocity.
3. In addition to this calibration, calibration pulse in time domain can also be used for detection of join location.
4. Based on experiences measurement in the field and in the laboratory, the following problems have been observed:
   - Poor reflection pulse,

     Poor reflection pulse will result in wrong propagation pulse velocity. The impact of wrong calibration on the test result is that localisation PD source in the cable system cannot be obtained correctly and this result cannot be used as input for condition assessment of cable system.

- One range calibration

  Applied one range calibration has two possibilities consequence; PD range is too low or PD range is too high. Both consequences will affect the PD parameter such as PDIV and PD magnitude.

- Wrong connection

  Imperfect connection during calibration may induce a lot of noise to the system that can affect the accuracy of calibration.

CHAPTER 5

Measurement Test Procedure

On-site Partial discharge diagnostic is performed to detect and to recognise and to localise PD occurrence in cable system. Detection, localisation and recognition of partial discharge at early stage of possible insulation failure in the cable system are very important in making decision maintenance [16]. Performing off-line PD measurement with DAC voltage is very powerful and sensitive measurement. The PD measurement is performed in several steps that have to be done in correct way in order to obtain a high quality measurement result.

During performing test, DAC voltage applied to the test object diagnostic and parameters are measured. In performing PD measurement, several problems have been observed in:

- Performing PD background noise
- Selection of proper PD range
- Selection of test voltage level

In this chapter, the problems during performing PD measurement are discussed and measurement test procedure is proposed.

5.1 Different type of testing on power cable

5.1.1 After-laying test

The cable systems are installed in the field and connected to the power network. During installing the cable systems in the field, defect may be introduced which may lead to the failure in the system. After-laying test are performed to check the mounting and laying quality of a new cable system [6]. PD diagnostic is one of applications test which used to check quality of the insulation cable at start of lifetime of a cable system. The goal of partial discharge on-site testing on new installed power cables during after-laying test are [9]:

- Recognition of poor workmanship in cable accessories,
- to check the PD-free condition of cable accessories up to 2Uo,
- localisation of PD source in case of PD occur in the cable system

- to evaluate in case of PD occur in the cable, the PD level in [pC] and repair of the particular accessory

For a new PILC cable, PD level up to 500 pC is accepted and for new XLPE cable, PD level < 50 pC is accepted [12].

5.1.2 Diagnostics of service aged cables

Diagnostic test is performed to the service aged cable system to assess current condition of the cable system. The goals of PD on-site testing/diagnosis on service aged power cables [9]:

- to support the maintenance and operation decisions,
- to detect and localise PD's and other degradation symptoms in cable insulation and cable accessories,
- In the case of PD occurrence to evaluate the PD's (PDIV, PD-levels, PD patterns) and to compare with the acceptance norms for particular types of cable insulation and accessories.

For the aged PILC cable, PD level up to 2000 pC is accepted and for aged XLPE cable, PD level < 50 pC is accepted [12].

5.2. Performing PD Measurement.

During performing PD measurement, PD parameters are recorded and stored in the measurement tool. These PD parameters are information source to assess the condition of component of cable system. Measurement should be performed properly to obtain all parameters that will be used in condition assessment of components of cable system.

5.2.1. Measurement PD background noise.

The sensitivity of the PD measurement tends to decrease with the increasing of the environmental noise. Disturbances can occur even if the cable system is not energized. To achieve a good PD measurement, during performing measurement, PD background noise should be low enough to permit a sufficiently sensitive and accurate measurement of the specified partial discharge magnitude. Performing measurement of PD background noise is necessary in order to distinguish the PD from cable defect and PD from noise.

Background noise divided in two categories [13]:

- Background noise from vicinity which occur even if even the test circuit is not energised. The example of these kind of disturbances are switching operation in other circuit, high voltage test in the vicinity, radio transmission etc.
- Background noise which only occur when the test circuit is energised but which do not occur in the test object. These noises usually increase with increasing voltage. Sparking of imperfectly earthed object in the vicinity of or imperfect connections in the area of the high voltage can also cause disturbances [13].

One of example disturbances which occur when the test circuit is energized was observed in the laboratory. Disturbance caused by voltage induced by cable test to imperfectly earthed object in the vicinity of the test object [13]. Figure 5.1 (a) shows the illustration of the induced interference from floating parts in the vicinity of the measurement site and figure 5.1 (b) shows the laboratory experience where some voltage was induced by test voltage and periodically discharged through the cage.

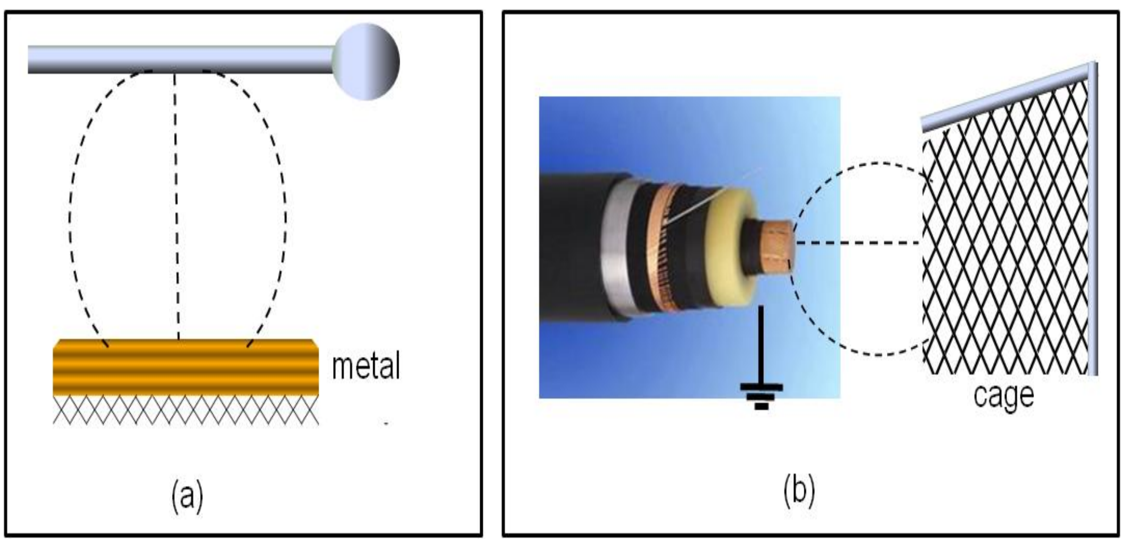
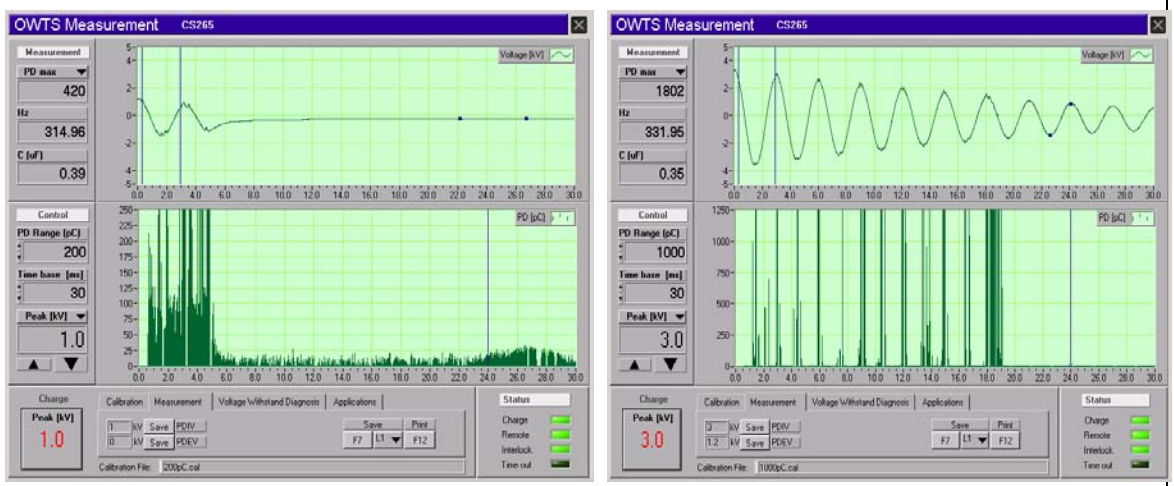


Figure 5.1: Induced interference from floating parts in the vicinity of the test area.

The effect of this problem is the very high disturbances which increase proportionally with the voltage test.

Figure 5.2 shows the example of measurement which disturbed by floating part in the vicinity of test area. In the first measurement at 1 kV voltage (figure 5.2.a), the maximum PD magnitude is 420 pC. This value can not be considered as PD activities in the insulation cable because the magnitude is too high for applied voltage test at 1 kV. When applied voltage test increased to 3 kV, the maximum PD magnitude increases to 1802 pC as shown in figure 5.2 b.

To avoid high disturbances caused by discharges from floating part in the vicinity of the cable system is to keep the area in the vicinity of the measurement tool must free from foreign bodies, small or large. In this way the floating part can be avoided.



(a) (b)

Figure 5.2: Measurement example obtained from a 644 XLPE cable in the laboratory, It shows that by increasing the DAC voltage from 1 kV (a) to 3 kV (b), the noise caused by floating part in the vicinity of the test area are increased.

PD measurement performed without performing background noise measurement will result in ambiguity interpretation of PD sources whether from cable defect or noise. Figure 5.3 shows OWTS measurement report obtained from PD measurement on XLPE from station PK 29B to station PK 178. This measurement was performed without performing measurement background noise. It shows the maximum PD level observed in this cable is 10 pC. It is difficult to interpret the source of this PD whether from cable defect or noise because the PD background noise was not performed.

SEITZ Instruments

OWTS MEASUREMENT REPORT

Date	Montag, 20. Februar 2006 09:54		
Inspector	Ir. A Hari Kurniawan		
Location	Tanjung Priok-Jakarta		
Cable from	PK 29B to PK 178		
CableSection	1	Year	0
Phase to Ground Voltage	12 kV (RMS)	Length	403 m

	L1	L2	L3
GroundNoise [pC]	-	-	-
PDIV [kV RMS]	4.9	4.2	4.9
PDEV [kV RMS]	-	5.5	-
PDmax [pC] (PDIV)	1	1	1
PDlevel [pC] (PDIV)	-	1	1
PDmax [pC] (Uo)	10	10	10
PDlevel [pC] (Uo)	10	9	9
PDmax [pC] (1.7*Uo)	-	-	-
PDlevel [pC] (1.7*Uo)	-	-	-
PDmax [pC] (2*Uo)	-	-	-
PDlevel [pC] (2*Uo)	-	-	-
Capacitance [uF]	0.171	0.171	0.172
Frequency [Hz]	487.80	483.89	485.85
Diel. Losses	4.67E-3	4.79E-3	4.63E-3

Figure 5.3: PD measurement without performing PD background noise.

5.2.2 Selection of proper PD Range

Prior to PD measurement, PD calibration test performed. As described in the previous chapter, calibration has to be performed in several ranges because the expected maximum PD magnitude can not be predicted precisely and the importance of performing measurement at several voltage level.

The quality of PD measurement is strongly affected by selection of proper PD range. When performing PD measurement test, the PD range should be selected properly, in such a way that the PD range is not too high or not too low compare to the maximum PD magnitude observed. The effect of PD range/calibration range is too high or too low compare to maximum PD magnitude, are described in section 4.3.2.

Selection PD range can also affect PD parameter such as PDIV and PD magnitude. Measurement using high PD range can result in higher PDIV than actual PDIV. As PD magnitude depends on applied voltage, PD magnitude at PDIV is normally low, this low PD magnitude cannot be detected by using high PD range as result PDIV will be observed at higher applied voltage. Overall this measurement does not show the real condition of cable system.

Figure 5.4 shows two measurements performed at different PD ranges. Measurement at PD range 200 pC, PDIV was observed at 8 kV (figure 5.4 a). Using PD range 10000 pC, measurements up to 9 kV were observed as PD free and PDIV was observed at voltage level 10 kV (figure 5.4 b). It shows that the result of PD measurement using high PD range does not give a good picture of condition of cable system.

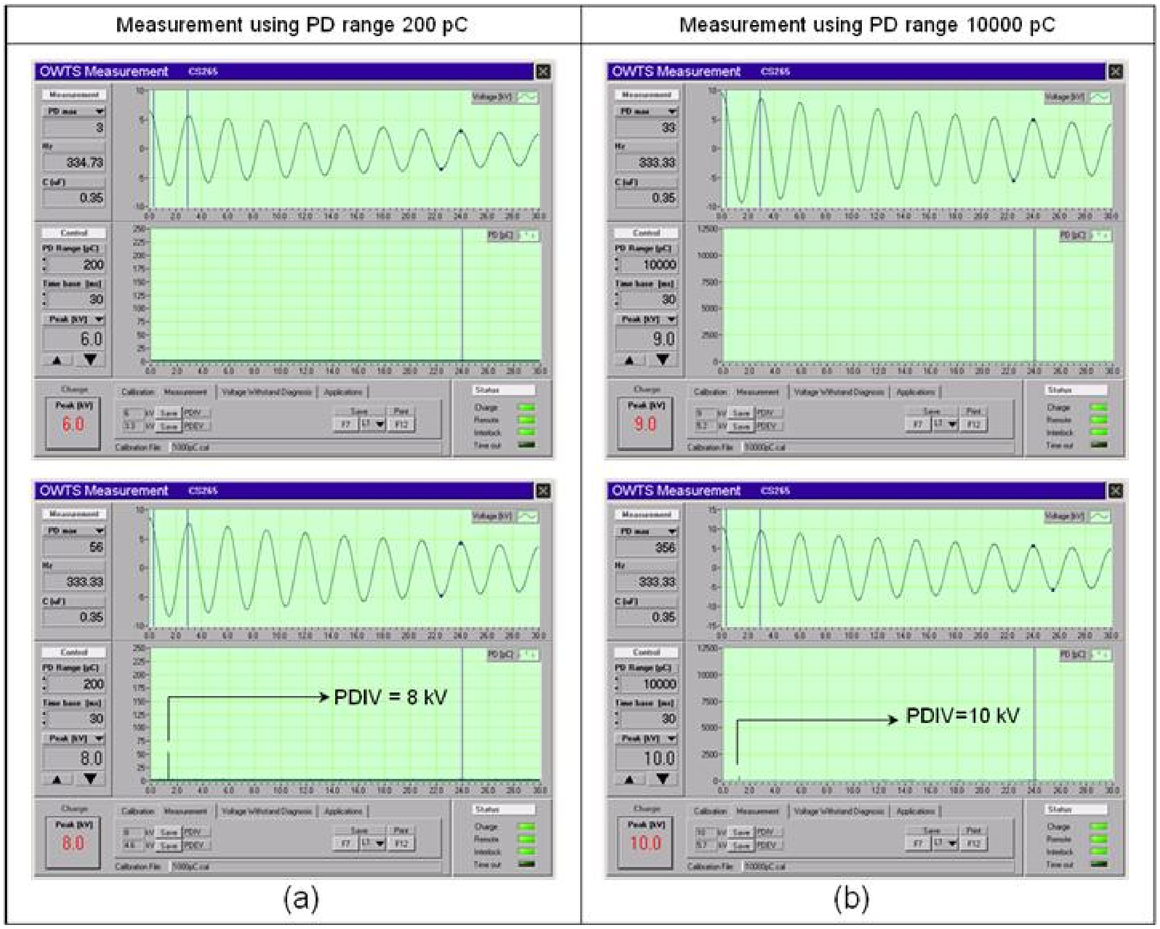


Figure 5.4: Higher PDIV was observed with higher PD range,
(a) Using PD range 200 pC, PDIV was observed at 8 kV
(b) Using PD range 10000 pC, PDIV was observed at10 kV

5.2.3 Selection of test voltage levels

One of the advantages of performing PD measurement using damped AC (DAC) voltage is that the test can be carried out at different voltage levels. Performing a number of PD measurements at different voltage levels will give representative picture of PD occurrence in the cable insulation which is needed in the evaluation of PD data. Performing measurement at several test voltage levels also gives possibility to evaluate the PD process in the cable system using q-V curve. Figure 5.5 shows q-V curve which is used to interpret PD occurrence in the termination. Sudden increase of PD activity during increase of the test voltage may indicate a serious localise defect in the insulation as shown in index condition 1 in figure 5.5.

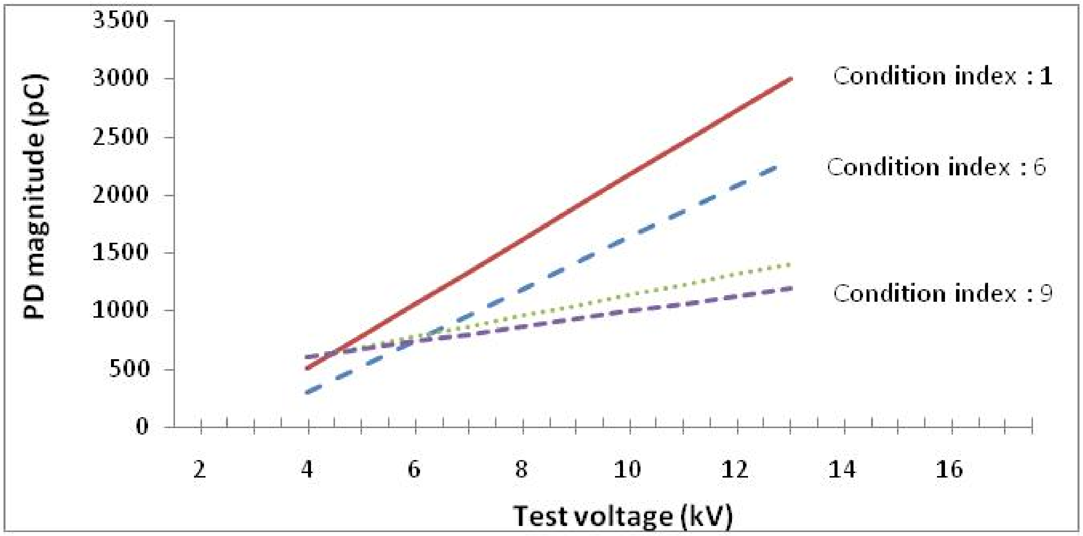


Figure 5.5: Trend lines with condition index of the cable termination [11]

The following are several considerations that have to be taken into account in selection of test voltage levels during PD measurement using OWTS system:

1. In real-time registration of PD inception voltage (PDIV), test voltage have to be applied from small voltage and increased up to PD inception voltage (PDIV) obtained.
2. PD observed at Uo represents a great threat because it appears constantly during service operation. Therefore PD measurement should be performed at Uo.
3. When there is an earth fault in the system, over voltage up to 2Uo occurs. PD ignited at this voltage remains active as long as the over voltage higher than PDEV. Over voltage in several hours duration is a threat.
4. For measurement which PDIV lower than Uo, it is important to observe the growth in PD magnitude and the increase in PD intensity in function of test voltage.
5. For measurement which PDIV higher than Uo, the increase in PD magnitude and the increase in PD intensity should be considered in relation to permitted values.
6. Special case for the 3-core belted power system. The operation voltage between phases in 3-core belted power cable is √3 nominal voltage. Therefore it is necessary to perform measurement at least √3 Uo in order to produce the operation stress [6].

Based on these considerations, in measurement using OWTS system, the following tests are recommended:

Table 5.1 Recommended PD measurement using OWTS system

No.	Measurement	Voltage level	Number of Measurements
1	PD background noise level	0 kV … 0.5kV	1
2	PD inception voltage (PDIV)	First PD pulse occur	3
3	PD occurrence at	Uo	3
4	PD occurrence at	1.5 x Uo	3
5	PD occurrence at	2 x Uo	3
6	PD extinction voltage (PDEV)	At least 20 % above PDIV	3

In particular the number of measurements is an important issue. Depending on PD occurrence frequency this number has to be chosen in that way, that sufficient PD pulses will be registered for further analyses. The number of measurement as proposed in table 5.1 is an example.

5.3.Measurement Test Procedure

The following test procedure is proposed to have a good result of PD measurement:

1. Connection setup

   During performing PD measurement, the cable system disconnected from network and the remote termination is left open. Measurement system is connected to the cable system as described in chapter 4.
2. Object definition

   As described in chapter 3, prior to PD measurement, relevant information about object test should be defined.
3. Calibration

   Calibration should be performed at several PD ranges from the lowest range up to the highest expected PD level. Due to the differences capacitance and the length between the phases are minimal, performing calibrations on one phase is sufficient;
4. Selection PD range

Before applied voltage to cable system, proper PD range has to be selected. For measurement PD background noise and observing PD inception voltage (PDIV) the lowest PD range has to be selected. After PDIV observed, PD calibration can be change according to PD magnitude which occurred in the cable system.

5. PD background noise

   PD background noise is measured by applied a low voltage or a zero voltage to the cable system. This is very important to distinguish between internal PD related defect in the insulation and external PD caused by noise. Background noise should be lower than acceptable level e.g 20 PC for measurement of XLPE cable system or 100 pC up to 150 pC for measurement of PILC cable system. If background noises higher than acceptable level, the source of background noise should be found and eliminated. In the case of the background noise is originates from external sources and cannot be eliminated, this background noise is noted as reference in PD analysis.
6. The test voltages are increased in steps of 1 kV until the first PD occurrence is observed. The voltage when the first PD occurrence observed is defined as PDIV. During observation of PDIV, the lowest PD range at given noise level should be used;
7. Performing several measurements at PDIV in order to collect different PD properties;
8. Increasing voltages in steps (e.g. $3kV_{peak}$ per step) up to $2*U_0$. The different PD properties are collected at each voltage levels. At each voltage level measurement are performed 3 times.
9. PDEV is determined by decreasing voltage from 2 Uo until partial discharges is cease to occur in the test object.
10. Steps 5, 6, 7 and 8 are repeated for the other two phases. Special step for 3-core belted cable system, measurements at all three phases together (three phases in parallel) are necessary.

Figure 5.6 shows the flowchart of PD measurement test procedure on cable system using OWTS system.

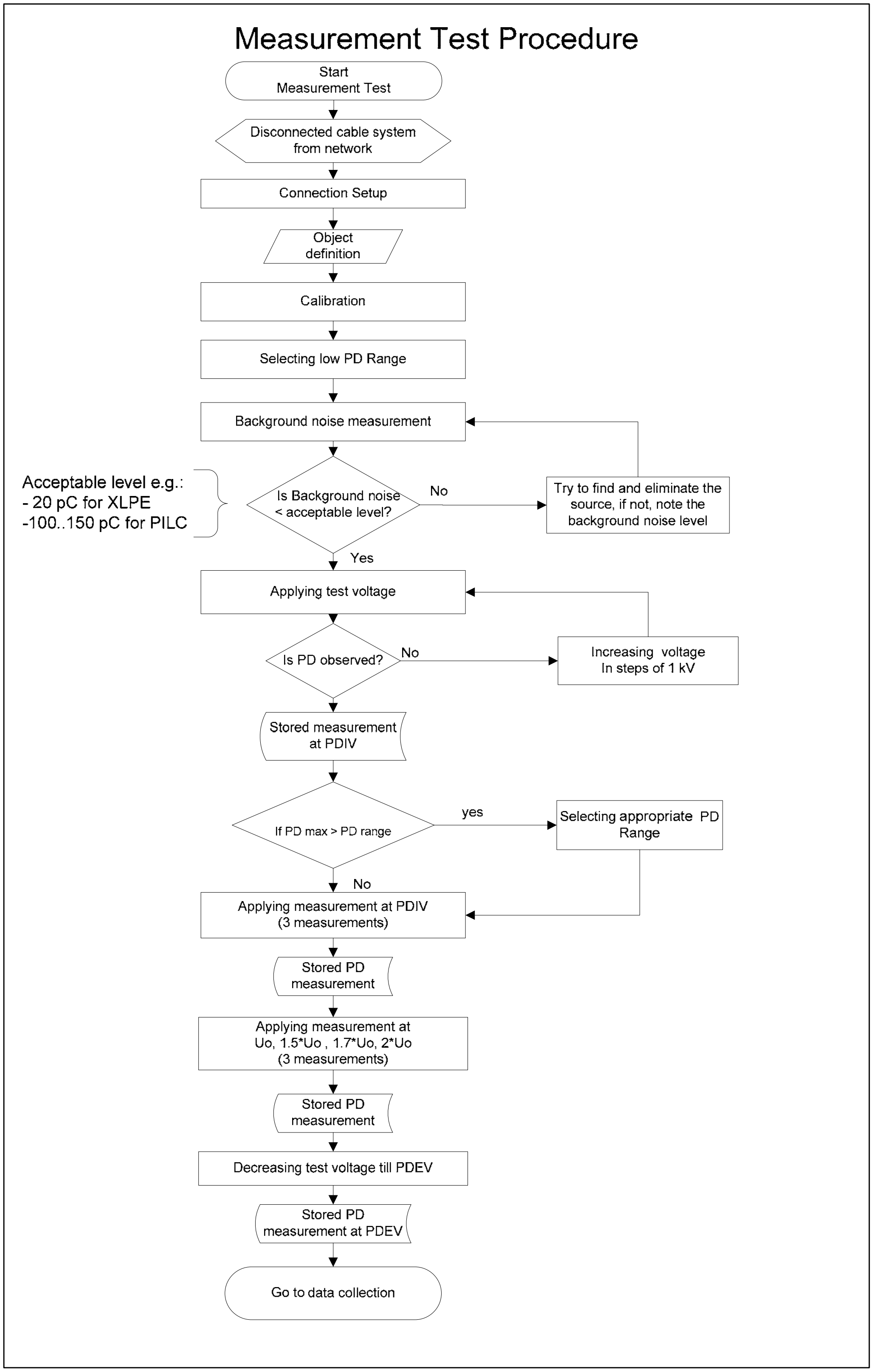


Figure 5.6: Flowchart measurement test procedure

5.4 Conclusions.

In this chapter, generic problems obtained during performing PD measurement are presented. To obtain a good representative of PD occurrence in the cable insulation cable, the following measurement should be taken in to account:

1. PD background noise test should be performed in order to distinguish PD from cable system and PD produced by disturbances.
2. PD range should be selected properly to increase the sensitivity of the measurement.
3. PD measurement should be performed in several voltage levels in order to get representative picture of PD occurrence in the cable system. The number of measurements in each voltage level has to be chosen in such away, that sufficient PD pulses will be registered for further analysis.

CHAPTER 6

Data Collection and Analysis

Partial discharge measurement is one of the sources information for the condition assessment of the cable system. While performing PD measurement on distribution cable system, the existence of partial discharge above specified sensitivity are detected and several PD parameters are recorded and stored in measurement tool. Furthermore the location of PD source is analysed to know which components have PD activities in the cable system. For analysis of location of PD activities on a cable system, time domain reflectometry (TDR) is used and the result of PD localisation is represented in PD mapping. The location of PD activities is determined by calculating the time different between the original pulse and the reflection pulse. The accuracy of PD localisation is determined by the accuracy in selecting of original and reflection pulse during calibration. Inaccuracy in selection of original pulse and reflection pulse will result in wrong localisation of PD activity and at the end a good condition assessment of cable system can not be obtained from this localisation.

All relevant information obtained from a PD measurement on cable system should be collected and this data collection is called *fingerprint* of a power cable [10]. The fingerprint of a power cable is very important in condition assessment of cable system because it gives indication about the condition of the cable system and its accessories.

The fingerprint may consist of the following two types of data:

- PD mapping
- PD parameters

This chapter discusses data collection obtained from PD measurements on distribution power cable system and data analysis that can be done using these data. Several problems which observed during performing PD mapping are also discusses in this chapter.

6.1 Performing PD mapping

PD mapping is the representation of the PD occurrence in the length of the cable system. In the PD diagnostic using OWTS system, PD localisation is performed on the OWTS explorer. PD mapping contains all measured partial discharge as well as the location from which PD originated in the cable system. The weak spots in the insulation of different component can clearly be seen in this PD mapping and quick assessment of the components can be made.

Analyzing the PD location need an accurate selection of the matching original pulse and reflected pulse. The quality of the PD mapping is determined by the accuracy in selection of the matching original pulse and reflected pulse. The user who perform PD mapping should be able to recognize the correct original pulse and its matching reflection pulse. General problem obtained during localisation of PD occurrence:

Selection of original and reflection pulse

Selection of original and reflection pulse determines the location of PD activities in a cable system. The following are example of some problems that might occur during selection of original and reflection pulse in time domain reflectometry:

1. Detection PD occurrence in the terminations

   PD source originated from one of terminations is indicated by the time difference between original pulse and reflection pulse is equal to the time different between the injected artificial PD pulses at calibration. The problem may be faced in determining the position of the termination whether in remote termination or near termination.

   Figure 6.1 shows an example of PD originated from terminations. Figure 6.1a and figure 6.1b show the same time interval between the PD pulses ($\Delta t = \Delta t_{calibration}$). The position of the PD source can be determined by analyzing the width of the pulse. PD pulse originating from remote termination is wider than PD pulse originating from near termination.

2. PD source is located closely the remote termination.

When PD source is located closely to the remote termination, time different between the original and the reflection pulse is smaller than $\Delta t_{calibration}$ and the detected PD pulses are superimposed. Figure 6.2 shows the PD pulses are superimposed in the time domain. In OWTS explorer, it is possible that TDR peak-match algorithm select pulse A’ as the reflection pulse. The user should check and select pulse A as original pulse and B as reflection pulse.

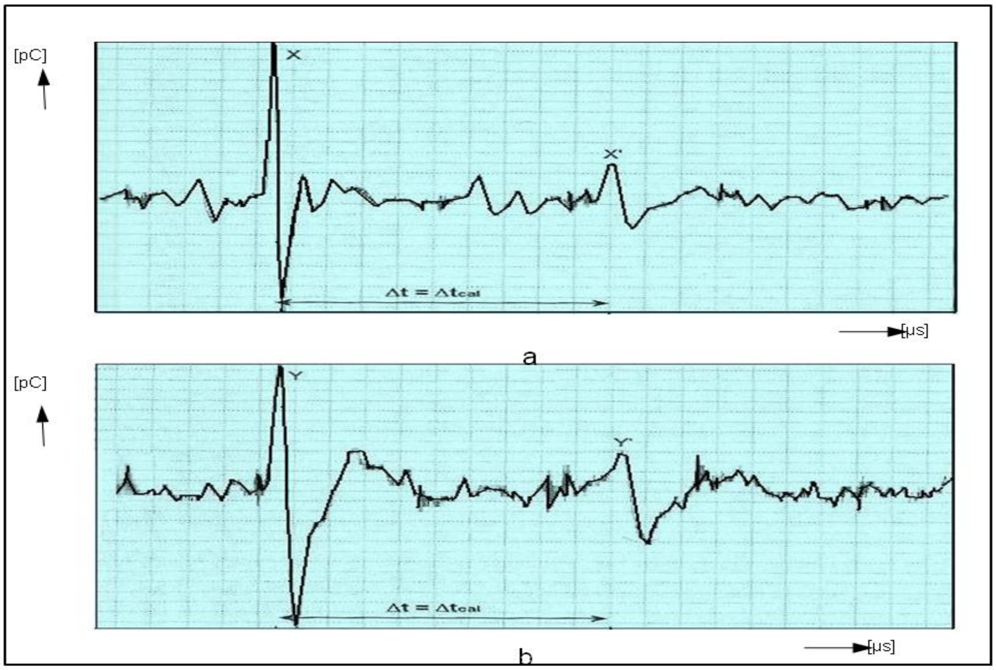


Figure 6.1: PD pulses in time domain obtained from cable terminations ($\Delta t = \Delta t_{cal}$)[6]:
a. PD source in the near termination
b. PD source in the remote termination

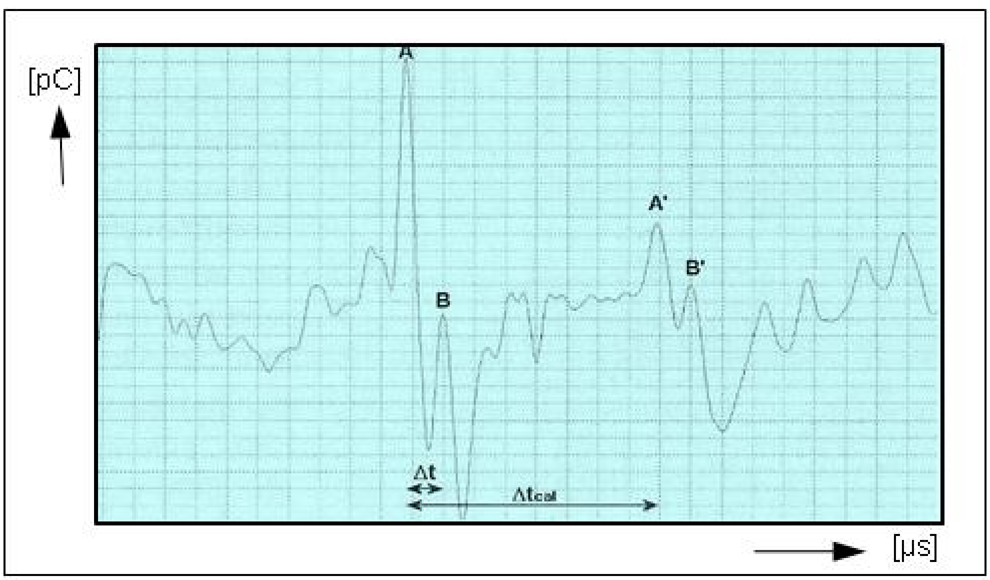


Figure 6.2: PD pulses in time domain originated from PD sources close to the remote termination [6].

3. Multiple PD sources in a cable system

   Multiple PD events can be active in a cable system during performing PD measurement at the same time [6]. Figure 6.3 shows multiple PD event occur in a cable system analysed in time domain. Analysing time different between the original pulses (Ai, Bi, Ci) and their reflection shows that A and C have the same time different. It indicates that PD event A and PD event C are originated from the same location and PD event B is originated from another location.

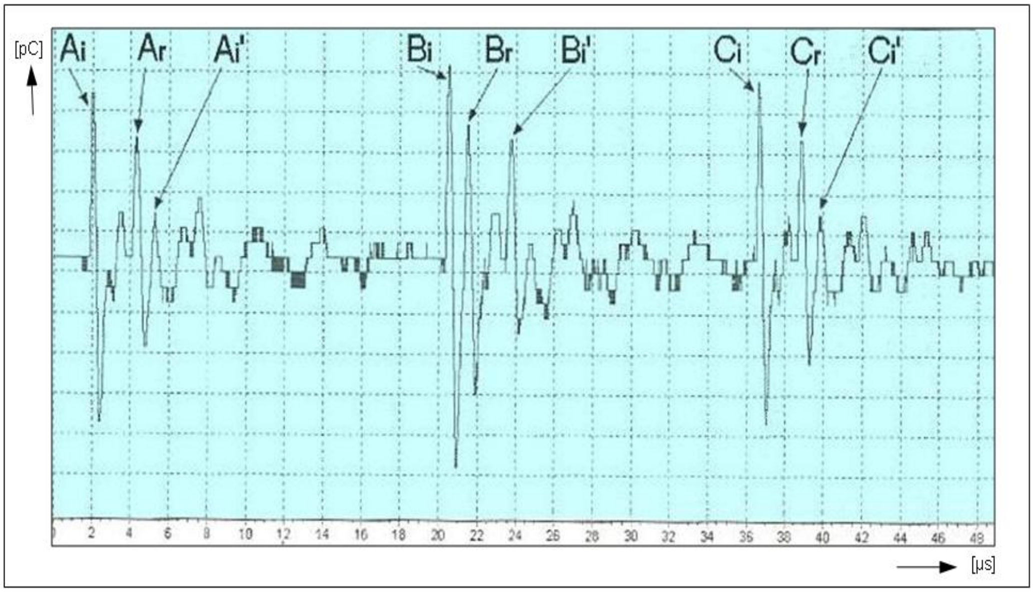


Figure 6.3: Multiple PD sources occurring in a cable system. Time different [6].

The uses of automatic mode

In OWTS explorer, there is an option to perform PD mapping use automatic mode. Using this automatic mode, the TDR peak-match algorithm selects the original pulse and its reflection and accepts it as PD occurrence in the cable system automatically. This option can lead to erroneous interpretation of localisation data because TDR peak-match algorithm does not always select the reflection pulse that matches the original discharge pulse, meanwhile using automatic mode in the OWTS explorer means all pulses and reflections that are selected by TDR peak-match algorithm will automatically be accepted. In this case some of pulses that are accepted might be wrong.

Wrongness in selecting and accepting of the original and reflection pulse will result in wrong localisation of PD occurrence in the length of the cable system. This case will affect the quality of measurement and a good assessment of the cable system can not be achieved from that measurement.

To obtain a good PD mapping, using manual mode is suggested. Using manual mode in OWTS explorer gives possibility to check and select the original and reflection pulse correctly.

In PD mapping, localisation of PD occurrence and PD level are shown along the length of the cable system. Two types of PD mapping which indicates the PD occurrence can be obtained in the cable system:

- Concentrated PD, this type of PD mapping indicates weak spot related to degradation of insulation. The PDs occurs at a specific location in the cable system.
- Scattered PD, this type of PD mapping indicates PD occurrence in the cable system which can be effect of the pressure and temperature changes in the paper oil insulation caused by switching off the cable system and short cooling process [6]. Scattered PD can also be obtained by wrongly accepted PD pulse caused by disturbances / background noise [17].

Looking at experience in performing PD measurements by PLN, most of PD mapping were made by using automatic mode as result more PD occurrence were observed in PD mapping. Figure 6.4 shows the comparison between PD mapping were made by PLN using automatic mode and PD mapping that were performed by using manual mode.

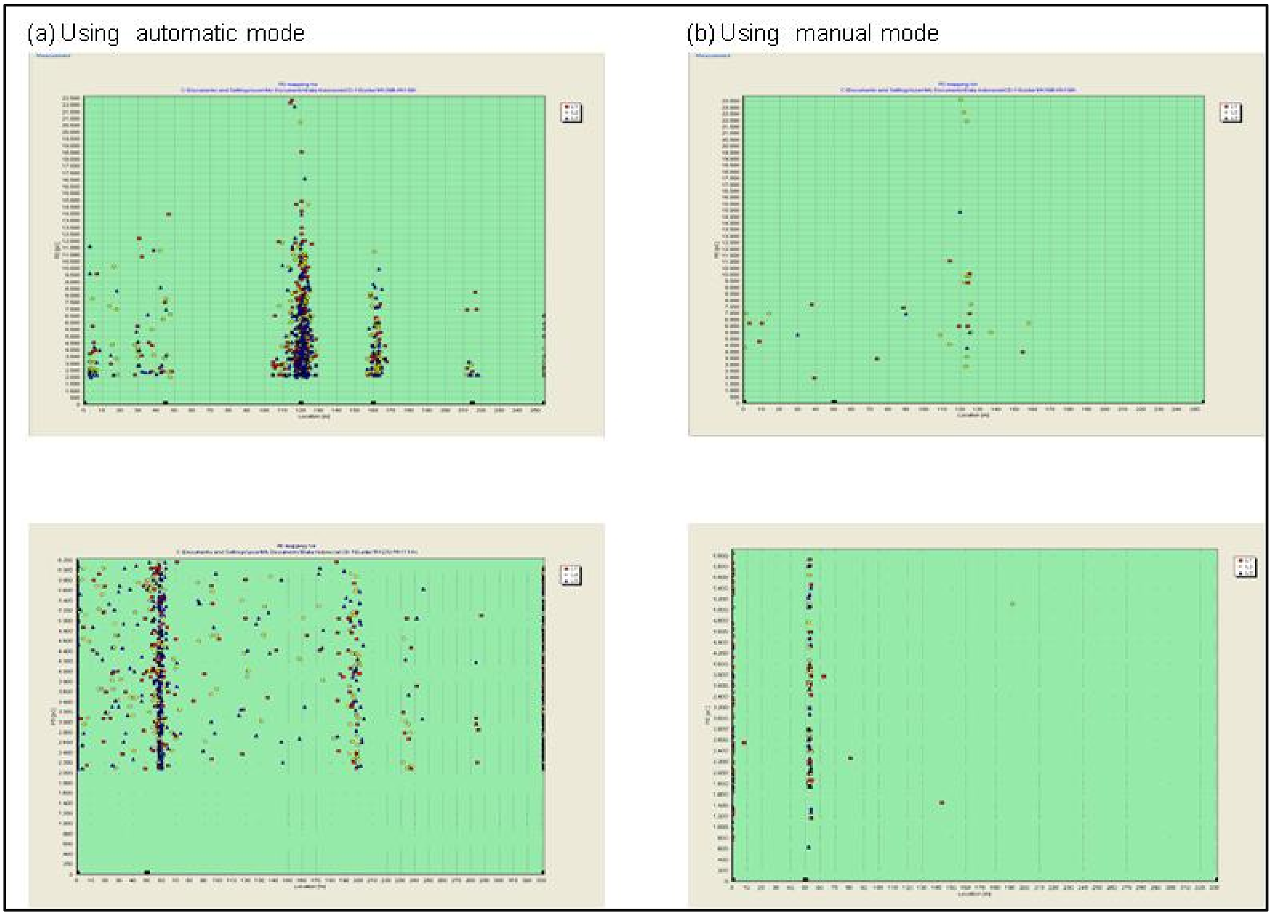


Figure 6.4: the comparison between PD mappings made by using automatic mode and PD mapping that made by using manual mode

6.2 PD Parameters

After performing PD mapping in OWTS explorer, database report can be generated. The database report contains all information from PD measurement on cable system. This information together with PD mapping are collected in a so called fingerprint of a power cable [10]. Fingerprint of cable system can be used to analyse the existence of partial discharges in the cable system. PD parameters obtained from PD measurement can be provided at component level as well as at cable system level. The PD parameters of cable system which obtained from PD measurement using OWTS system containing the following parameters:

a. PDIV : the partial discharge inception voltage is the voltage at which the first PD is observed in the component;

b. PD_{max} at PDIV : the maximum PD magnitude/level occurring at partial discharge inception voltage (PDIV);

c. PD_{avg} at PDIV : the average PD magnitude/level occurring at partial discharge inception voltage (PDIV);

d. PD_{max} at U_o : the maximum PD magnitude/level occurring at nominal voltage (U_o);

e. PD_{avg} at U_o : the average PD magnitude/level occurring at nominal voltage (U_o);

f. PD_{max} at 1.7 U_o : the maximum PD magnitude/level occurring at 1.7 times nominal voltage;

g. PD_{avg} at 1.7 U_o : the average PD magnitude/level occurring at 1.7 times nominal voltage;

h. PD_{oc} : the number of partial discharges that occurred in a particular component;

i. PD Pattern : The representation of the appearing partial discharges as a function of phase angle of the applied test voltage ;

Figure 6.5 is a proposed procedure of data collection to obtain finger print of a cable system from Partial discharge measurement using OWTS system.

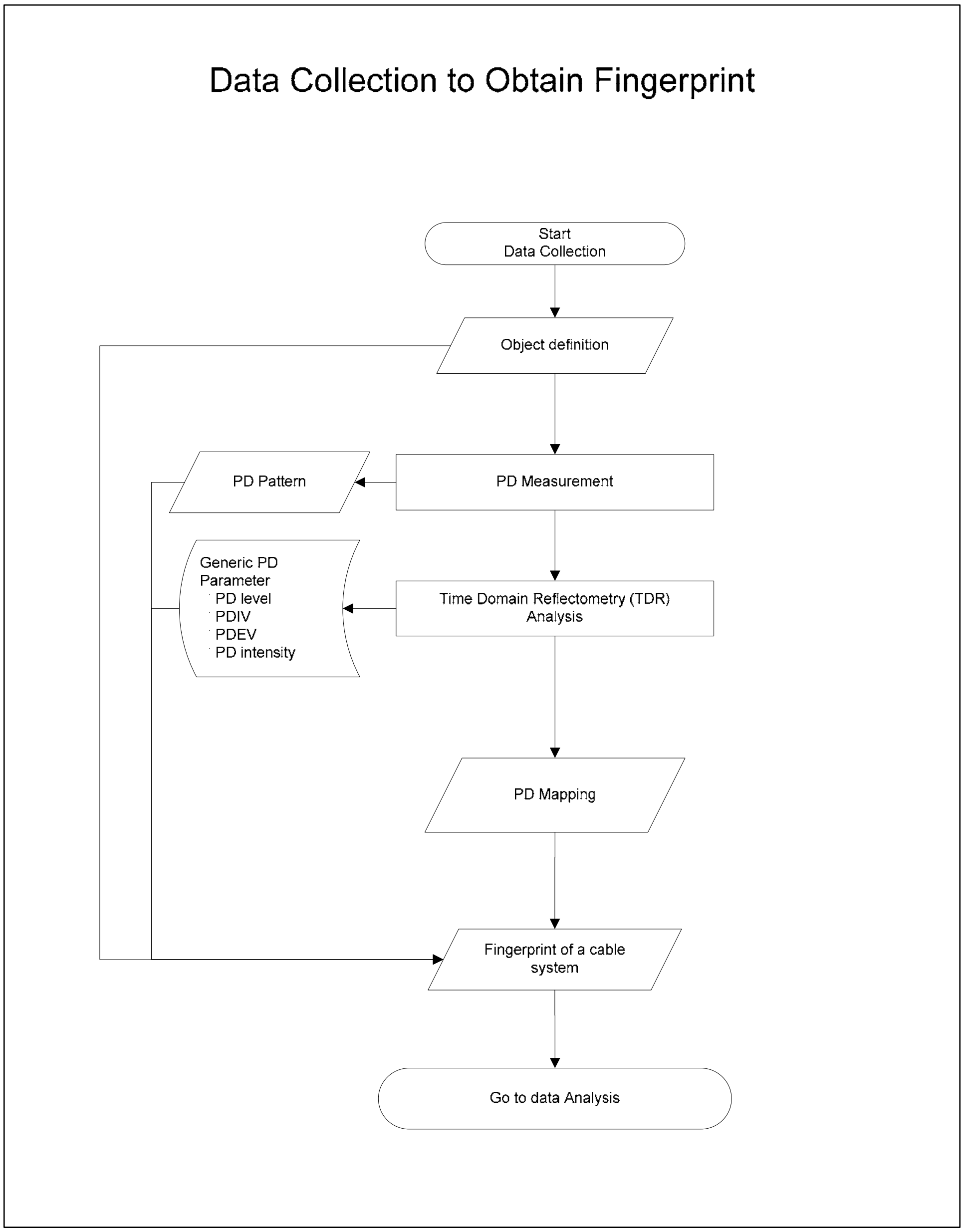


Figure 6.5: Flowchart data collection to obtain fingerprint of a cable system.

6.3 PD Measurement Report

After performing PD measurement, the PD test provider should provide measurement report to the owner of the cable system. Depending on the needs of the owner cable system, the format of PD measurement report may vary. In general a PD measurement report should contain information about type of measurement test, result of measurement test, conclusion and recommendations on possible corrective action to be taken. These information and measurement data that should be included in the PD measurement report are described in this section.

6.3.1 Measuring circuit and cable data

Measuring circuit describes the method that used in performing calibration and PD measurement. Test circuit and cable data are also included in this report. PD background noise must also be provided so that PD from internal system and external system can be distinguished.

In general measuring circuit and cable data consists of the following data:

- Measurement and calibration method
  In this section, the PD test provider should describe the measurement method and the calibration method that are used during measurement. The measurement tool and standard measurement that are used should be described clearly.
- Cable data
  Cable data contains relevant information about cable system e.g. location, owner, length, installation year, voltage rating etc.
- Test circuit
  In the test circuit, the connection of the measurement system to the cable system is depicted.
- PD background noise.
  Due to the fact that background noises are often present during performing PD measurement, the level of PD background noise should be noted in the PD measurement report.

6.3.2 Measuring Results.

Depending on the needs of the owner cable system, the test provider can provide the measurement result in different type. Measuring result consists of PD pattern, PD mapping and q-V curve. These results are provided in form of graph and these graphs must be described briefly. Figure 6.6 shows an example of PD measurement results of a PILC cable system. PD pattern in 2-dimensional (2D) at test voltage Uo and 2*Uo are provided for each phase. Partial discharge levels in function of voltage are also provided in the measurement result. The localisation of PD events along the length of the cable is provided in PD mapping. PD mapping can be provided in several voltages level (e.g. at PDIV, Uo, 2*Uo). PD mappings are provided in PD magnitude in function of the length of the cable and PD intensity in function of the length of the cable. Figure 6.7 shows example of PD mapping which are included in measurements report.

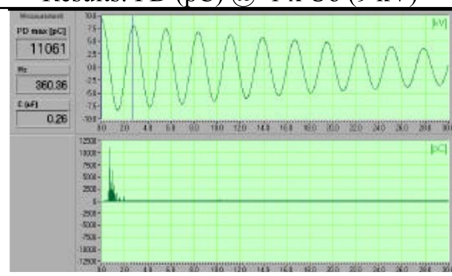
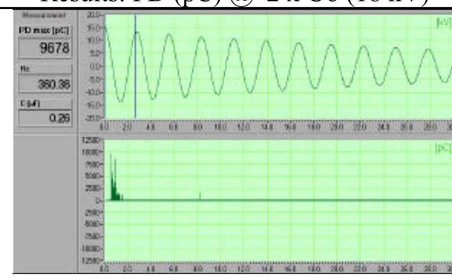
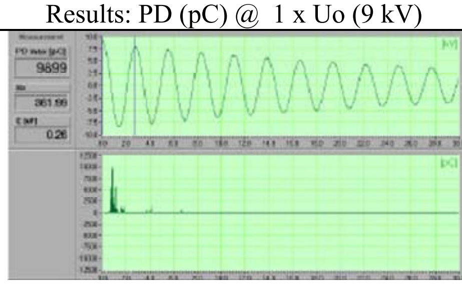
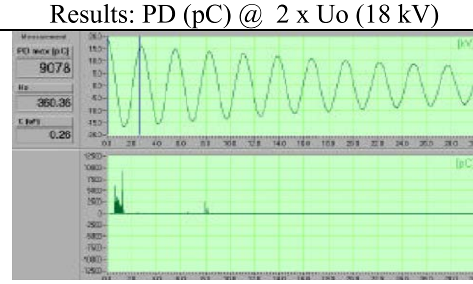
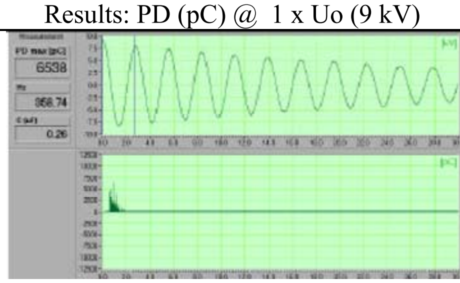
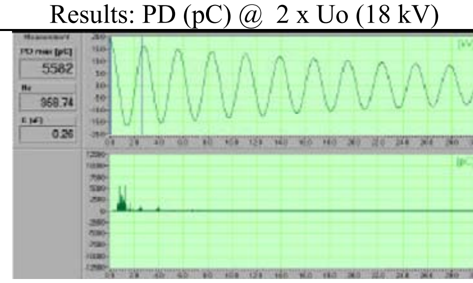
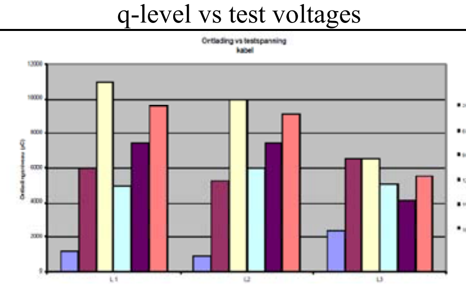
Phase L1	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		
Phase L2	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		
Phase L3	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		
Date	Notes	q-level vs test voltages
23-07-03	The figure below shows PD magnitude as a function of test voltage. PDIV was observed at 3kV. This means that during operations partial discharges cable are present. PD level at U_{nom} is ± 11.000pC discharge level. At higher higer voltage, PD level decreases up to ± 9.100pC at 18kVtop	

Figure 6.6: Example PD pattern and q-level vs test voltages which are included in PD measurement results

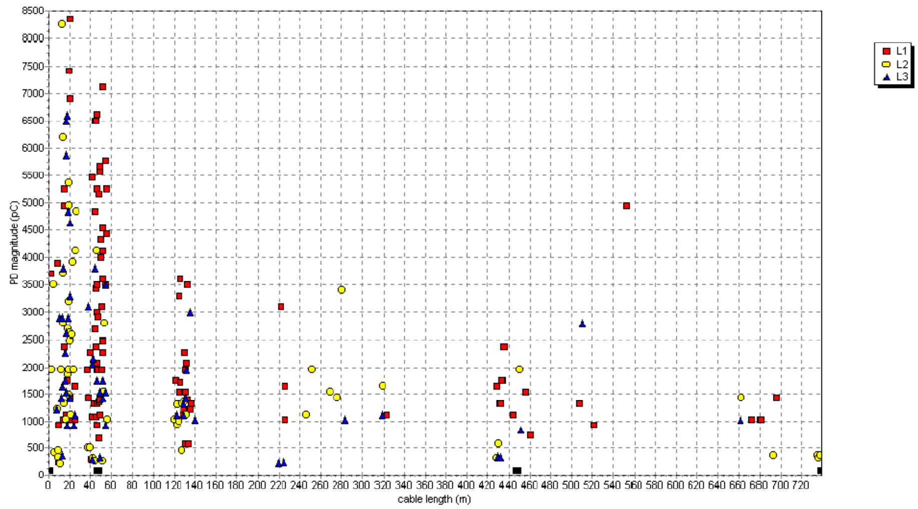
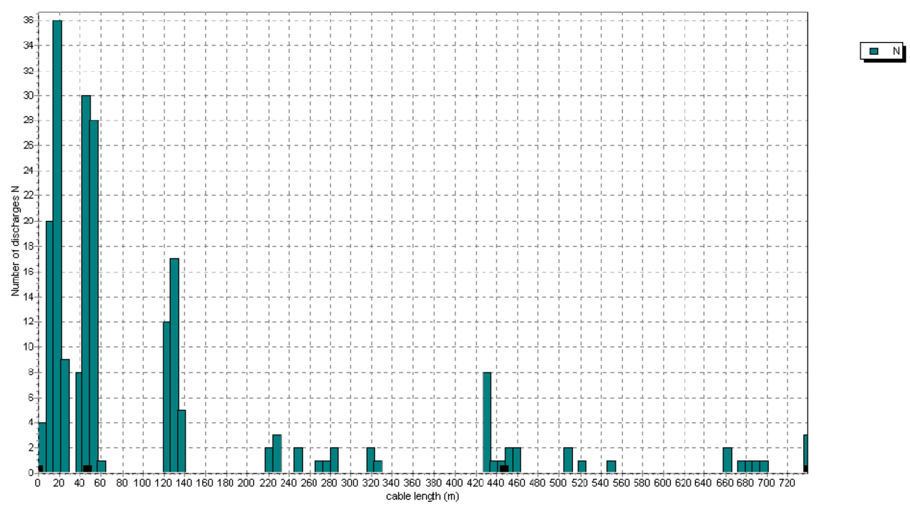
Date	Localisation of PD occurrence at 9 kV (Uo)
23-07-03	
	Concentration of Partial discharges at 9 kV (Uo)
	
	Notes
	After localization it can be seen that PD concentration is present in 46.5 meters from the station. Furthermore, there are discharges detected at near termination and a number of places in the cable insulation. Also, a slight concentration detected at 447 meters from near termination.

Figure 6.7: PD mapping which are provided in the measurement report.

6.3.3 Conclusions and recommendations

In the last part of PD measurement report, conclusion and recommendation must be provided. In the conclusion, the condition of the cable system based on the result of measurement should be described. Conclusions should also be able to describe the existence of partial discharges in the cable system briefly. Recommendation contains the recommended actions that should be taken based on PD measurement result. This recommendation is used by the cable owner as a source for maintenance decision.

6.4 Data Analysis

The existence of partial discharge on the cable system has to be analysed in order to know the severity of the partial discharger to the cable system. Analysis can be done using fingerprint of cable system which are obtained from PD measurement. The analysis of fingerprint of a cable system can be done in two groups; using the generic part (basic quantities) or using analysis part (derived quantities).

6.4.1 Generic part

Generic part is performed by analysing the basic quantities of PD parameters which are obtained from PD measurement. PD parameters that are used for generic part analysis consist of:

- PD level in pC or nC at PDIV, Uo, 1.7 Uo
- PDIV
- PDEV

Due to the fact that a new cable system should be PD free up to 2 Uo, partial discharge analysis for a new cable system is performed to check whether a cable system is PD free or not. Cable system was observed as PD free is considered as a good cable system and further analysis for this cable is not necessary. If partial discharge was observed in the cable system, further analysis is to check if partial discharge inception voltage (PDIV) and partial discharge extinction voltage (PDEV) whether it is lower than nominal voltage or higher than nominal voltage. If PDIV observed lower than nominal voltage, it means during normal operation the partial discharges are active in the cable. In the case that PDIV is just above nominal voltage and PDEV is lower than nominal voltage, small over voltage in the cable system will ignite the PD and PD will remain active in the cable system. This means PD will accelerate the aging process of the cable system in the location of PD the PD source. Further analysis for this cable system has to be done to analysis the location of the PD source.

Because the partial discharges are commonly observed in the old cable system, analysis of partial discharge is more intended to check whether the PD level is acceptable or not. A Just like in a new cable system, PDIV and PDEV in the old cable system are also analysed. Further analysis is performed to the cable system with PDIV or PDEV is lower than nominal voltage.

6.4.2 Analysis Part

Analysis part is performed to cable system after generic part has been analysed. This analysis is performed to see how serious the existence partial discharges in the cable system. This analysis can be done in three ways:

- Q-V curve analysis
- PD mapping analysis
- PD pattern analysis

Q-V curve analysis

By performing PD measurement at several voltage levels up to 2 Uo, it is possible to analyse the increasing of the PD levels in a function of the test voltage. This analysis is performed by making q-V curve.

Analysis of PD level in function of test voltage is very important due to:

- Information about the PD development in case of service AC overvoltage;
- Indication about future degradation development.

Partial Discharges level which is started at PDIV and it will increase with the increasing of the voltage up to 2 Uo. A slow increase of PD activities in function of the test voltage may indicate less harmful than a sudden increasing of PD level. Sudden increase of PD activity during increase of the test voltage may indicate a serious localise defect in the insulation.

Figure 6.8 shows two q-v curve of two different cable systems. Figure 6.8a indicates a slow increase of PD level when test voltage increased up to 2 Uo. Figure 6.8b shows sudden increase of PD levels in function of test voltage. Condition of cable system in figure 6.8a is less harmful than the condition of the cable system shown in figure 6.8b.

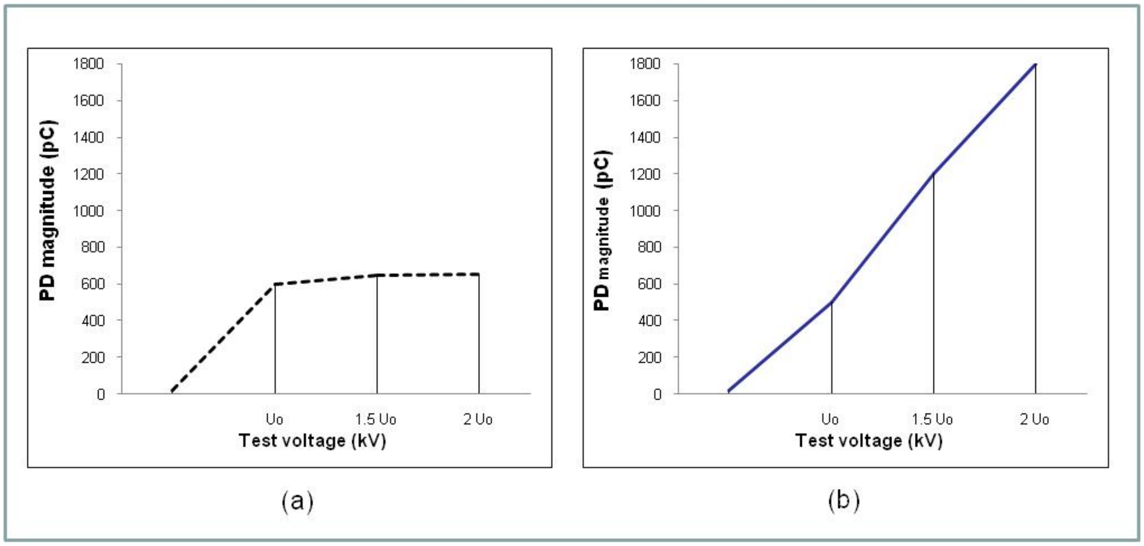


Figure 6.8: PD magnitude (q) in function of test voltage (v).

PD mapping analysis in function of location

PD mapping analysis is performed to see location of the partial discharge sources along the length of the cable system. In this analysis, the typical PD occurrence can be seen whether the partial discharges are concentrated in the component of the cable system or partial discharges are scattered along the length of the cable. The concentrated PD mapping indicates the weak spot in component of the cable system. PD events which are scattered along the length of the cable system do not indicate the ageing in the cable system, certain level of PD can be accepted depending on the type of the insulations, joints and terminations [10].

PD mapping in function of location can also be analysed by providing PD mapping at different voltages. In this case the PD activity can be determined whether occur during operation or not. Figure 6.9 shows the PD mappings which are provided at two different voltages, figure 6.9a is PD mapping in function of the location at applied test voltage $\leq$ Uo and figure 6.9 b is PD mapping in function of the location at applied test voltage $\leq$ 2 Uo. It can be seen in figure 6.9a PD measurement at test voltage up to Uo is PD free, it means that during operation there is no PD activities in the cable system. Figure 6.9b shows that PD activities observed at the test voltage higher than Uo. It means that in the case of service AC over voltage occurs, the PD activities may occur in the cable system.

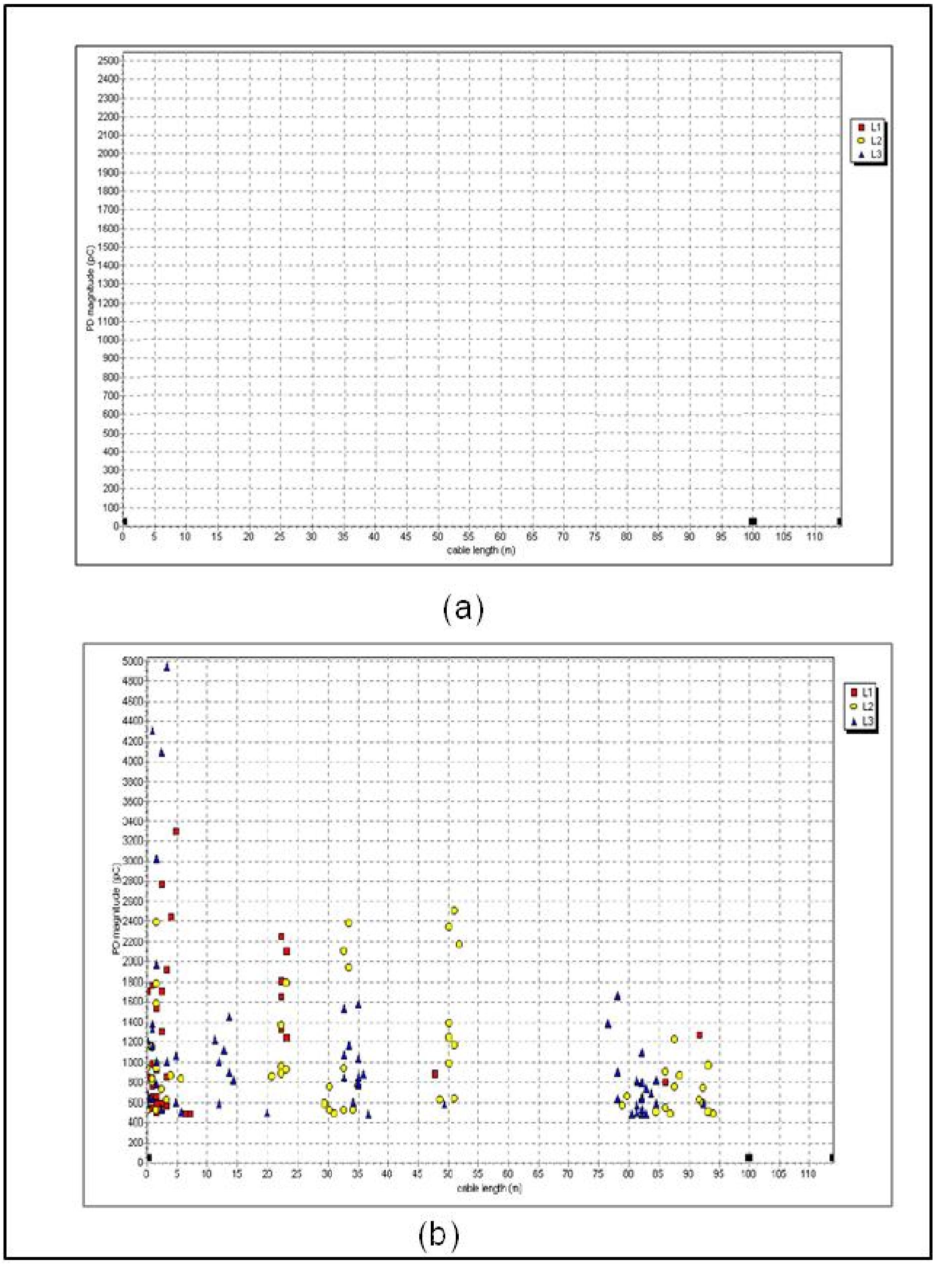


Figure 6.9: PD mapping are provided at different test voltages.

(a) At test voltage up to Uo, cable system is observed as PD free

(b) PD measurement up 2 Uo PD activities observed in the cable system

PD pattern

PD pattern analysis is used to determine the type of defect in the component of cable system. In PD measurement at DAC voltage, there are two types of PD pattern that can be obtained from measurement [6]:

1. The 2-dimentional (2D) PD pattern.

The 2-dimentional PD pattern is the applied DAC voltage and each PD occurrence level in function of time. Typical PD pattern from different types of insulation can be clearly distinguished [19]. PD pattern in an oil filled system, PD in voids, gaps or for example from PD between paper layers in a dry area of PILC cables can be clearly distinguished therefore PD pattern can be used to determined the source of PD occurrence in the cable system. Similar PD pattern for all phases in a cable system may indicate the PD sources coming from external noise. In addition to those analyses, PD pattern can also be used to determine the existence of PD activities in the cable system by providing PD patterns at different voltages for each phase. Figure 6.10 show PD pattern from PD measurement on XLPE cable system. In the PD pattern at test voltage Uo, There was no PD observed in the cable system. PD activities were observed at the test voltage 2 Uo, this situation indicated that during operation PD there is no PD active in the cable system. Partial discharges can only occur in the cable system if over voltage occur in the cable system.

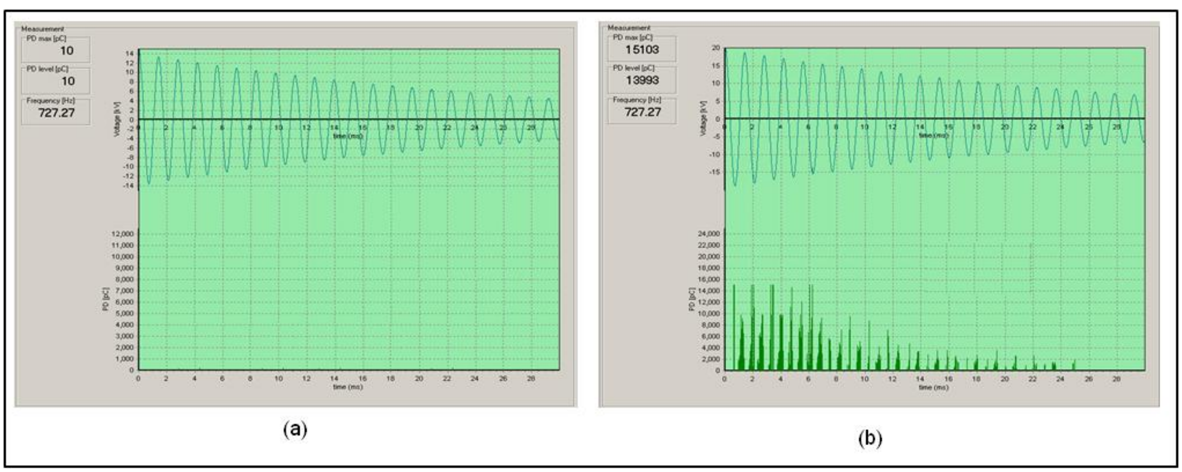


Figure 6.10: PD Patterns are provided at different test voltages.

(a) At test voltage up to Uo, cable system is observed as PD free

(b) PD measurement up 2 Uo PD activities observed in the cable system

2. The 3-dimentional (3D) PD pattern.

The 3-dimentional (3D) PD pattern is the representation of the appearing partial discharges as a function of phase angle of the applied test voltage [6]. PD patterns vary depending on in which cable component the PD source is located and depending on the typical defect in the component, therefore this PD pattern can be used to determine the type of defect in the component of cable system.

6.5 Conclusions

1. After performing partial discharge measurement, PD localisation is performed to determine the location of PD events along the length of the cable system. PD mapping is obtained as result of PD localisation. The quality of PD mapping is determined by the accuracy of selection of the matching original pulse and its reflection in time domain.
2. Partial discharges information obtained from PD measurement is collected to get fingerprint of the cable system.
3. Fingerprint of a cable system can be used to analyse the harmfulness of existence of partial discharges in the cable system.
4. Fingerprint of a cable system can be analysed in two groups:
   - Generic part is performed by analysing the basic quantities of PD parameters.
   - Analysis part is performed by analysing the derived quantities of PD parameter.
5. Analysis of partial discharge for a new cable is done to check whether the cable system is PD free or not up to test voltage 2 Uo. If partial discharges observed in a new cable system, localisation is performed to find the location of the PD source.
6. Analysis of partial discharge for an old cable is more intended to analyse whether the partial discharges level observed in the cable system is acceptable or not. In the case of PD presence in the cable some norms are needed to estimate the level.

CHAPTER 7

Condition Assessment

The final result of PD measurement should be provided in the form of PD measurement report. Based on this report the condition assessment of the cable system can be determined. The PD measurement report should be able to describe the actual condition of the cable system so that the owner can used this report as data input for maintenance decision. The following are the functions of the PD measurement report:

- To describe the actual condition of a cable system.

  Based on PD measurement the actual condition of the cable system decribed in the PD measurement report. The condition of the cable system described whether cable system is PD free or PD observed in the cable system.
- To provide information for further analysis of the cable status.

  Analysis that are performed to the fingerprint of cable system will give information about the status of the cable system. The condition assesment of the cable system is made based on this analysis.
- To give basic information for maintenance steps e.g:

  Based on analysis of PD measurement the recommandation for meintenance steps can be made. The following are some example of recomandation which are commonly used in PD measurement reports:
  - Condition of the cable system is OK, the next inspection can be performed within 5 years
  - Condition of the cable system is doubtful, PD measurement should be performed within one year.
  - Cable system is not OK , immediately replacement is required.

As described in the previous chapter, PD measurement report should contain measurement test information, measurement result, conclusion and recommendations for the next maintenance steps.

In this chapter three examples of PD measurement report which represent the three status/conditions of the cable system are provided. The first report is PD measurement report which indicates a cable system in a good condition, the second reports is PD measurement report of a cable system where the PD activity in the cable system is doubtful and the last report is report PD measurement of a cable system in condition Not OK.

7.1. Measurement system

For all three reports, the measurement system information is described as the following:

The PD measurements on 6 kV cable have been performed using OWTS 25 system. To perform PD measurements the cable section has to be on-site energised. For this purpose, OWTS 25 applies damped AC voltages [IEC 60060-3 Ed. 1/CD, IEEE 400.3, IEC 60270, IEC 8885-3].

Each of the phases of the cable is energized separately by damped AC voltages. In particular after charging the cable section up to selected voltage level (max 18 kV peak) the LC circuit as obtained from the cable capacitance and the external inductance (0.75 H) as present by the OWTS 25 system produces damped AC voltages in the range of 15 Hz- 500 Hz).

Calibration method:

According to IEC60270:

PD pulse is injected from calibrator to the cable system. The OWT System calibrates the PD magnitude and PD propagation pulse.

Analysis:

The following condition is detected depending on the following factors:

- Partial discharge inception voltage (PDIV)
- PD Intensity and PD magnitude.
- Location of the discharges
- PD pattern

Measuring equipment used:

Measurement Unit: OWTS 25 system (ser.no. 127.0202.001), Seitz Instruments AG

Calibrator: CAL1D (ser.no. 337), Power Diagnostix

Calibrator: CAL1E (ser.no. 338), Power Diagnostix

Software used:

OWTS 25, manufacturer Seitz instruments AG (application under Windows NT)

Standards:

Standards are based on experiences with partial discharge measurements on medium voltage cables in different medium voltage networks.

7.2. PD measurement report of a good cable system.

This measurement is an example of PD measurement which was performed to a cable system in a good condition.

Cable Data:

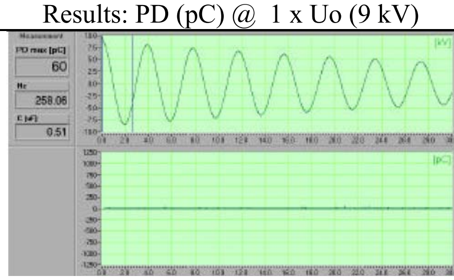
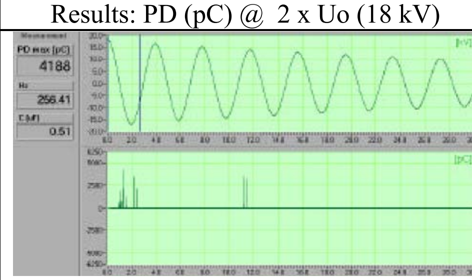
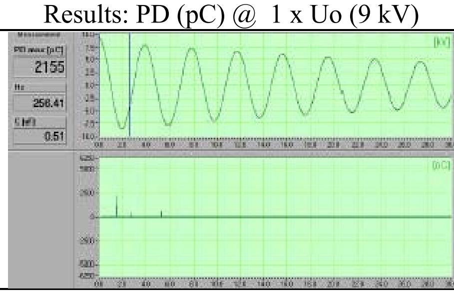
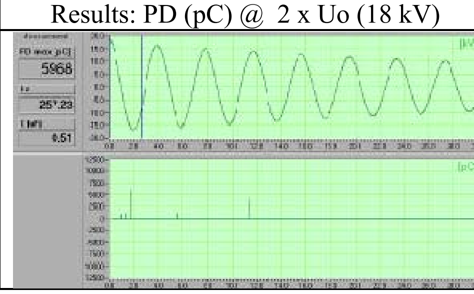
Insulation type : PILC

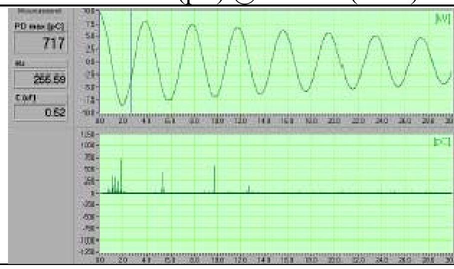
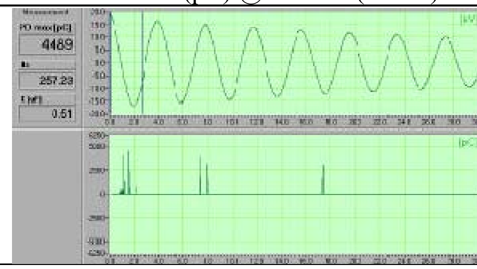
Cable length : 114 m

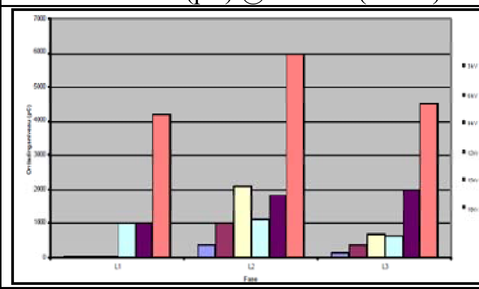
Voltage rating : Uo =10 kV

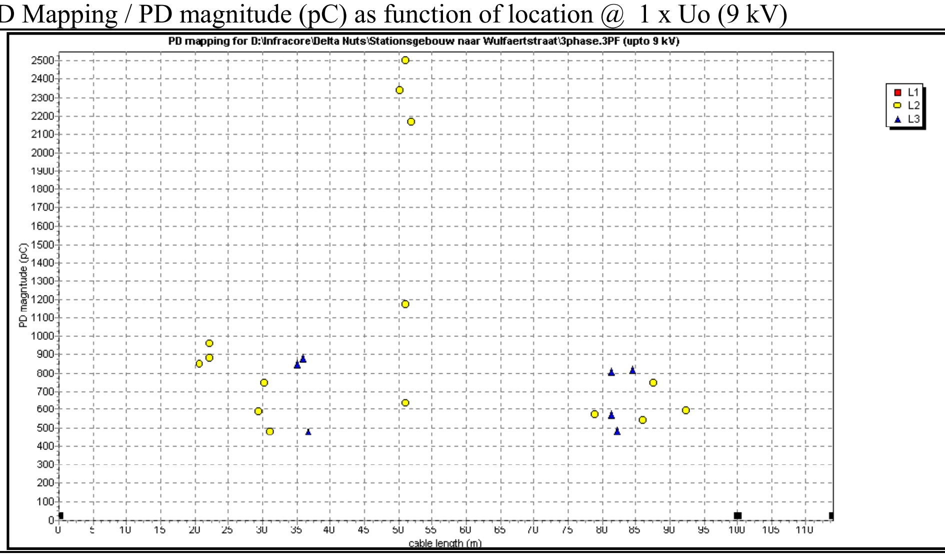
Cable capacitance (one phase): 0.51 μF

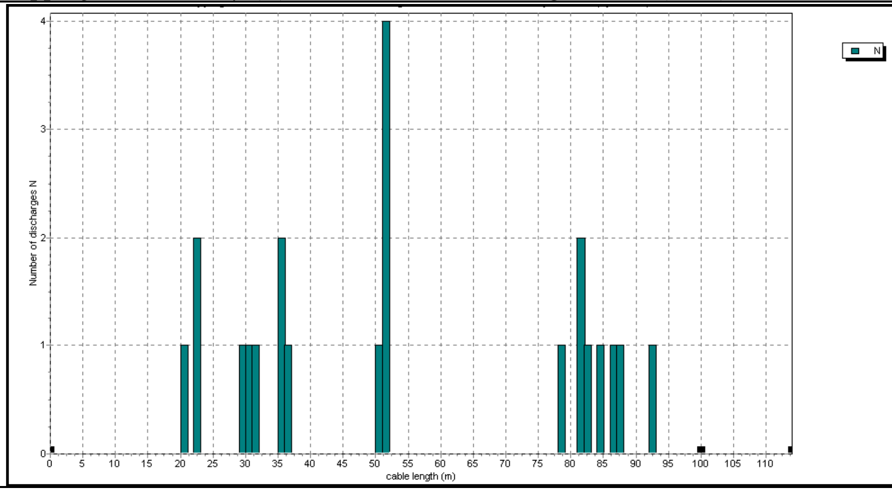
7.2.1 Measurement result

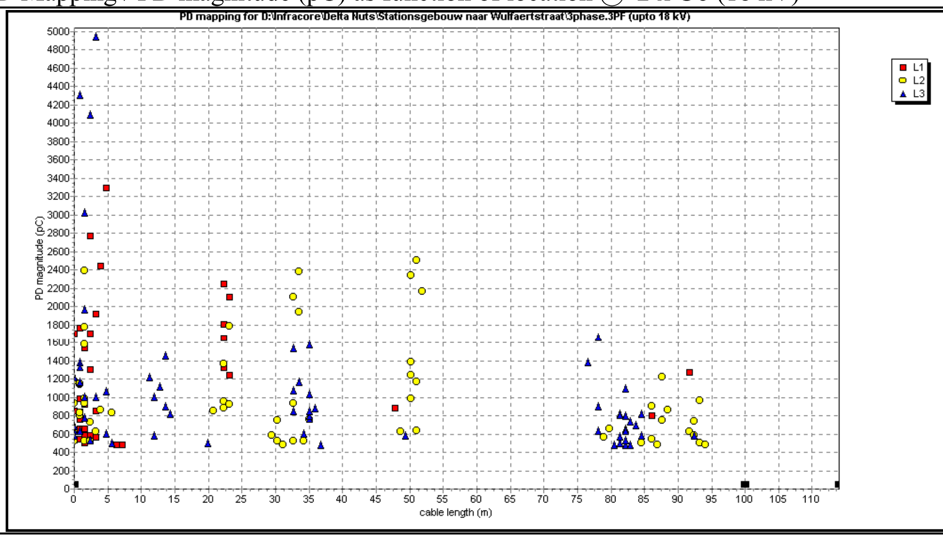
Phase L1	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		
Phase L2	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		

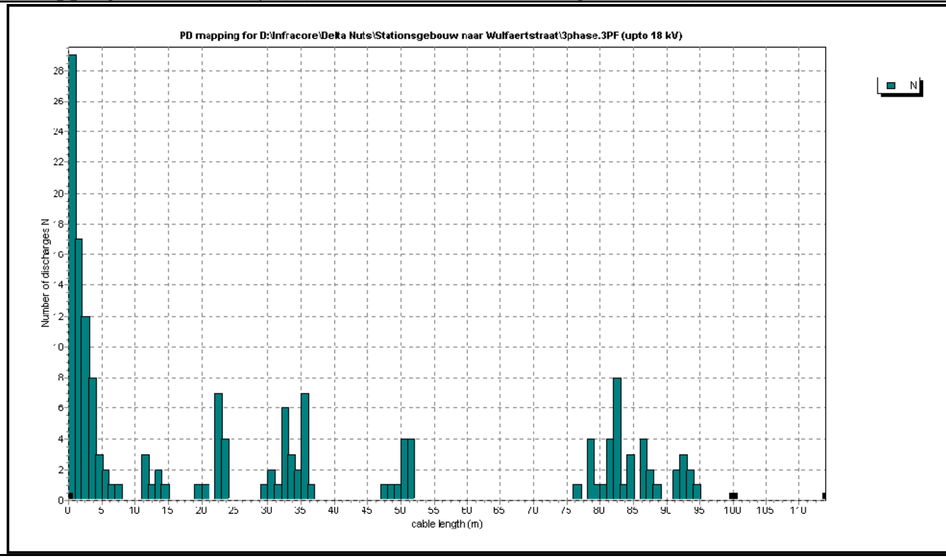
Phase L3	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		

Date	Comments	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03	The figure below shows the partial discharge as a function of the test voltage. PDIV is observed at 6 kV_{peak}. This means that during operation partial discharges present in the cable system. PD_{max} at Uo is ± 2.100pC. PD_{max} at test voltages the PD level 2 Uo kV_{peak} is ± 6.000pC.	

	Measurement Result
Date	PD Mapping / PD magnitude (pC) as function of location @ 1 x Uo (9 kV)
23-07-03	
	There is no strength PD concentration observed

Date	PD Mapping / PD intensity (N) as function of location @ 1 x Uo (9 kV)
23-07-03	

	Measurement Result
Date	PD Mapping / PD magnitude (pC) as function of location @ 2 x Uo (18 kV)
23-07-03	
	There is no strength PD concentration observed

Date	PD Mapping / PD intensity (N) as function of location @ 2 x Uo (18 kV)
23-07-03	
	Comments After localization it can be seen that there are some partial discharges in the cable insulation. There is also a concentration observed in 0 m.

7.2.2 Conclusions and Recommendations

Date	**Conclusions of the measurements**
23-07-03	Based on PD measurement, it can be concluded that: 1. PD activities are observed during operation 2. Partial discharges in 0 meters from measurement side are almost certainly caused by the test connection. The other discharges do not lead to immediate follow-up action. 3. It is recommended to perform PD measurement on this cable in the next 5 years.
Date	**Recommendation**
23-07-03	The next measurement should be performed in 2008

7.3. PD measurement report of a cable system with doubtful condition.

This measurement is an example of PD measurement which was performed to a cable system where the existence of PD activities is doubtful.

Cable Data:

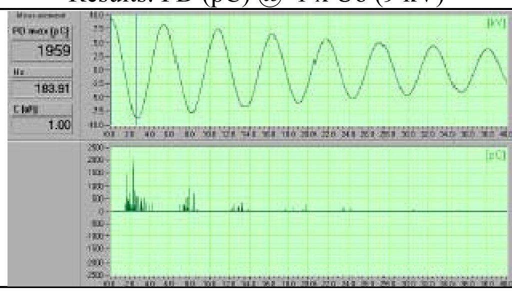
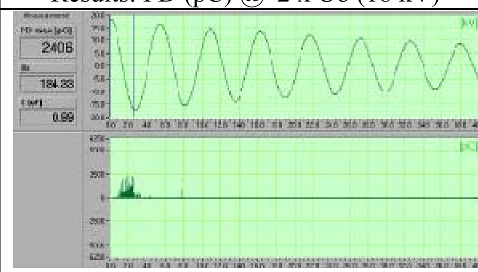
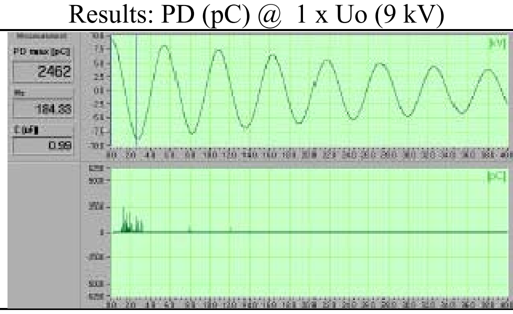
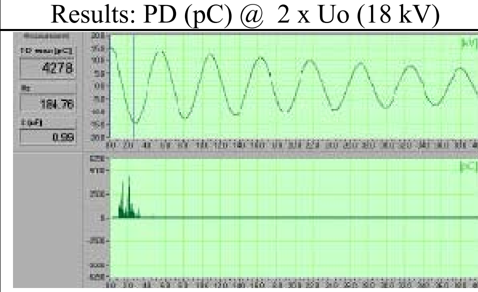
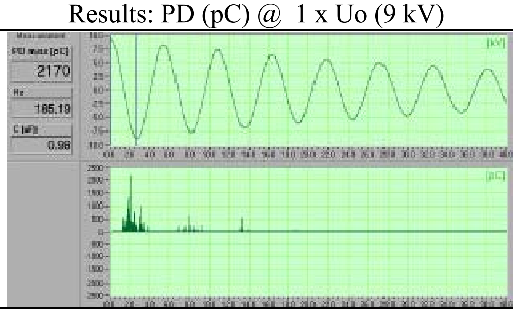
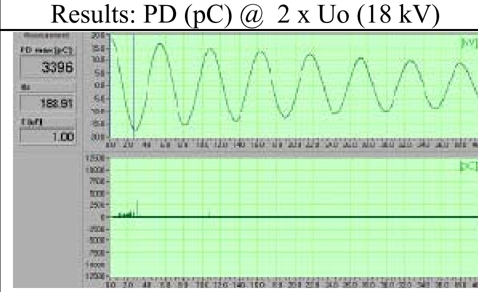
Insulation type : PILC

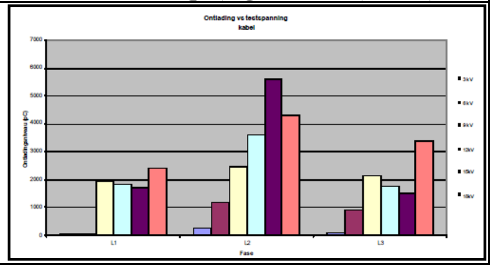
Cable length : 2937.5 m

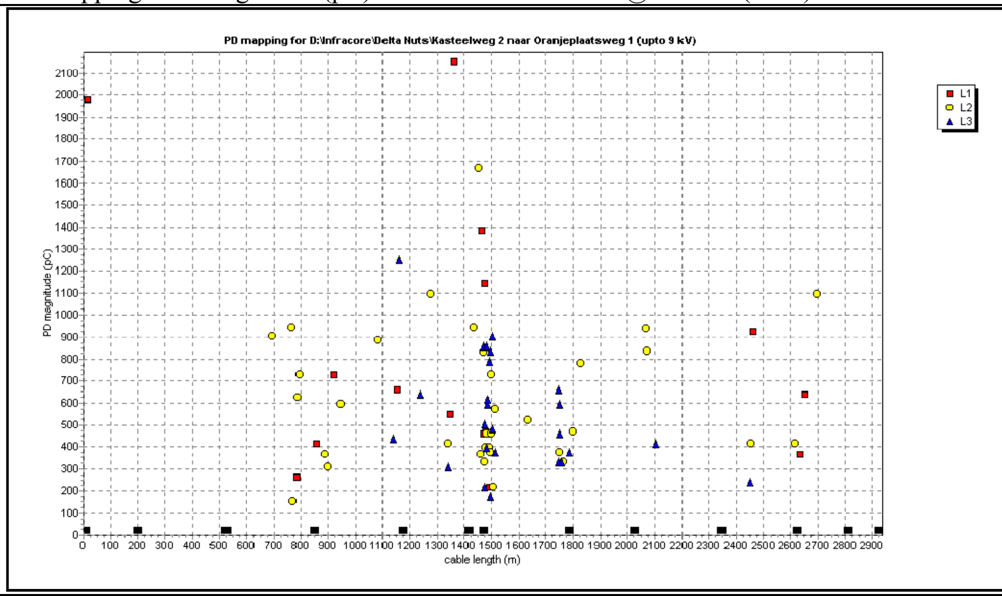
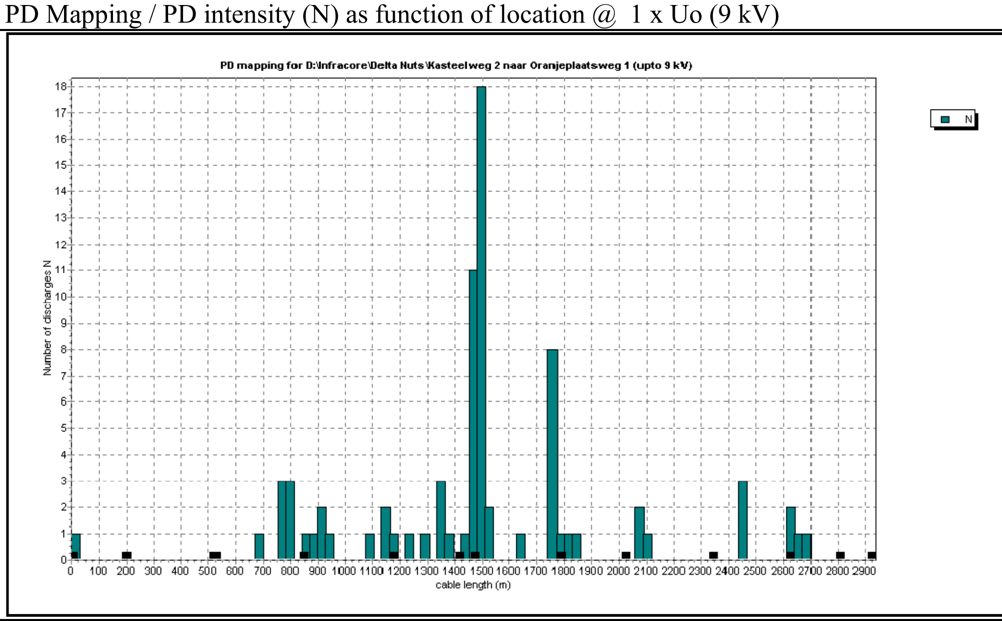
Voltage ratting : Uo =10 kV

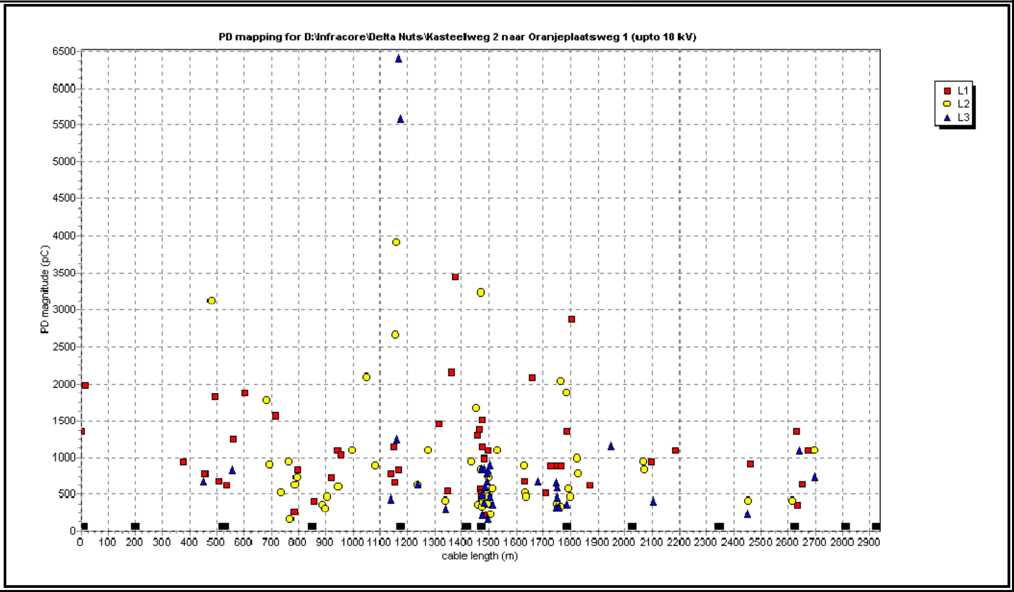
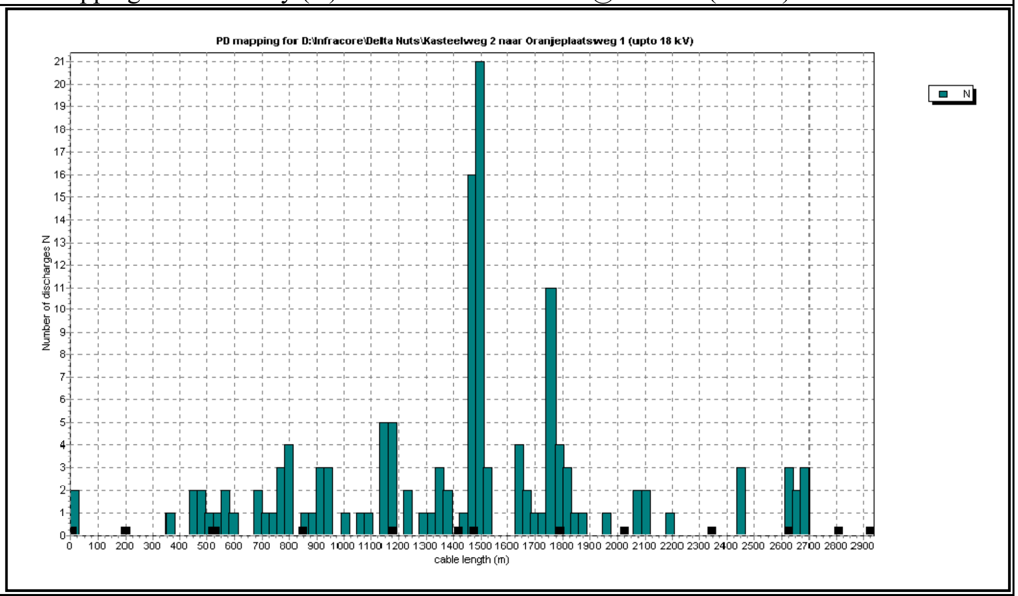
Cable capacitance (one phase): 1 μF

7.3.1 Measurement result

Phase L1	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		
Phase L2	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		
Phase L3	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03		

Date	Comments	Results: PD (pC) @ 2 x Uo (18 kV)
23-07-03	The figure below shows the partial discharge as a function of the test voltage. PDIV is observed at 3 kV_{peak}. This means that during operation partial discharges present in the cable system. PD_{max} at Uo is ± 2.400pC. PD_{max} at test voltages the PD level 2 Uo kV_{peak} is ± 4.300pC.	

	Measurement Result
Date	PD Mapping / PD magnitude (pC) as function of location @ 1 x Uo (9 kV)
23-07-03	
	PD concentration is observed at test voltage up to 9 kV
Date	PD Mapping / PD intensity (N) as function of location @ 1 x Uo (9 kV)
23-07-03	

	Measurement Result
Date	PD Mapping / PD magnitude (pC) as function of location @ 2 x Uo (18 kV)
23-07-03	
	PD concentration is observed at test voltage up to 9 kV
Date	PD Mapping / PD intensity (N) as function of location @ 2 x Uo (18 kV)
23-07-03	
	Comments After localization PD, it can be seen that there is concentration PD activity in location 1472 m from measurement side.

7.3.2 Conclusions and Recommendations

Date	**Conclusions of the measurements**
23-07-03	Based on PD measurement, it can be concluded that: 4. PD activities are observed during operation 5. PD concentration with Pd_{max} ±1.500pC is observed in the joint at 1472 meters from the measurement side. Based on experiences, this PD magnitude does not exceed the standard PD maximum for joint. 6. It is recommended to perform PD measurement on this cable next years.
Date	**Recommendation**
23-07-03	The next measurement should be performed in 2004

7.4. PD measurement report of a bad cable system.

This measurement is an example of PD measurement which was performed on a cable system with bad condition.

Cable Data:

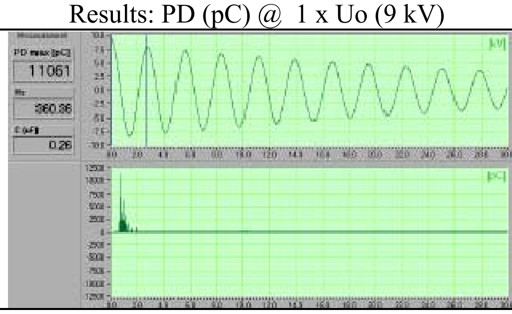
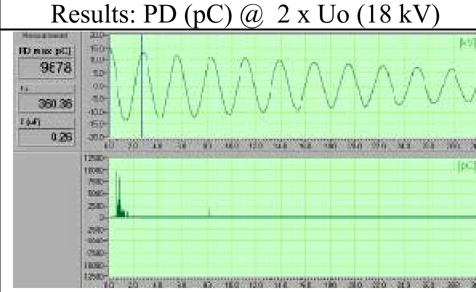
Insulation type : PILC

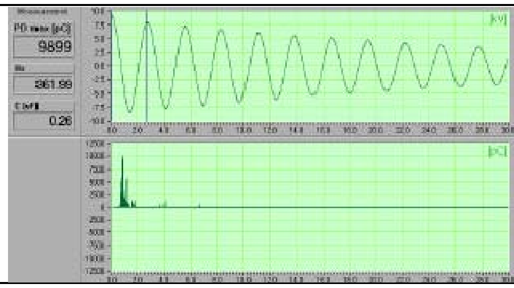
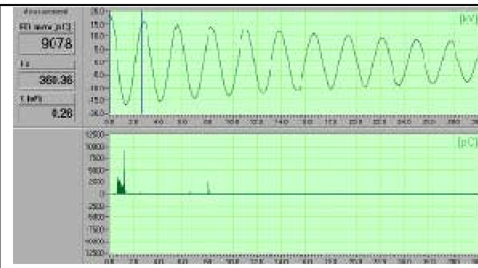
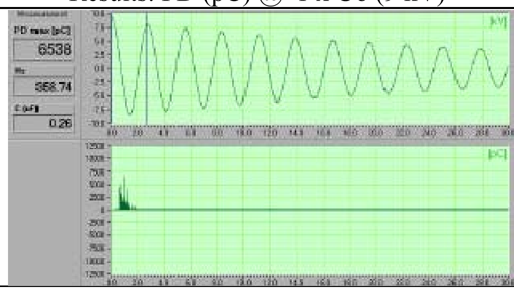
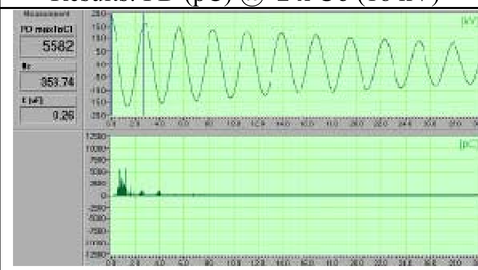
Cable length : 739 m

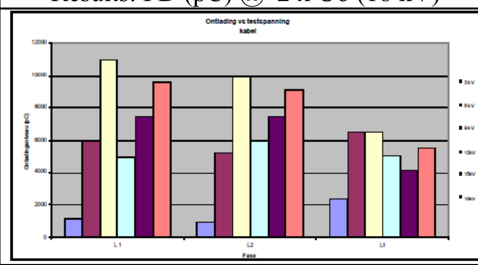
Voltage ratting : Uo =10 kV

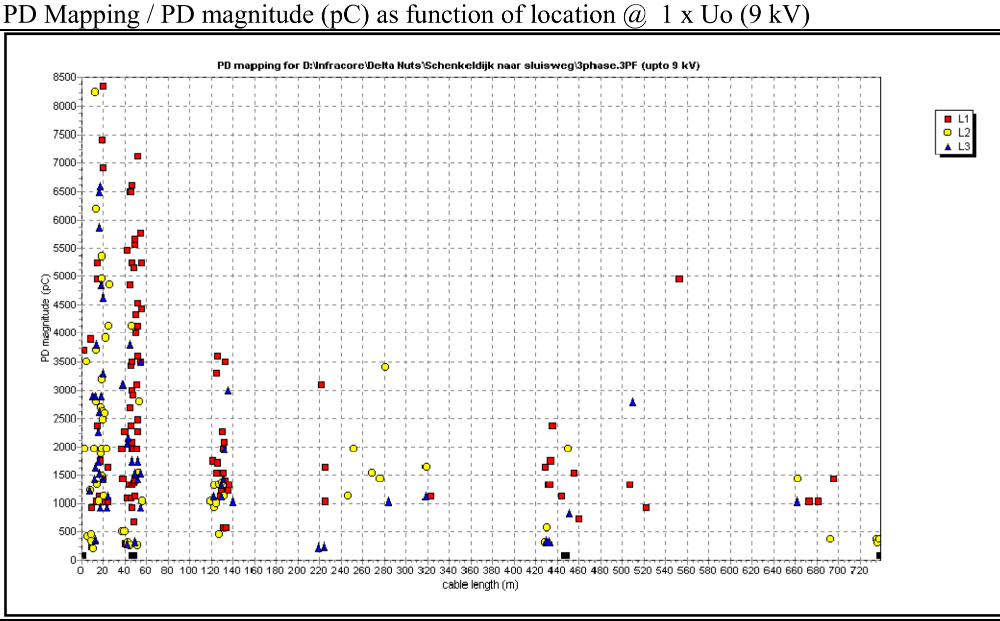
Cable capacitance (one phase): 0.26 µF

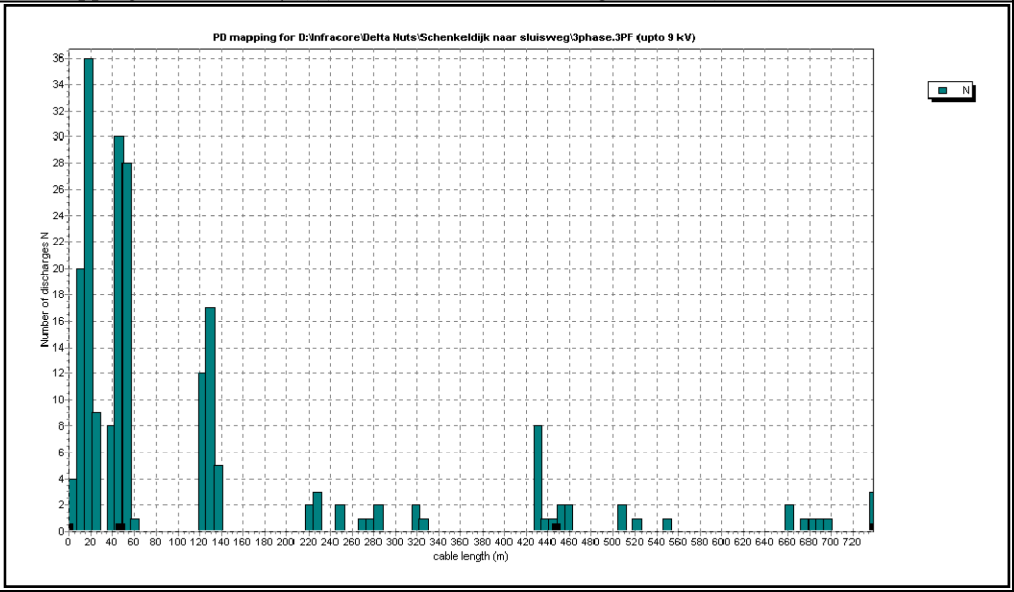
7.4.1 Measurement result

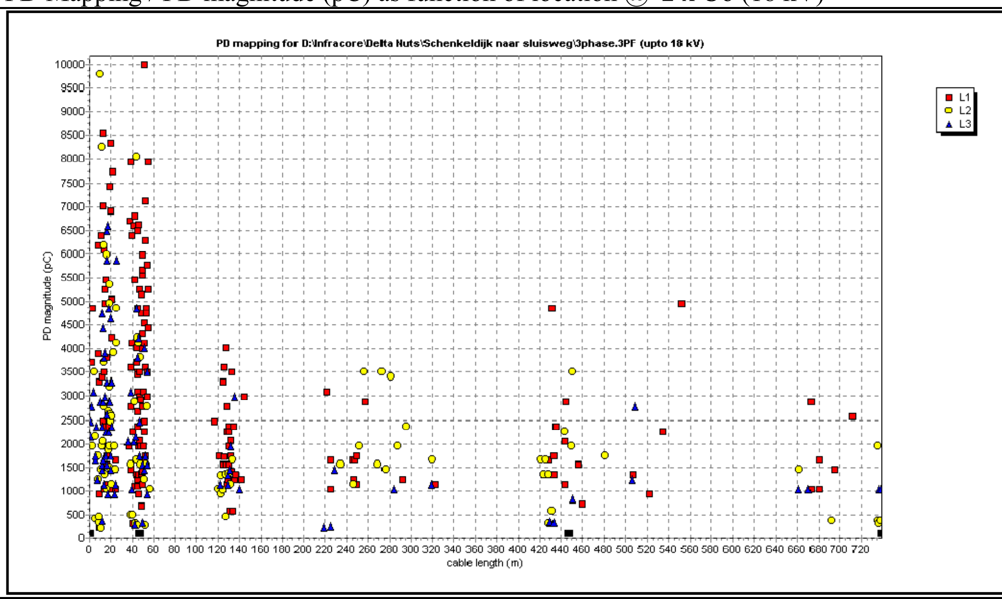
Phase L1	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
21-10-03		
Phase L2	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)

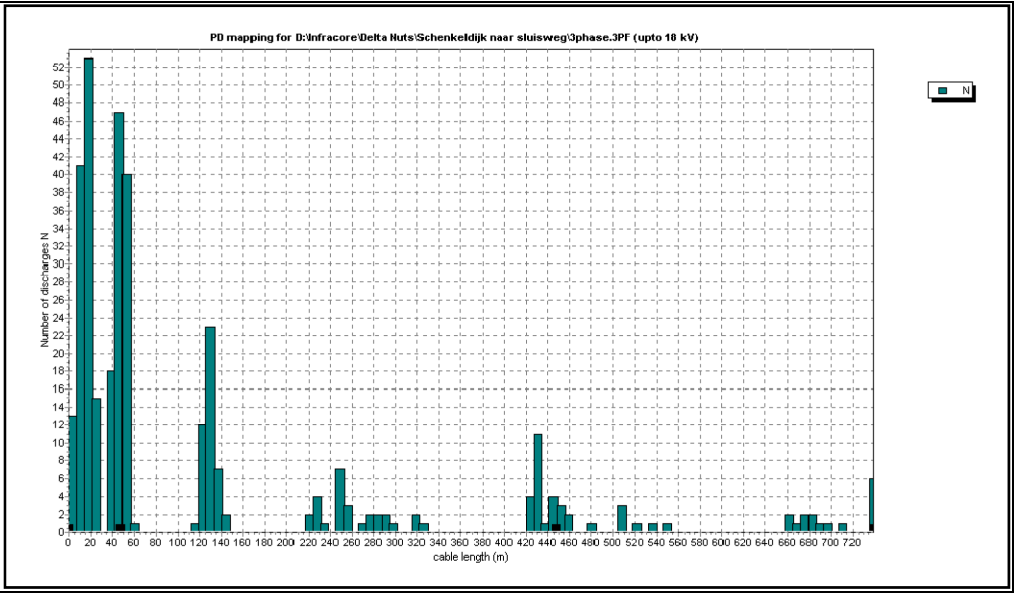
21-10-03		
Phase L3	Measurement Result	
Date	Results: PD (pC) @ 1 x Uo (9 kV)	Results: PD (pC) @ 2 x Uo (18 kV)
21-10-03		

Date	Comments	Results: PD (pC) @ 2 x Uo (18 kV)
21-10-03	The figure below shows the partial discharge as a function of the test voltage. PDIV is observed at 3 kV_{peak}. This means that during operation partial discharges present in the cable system. PD_{max} at Uo is ± 11.000pC. PD_{max} at test voltages the PD level 2 Uo kV_{peak} is ± 9.100pC.	

	Measurement Result
Date	PD Mapping / PD magnitude (pC) as function of location @ 1 x Uo (9 kV)
21-10-03	
	PD concentration is observed at test voltage up to 9 kV

Date	PD Mapping / PD intensity (N) as function of location @ 1 x Uo (9 kV)
21-10-03	

	Measurement Result
Date	PD Mapping / PD magnitude (pC) as function of location @ 2 x Uo (18 kV)
21-10-03	
	PD concentration is observed at test voltage up to 9 kV
Date	PD Mapping / PD intensity (N) as function of location @ 2 x Uo (18 kV)

21-10-03	
	Comments After localization PD, it can be seen that there is concentration PD activities in location 46 m and in 0 m from measurement side. A slight concentration is also observed in 447 m from measurement side.

7.4.2 Conclusions and Recommendations

Date	**Conclusions of the measurements**
21-10-03	Based on PD measurement, it can be concluded that: 1. PD activities are observed during operation 2. PD concentration in 0 meter from measurement side may caused by connection of measurement system. 3. PD concentration with Pd_{max} ± 5000pC is observed in the joint at 46.5 meters from the measurement side. Based on experiences, this PD magnitude exceed the standard PD maximum for joint.

Date	**Recommendation**
21-10-03	Immediately replacement of joint in 46.5 meter from measurement side is required.

7.5 Conclusions

1. After performing PD measurement, the result of the measurement is provided in the PD measurement report. PD measurement report describes the condition asssessment of the cable system and provides information for further analysis of the cable system. PD measurement report also gives recommendation for maintenance report.
2. To obtain sufficient information for condition assessment of cable system, PD measurement report should contain measurement test information, measurement result, and recommendations for the next maintenance steps.
3. In this chapter three examples of PD measurement report which depict three condition of cable system are provided.

CHAPTER 8

Conclusions and Recommendations

Due to the facts that performing partial discharge measurement at damped AC voltage using OWTS system is powerful measurement and condition of cable system in the field is very complex, it is importance to have a procedure to obtain a good PD measurement. In this thesis guidelines procedures have been proposed in performing PD measurement to have sufficient information for condition assessment of cable system

8.1 Conclusions

Based on experiences obtained by PT PLN (Persero) Jakarta Raya dan Tangerang and German, focus should be paid to several aspects to obtain sufficient information for condition assessment:

1. Object definition

   Object definition is very important in interpretation of existence of PD occurrence in the cable system. Lack information about the component will result in ambiguity in interpretation of PD data. Relevant information about cable system, insulation types and accessories should be collected in order to obtain good interpretation of PD data.

2. Calibration

   The quality of calibration affects the whole quality of PD measurement. Due to the PD occurrence is a stochastic process, the PD magnitude cannot be predicted precisely, so it is necessary to perform calibration in several ranges. Performing one range calibration will affect the ability of the measurement to measure high PD magnitude or low PD magnitude. In this thesis the calibration procedure have been proposed in order to obtain a good quality of calibration.

3. Performing measurement

   - In order to have a sensitive measurement, selection of proper PD range is important.
   - To obtain a sufficient information for PD analysis, PD measurement must be performed at several voltage levels.

- PD background noise should be measured to distinguish PD from external source and PD related defect in the cable system

4. Data collection and analysis

   After performing PD measurement, relevant information about PD occurrence is collected and this data is called fingerprint of a cable system. The fingerprint is analysed to determines the condition of the cable system

5. Condition Assessment

   The final result of PD measurement is provided in the PD measurement report. The PD measurement report describes the condition assessment of the cable system and gives information of maintenance steps.

8.2 Recommendations

1. Due to PD measurement is a complex and very sensitive measurement, skilled operators required to performed measurement. Giving special training for new operators and retraining for old operator is necessary to ensure the operators can perform measurement correctly.
2. This study is focused on condition assessment of cable system based on analysis of the existence partial discharges in the component of cable system. The next study can be focused on other diagnostics like dielectric losses or dielectric response.

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List of abbreviations

2 D	Two Dimensional
3 D	Three Dimensional
AC	Alternating Current
CF	Calibration Factor
DAC	Damped Alternating Current
DC	Direct Current
HV	High Voltage
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
MV	Medium Voltage
OWTS	Oscillating Wave Test System
PD	Partial Discharge
PDEV	Partial discharge extinction voltage
PDIV	Partial discharge inception voltage
PDmax	Maximum PD level
PILC	Paper-insulated lead-covered
TDR	Time Domain Reflectometry
XLPE	Cross-Linked PolyEthylene

List of Symbols

C	Capacitance
E_0	Operating field strength
f	Frequency
i_C	Current wave of cable
L	Inductance
l	Length of cable system
q	Discharge magnitude
R	Resistance
t_{ch}	Charging time

v	Propagation velocity for PD waves
v_{avg}	Average propagation velocity
x_i	Location of discharge i
y_p	Proximity coefficients
Z_0	Characteristic impedance
Z	Impedance
Δt_{cal}	Propagation time of twice the cable system length
ΔV	Voltage drop as a result of a discharge
ε_0	Permittivity of vacuum
ε_r	Relative permittivity

List of Units

C	Coulomb
F	Farad
H	Henry
Hz	Hertz
m	Meter
s	Second
V	Volt