TAMPERE UNIVERSITY OF TECHNOLOGY

OSSI BERGIUS

IMPLEMENTATION OF ON-LINE PARTIAL DISCHARGE MEASUREMENTS IN MEDIUM VOLTAGE CABLE NETWORK

Master of Science Thesis

Examiner: Professor Pekka Verho
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ABSTRACT

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The reliability of power supply has become an increasingly significant factor in modern society. The aging of the existing network, the increased quality requirements of electric supply and the risk of major interruptions due to storms are factors that are driving towards the cabling of the distribution network. It is important to develop a condition management process for medium voltage cables to be able to optimize the construction and total life cycle costs of such of a cable network. Due to its hidden structure the condition of a cable network can be evaluated only by means of measurements. It is widely acknowledged that a clear dependence exists between the deterioration of the cable and partial discharges. For years, partial discharge measurements have been used as part of condition management in case of single expensive electrical equipment like generator etc. and it is proofed to be a working solution.

The goal of this work is to bring out the main principles of on-line partial discharge measurements and the current situation in case of extruded medium voltage cables. In addition, aging and other phenomena leading to faults and partial discharges related to these phenomena in extruded medium voltage cables have been studied. Finally, guidelines about how on-line partial discharge measurements could be used as part of condition monitoring of medium voltage cables have been created. The nature of this work is a literature survey and the source material mainly consists of international publications.

The temperature, voltage stress and moisture are the main factors that accelerate the aging of solid insulation. Thus overloading should be avoided, voltage stresses should be minimized and water proof components should be used. Cable joints and terminations seem to be the most fault prone components in the medium voltage cable network and in most cases partial discharges can be spotted before the breakdown. It is also noted that the quality of workmanship in the installation of cable accessories plays an important role while the reliability of these components is concerned. This work concludes that on-line partial discharge measurements are the most suitable for detecting problems in the cable joints, terminations or metallic shield. The evaluation of the general condition of a cable system is very challenging with current on-line partial discharge measurement systems because voltage above normal operation voltage can’t be used during measurements. In addition, in many cases also the measurement sensitivity is not good enough. With continuous measurements, reliable time to next breakdown estimations can be made. The biggest challenges for continuous measurements are related to their cost-effectiveness. The future will show whether these kinds of measurement increase or not.

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Sähkönjakelun luotettavuudesta on tullut yhä merkittävämpi tekijä nyky-yhteiskunnassa. Nykyisen verkon vanheneminen, sähköjakelun lisääntyneet laatuvaatimukset ja riski myrskyjen aiheuttamista suurhäiriöistä ovat tekijöitä, jotka ajavat kohti sähkönjakeluverkon kaapelointia. Maakaapeliverkon rakentamisen ja käytön optimoimiseksi on välttämätöntä kehittää sille kunnonvalvontamenetelmä. Maakaapelien kuntoa on mahdollista arvioida ainoastaan mittausten avulla niiden rakenteen vuoksi. Eristemateriaalien vanhenemisen ja niissä esiintyvien osittaispurkausten välillä on havaittu selkeä riippuvuus. Osittaispurkausmittauksiin perustuvaa kunnonhallintaa on käytetty jo useita vuosia yksittäisten kalliiden laitteiden yhteydessä ja menetelmä on havaittu toimivaksi.

Tämän diplomityön tavoitteena on tuoda esille käytönaikaisten osittaispurkausmittausten pääperiaatteet ja tämän hetkinen tilanne keskijännitteisten muovikaapelien osalta. Lisäksi on tutkittu muovieristeisten keskijännitekaapelien vikaantumiseen johtavia ilmiöitä ja niiden yhteydessä esiintyviä osittaispurkauksia. Lopuksi on pohdittu ja luotu suuntaviivoja, kuinka käytönaikaisia osittaispurkausmittauksia voitaisiin hyödyntää keskijännitekaapelien kunnonhallinnassa ja sitä kautta elinikäkustannusten minimoinnissa. Työ on luonteeltaan kirjallisuusselvitys ja lähdeaineisto koostuu lähinnä kansainvälisistä julkaisuista.

Lämpötila, jänniterasitus ja kosteus ovat päätekijöitä, jotka kiihdyttävät eristeiden vanhenemista. Tämän takia ylikuormitusta tulisi välttää, jänniterasitukset tulisi minimoida ja vedenpitäviä komponentteja tulisi käyttää. Kaapelijatkot sekä -päätteet näyttäisivät olevan keskijännitekaapeliverkon vikaherkimpiä komponentteja ja niissä yleensä esiintyy osittaispurkauksia ennen vikaantumista. Lisäksi on nähtävissä, että kyseisten komponenttien asennustyön laatu vaikuttaa merkittävästi esiintyvien vikojen määrään. Työssä tulee ilmi, että käytönaikaiset osittaispurkausmittaukset soveltuvat parhaiten kaapelijatkojen, -päätteiden sekä kosketussuojan heikentyneen kunnon havaitsemiseen. Kaapelijärjestelmän yleisen kunnon arviointi nykyisillä käytönaikaisilla osittaispurkausmittalaitteilla on erittäin haastavaa, sillä mittausta ei voida tehdä normaalia käyttöjännitettä korkeammalla jännitteellä. Komponenttien jäljellä olevan eliniän arvioiminen jaksoittain tehtävien käytönaikaisten osittaispurkausmittausten perusteella ei vaikuta kovinkaan lupaavalta menetelmältä, mikäli mittaus suoritetaan normaalilla käyttöjännitteellä. Syy tähän on muovikaapelien nopea vikaantuminen, joka tapahtuu yleensä vain muutaman viikon tai päivän kuluessa osittaispurkausten alkamisesta. Jatkuvien käytönaikaisten osittaispurkausmittausten perusteella voidaan luotettavasti havaita lähestyvä vikaantuminen. Jatkuvien mittausten suurimpana ongelmana on niiden vielä tällä hetkellä korkea hinta. Tulevaisuus näyttää yleistyvätkö tämän tyyppiset mittaukset keskijännitekaapelien yhteydessä.

PREFACE

This work is done to the Department of Electrical Energy Engineering at Tampere University of Technology. The work is funded by Smart Grids and Energy Markets (SGEM) project. This project consists of many different work packages from which this work belongs to packages 2.1 Large scale cabling in distribution network and 4.5 Condition management as a real-time process.

The work was supervised by Professor Pekka Verho from the Tampere University of Technology. I want to thank him for great comments and interesting conversations that helped to form the most important Chapters in this work. I also want to thank Research Fellow Pertti Pakonen who helped me a lot within the technical details and theory part of the work. Also the whole personnel of the Department of Electrical Energy Engineering at Tampere University of Technology deserve to be thanked for the great working environment.

Tampere, Finland
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Ossi Bergius
obergius@hotmail.com

CONTENTS

ABBREVIATIONS AND NOTATION

A	Cable age
a	Length between the measurement end and the fault site
C_{0k}	Geometrical capacitance
C_{avg}	Average cost of interruption
C_{m}	Mutual capacitance
C_{s}	Self-capacitance
c	Capacitance
F	Equivalent bandwidth
g	Conductance
H_{cn}	Transfer function for the distribution of current inside the RMU
H_{rmu}	Transfer function for a ring main unit
H_{T}	Transfer function of a cable system
$H_{\mathrm{n}}(\varphi)$	Pulse count distribution
$H_{\mathrm{qmax}}(\varphi)$	Maximum pulse height discharge distribution
$H_{\mathrm{qn}}(\varphi)$	Mean pulse height distribution
I	Current induced by partial discharge pulse
I_{CM}	Common mode current
I_{DM}	Differential mode current
i	AC current
i_{ind}	Induced partial discharge pulse current
J	Number of joints over the allowed limit
K_{u}	Kurtosis
$k_{\mathrm{v}}(\mathrm{cg})$	The price of disadvantage caused by unexpected outages to a certain customer group (€/kWh)
$k_{\mathrm{vm}}(\mathrm{cg})$	The price of disadvantage caused by unexpected outages to a certain customer group (€/kW)
L_{data}	Cable loading data
L_{m}	Mutual inductance
L_{s}	Self-inductance
l	Inductance
l_{c}	Cable length
m	Approximated voltage gradient
N	Number of discharges

$N_{\mathrm{C}}(\mathrm{cg})$	Number of customers in a certain customer group
N_{C30}	Number of customers that are left without power for longer than 30 minutes because of a cable fault
N_{F}	Number of faults experienced
n_1	Weighting coefficient for the number of joints over the allowed limit
n_2	Weighting coefficient for the cable age
n_3	Weighting coefficient for the number of faults experienced
n_4	Weighting coefficient for the cable loading data
q	Apparent charge
R_{in}	Radius of center conductor
R_{out}	Radius to the center of metallic sheath
R_{s}	Radius of each copper wire
r	Resistance
S_1	The importance of a cable
S_2	Failure risk
S_{k}	Skewness
s	Number 1, 2, 3, … of a consecutive discharge
T	Equivalent time length
t	Time
t_0	Time difference between direct pulse and three-times reflected pulse
t_1	Time difference between direct pulse and reflected pulse
t_2	Time difference between reflected pulse and three-times reflected pulse
t_{c}	Time it takes for a partial discharge pulse to travel through the whole cable length under test.
t_{i}	The outage time
t_{oa}	Pulse arrival time
U_0	Cable operation voltage to ground
u	Voltage
v	Travelling wave velocity
v_c	Partial discharge pulse velocity
W	Number of wires in metallic sheath
$W_{\mathrm{mp}}(\mathrm{cg})$	The amount of energy transferred to the user of a certain customer group from the network in a year (kWh)
w_1	Weighting coefficient for the cost of interruption

w_2	Weighting coefficient for the number of customers that are left without power for longer than 30 minutes because of a cable fault
x	Distance
Y	Admittance
Y_m	Mutual Admittance
Y_s	Self-Admittance
y_1	Admittance of conductor screen
y_2	Admittance of main insulation
y_3	Admittance of insulation screen
Z	Impedance
Z_0	Characteristic impedance of the line
Z_c	Characteristic impedance of cable
Z_load	Load impedance
Z_m	Mutual impedance
Z_s	Self-impedance
z	Impedance
Q_app	Induced charge
α	Attenuation constant
β	Phase constant
γ	Propagation constant
γ_pp	Propagation constant of phase to phase channel
γ_sp	Propagation constant of shield to phase channel
ε_k^*	Complex permittivity
$\varepsilon_k^{'}$	Real part of permittivity
$\varepsilon_k^{''}$	Imaginary part of permittivity
μ_0	Permeability of vacuum
ρ_1	Resistivity of center conductor
ρ_s	Resistivity of metallic sheath material
τ_c1	Transmission coefficient from cable 1 to the ring main unit
φ	Phase position
ω	Angular velocity
A/D	Analog-to-digital
CBM	Condition based maintenance
cg	Customer group
CM	Common mode
DCO	Disadvantage caused by outages

DM	Differential mode
EPR	Ethylene propylene rubber
GIS	Gas insulated system
GPS	Global positioning system
HFCT	High frequency current transformer
HV	High voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
PD	Partial discharge
PDIV	Partial discharge inception voltage
PD-OL	Partial Discharge testing On-line with Location
PE	Polyethylene
PILC	Paper insulated lead covered
PP	phase-to-phase
PRPD	Phase-resolved partial discharge
PRPDA	Phase-resolved partial discharge analysis
PRPS	Phase-resolved pulse sequence
PRPSA	Phase-resolved pulse sequence analysis
psdf	Power spectral density function
RDS	Redundant diagnosis system
RMU	Ring-main-unit
SCG	Smart cable guard
SNR	Signal-to-noise ratio
SP	Shield-to-phase
TDR	Time domain reflectometry
TOA	Time of arrival
TR	Time-resolved
TRA	Time-resolved analysis
TR-XLPE	Tree retardant cross-linked polyethylene
UHF	Ultra high frequency (300 – 3000 MHz)
VHF	Very high frequency (30 – 300 MHz)
XLPE	Cross-linked polyethylene

1. INTRODUCTION

The reliability of power supply has become more and more significant factor in modern society. The aging of distribution networks, the increased quality requirements of electric supply and the risk of major interruptions due to storms are factors that are driving towards the cabling of distribution networks. As an example Vattenfall Verkko Ltd., one of the biggest distribution network operators in Finland, made a decision in 2009 that cabling is their primary network construction method also in rural areas [1]. So there is a need for a condition management process for medium voltage cables. This process can be used to optimize the construction and total life cycle costs of such of a cable network. However, the condition of the cable network can be evaluated only by means of measurements due to its hidden structure. On-line partial discharge measurements are one possible solution for this problem. It is widely acknowledged that a clear dependence exists between the deterioration of the cable and partial discharges. For years, partial discharge measurements have been used as part of the condition management in case of single expensive electrical equipment like generator etc. and it has shown to be a good solution.

It is known that cables don't age uniformly. It is possible that only a small section of a cable is highly deteriorated and the other parts of the cable are in good condition. This small deteriorated section has a major influence on the reliability of the whole cable. It is easy to understand that replacement of the deteriorated section would have a major effect on the reliability of the whole cable. Obviously, the replacement of the whole cable would have at least the same effect on the reliability but that would be a lot more expensive. Partial discharge measurement can detect localized defects in a cable system. When, partial discharge measurements are used it is possible to replace only the highly deteriorated part of the cable. In this way it is possible to get the most out of the replacement budget when reliability is considered. This is one of the reasons why there is such an interest towards partial discharge measurements.

The goal of this work is to bring out the main principles of on-line partial discharge measurements and the current situation in case of extruded medium voltage cables. This means finding out the theoretical and practical limitations for measurement accuracy for an on-line partial discharge measurement in a cable network. Also the effectiveness of such a system on finding damages and predicting the time from damage to fault is evaluated. In addition, aging and other phenomena leading to faults and partial discharges related to these phenomena in extruded medium voltage cables have been studied. Based on the theory and experiences from real life measurement systems an implementation of on-line partial discharge measurements in a medium voltage cable network is introduced in this thesis. The final result of this work is a guideline how on-line partial discharge measurements could be used as part of the medium voltage cable life cycle management process. The nature of this work is a literature survey and the source material mainly consists of international publications.

This work is divided into three main sections. The first section (Chapters 2 and 3) discusses the construction of an extruded medium voltage cable and its accessories, the theory of partial discharges and the discharge phenomenon in medium voltage cable system. The idea of this section is to show how partial discharge phenomenon is linked to the condition of an extruded medium voltage cable system. The second section (Chapters 4, 5 and 6) introduces the main theory behind partial discharge measurements, the structure of an on-line partial discharge measurement system and the way the measurement data is analyzed. Here the factors which are limiting the measurement sensitivity are pointed out and different data analyzing methods are evaluated. The third section (Chapter 7) contains the created guidelines for the use of on-line partial discharge measurements in an extruded medium voltage cable system. Guidelines are based on the partial discharge theory and measurement system capabilities. At the end, Chapter 8 points out the main conclusions and recommendations.

1.1. Power cable diagnostic methods

Like mentioned before, the condition of a medium voltage cable can be assessed only through measurements. The focus of this work is only on on-line partial discharge measurements. However, there are also many other measurement methods that can be used to evaluate the condition of an extruded medium voltage cable network. This Chapter briefly introduces some of the other diagnostic measurements available.

Withstand tests are used to test the insulation performance of a power cable. A voltage higher than the nominal voltage is applied to test whether the cable’s insulation holds. International standards like IEEE Std. 400-2001 define the voltage levels and waveforms that should be used in withstand tests [2]. When DC voltage is used this test can be done in controlled or uncontrolled manner. A controlled withstand test makes it possible to stop the test before a fault takes place in a bad cable. An uncontrolled test is a go-no-go test. In case of extruded cables, DC withstand test should not be used. It can lead into unnecessary breakdowns of the cable insulation shortly after the cable has re-energized due to space charge formation. Thus AC voltage should be used. Anyway this test is only non-destructive if the cable withstands the test. [3; 4]

Insulation resistance test is used to check the condition of the main insulation. In this test, a high voltage is applied between all the phases and between each phase and the metal screen. This test can be done with megohmmeter which gives the ohmic value of the insulation resistance. In good insulation, the insulation resistance increases when measurement is continued. The ratio between insulation resistance value after 10 min and 1 min from the beginning of the test is called the polarization index. A polarization index of less than one indicates deteriorated insulation and need for immediate maintenance. [4]

Outer-sheath integrity test makes it possible to detect damage caused to the protective layer of the cable during transportation or installation. In this test, a high voltage is applied between the metal screen of the cable and earth. The resistance between the metal screen and earth is measured and if the value is not high enough it is an indication of outer-sheath damage. This test can be done with the same measurement system that is used in insulation resistance test. If the protective layer is damaged, this makes the cable more vulnerable to external influences like moisture.

Power factor and dissipation factor (tan δ) tests can detect if the cable under test is deteriorated by water trees. However, this test can't localize the water treed sections it can only show the overall picture. Thus only severe degradation by water trees can be detected by dissipation factor test on extruded cables. These tests measure insulation capacitance, AC dielectric losses and the ratio of measured quantities. Dielectric spectroscopy is a kind of advanced version of tan δ test where tan δ is measured as a function of frequency at different voltages. [3]

Off-line partial discharge test can detect deteriorated spots along the cable under test. The main principles of off-line partial discharge test are the same as in on-line partial discharge test. The main difference is that an external voltage source is used in off-line test. Thus higher voltages than operation voltage (2 - $3U_0$) can be used in off-line test. Higher voltage makes it possible to detect defects which are not detectable during normal operation. However, high voltages might ignite electrical treeing especially in aged cables. Thus off-line partial discharge measurements can be destructive [5; 6].

As we can see, there are many different measurement methods which can be used to evaluate the condition of a medium voltage cable. Each one of them has its own advantages and disadvantages and it depends on the actual situation which method is best suited. There is no one superior method that could detect all possible defects. At the moment the only diagnostic test that is widely used for medium voltage cables in Finland is the insulation resistance test. Some network companies also use the outer-sheath integrity test. Other types of diagnostic tests are used only in rare cases.

2. CABLE SYSTEMS

A medium voltage cable system starts from the high voltage substation and ends to a low voltage transformer. This work focuses on condition monitoring of extruded medium voltage cables and its accessories.

Cable failure probability usually follows the so called bathtub curve where the failure probability is high at the beginning and at the end of cable life. Figure 2.1 presents the bathtub curve. The main reasons for failures on newly installed cables are: bad workmanship or damage caused during manufacture, transportation or installation. The rise of failure probability at the end of cable's life is mainly caused by cable aging.

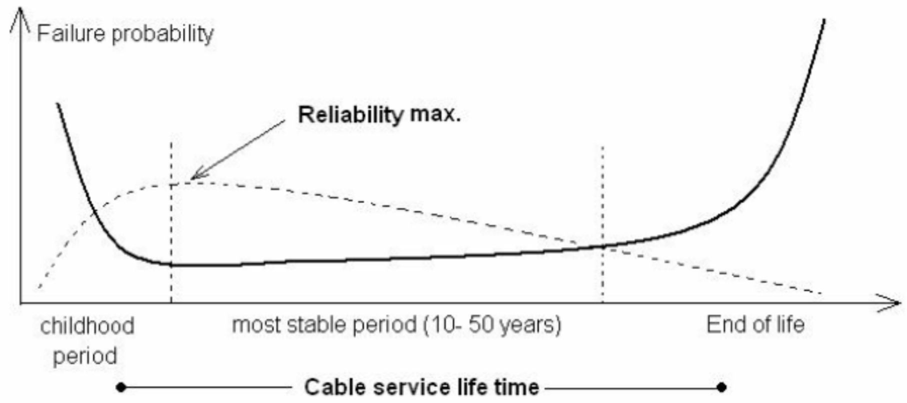


Figure 2.1. *The failure probability and the reliability of a cable as function of time [7]*

Medium voltage cable systems are generally very reliable. The average fault rate in Finland for distribution class cables is around 0,81 faults in a year per 100 km of cable [8]. This fault rate includes both extruded and paper insulated cables. Figure 2.2 presents cable failure causes in distribution class cables in Finland. With condition based maintenance it is possible to affect the amount of faults caused by technical reasons which covers 41 % of the faults. Natural phenomenon is the reason for 12 % of the faults. From these faults most are caused by lightning. The other reasons that are causing 47 % of the faults are related to digging and soil movement. Figure 2.3 introduces cable failure causes in Sweden. The statistics from Sweden have some difference compared with the ones from Finland. The differences might be due to different fault reporting practices or in Sweden they might have a better system preventing faults caused by digging actions.

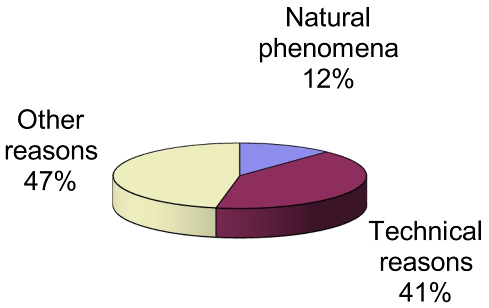


__Figure 2.2.__ Cable failure causes in distribution class cables in Finland [8]

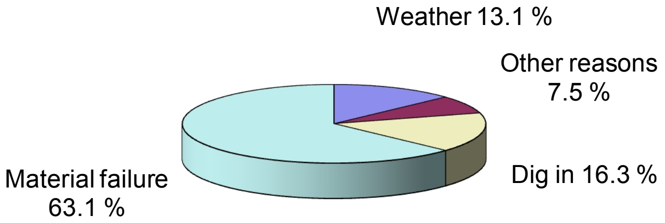


__Figure 2.3.__ Causes for medium voltage cable failures in Sweden [9]

Detailed cable fault statistics are hard to find in literature. One reason for this is the fact that the failure rate in extruded medium voltage cables is very low and thus there seems to be no reason to collect detailed fault statistics. There is not enough reliable failure statistics available to be able to say what the most common cable failure causes in XLPE insulated cables are. From a few statistics found it seems to be that most of the technical faults happen in cable joints and terminations [10; 11; 12]. From these cable joints seem to be the most fault prone components. This is an interesting observation and further research should be done to confirm this. Figure 2.4 presents cable failure causes in Macau.

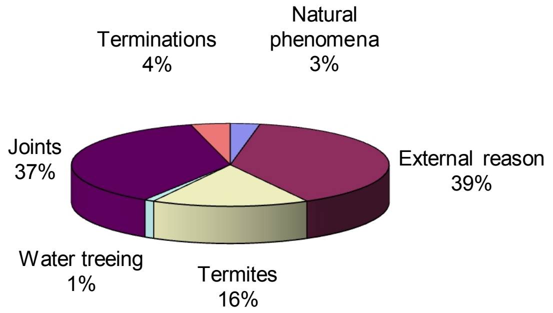


__Figure 2.4.__ Cable failure causes in 11 kV XLPE cable network in Macau [10]

2.1. Structure of an extruded medium voltage cable

The structure of a medium voltage cable affects greatly on its performance. The structure and manufacturing techniques of XLPE cables have greatly improved from the first generation cables which had extensive problems with water treeing. The cable types usually installed today have been available for about 20 years. The basic structure of an extruded medium voltage cable consists of a conductor surrounded by insulation, metallic shield and jacket. Figure 2.5 introduces the structure of a modern extruded medium voltage cable.

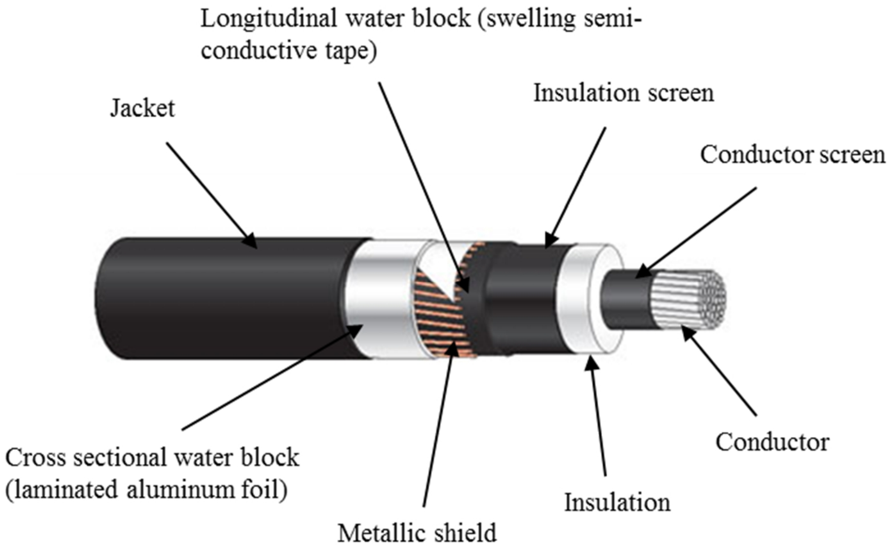


Figure 2.5. *Structure of extruded medium voltage cable [13]*

2.1.1. Conductor

The conductor is the main part of a cable. Its main purpose is to transfer electricity from place to place. The most commonly used materials in conductors are aluminum and copper. Mostly aluminum is used because it is lighter and less expensive. Copper is used in high capacity power cables due to its better conductance. Stranded conductors are used to make the cable more flexible. Because moisture has a negative effect on the cable the conductor is made longitudinally watertight with swelling powder or semi-conductive filling. [14]

2.1.2. Insulation

Insulation is the most crucial part of a cable as it isolates the live parts from the surroundings. The most commonly used insulation materials in extruded cables are cross linked polyethylene (XLPE), ethylene propylene rubber (EPR) and water tree retardant cross linked polyethylene (TR-XLPE).

As the insulation ages its electric strength decreases until a final breakdown happens. Temperature, electric field and moisture are the main factors affecting insulation aging. Moisture with electric field forms water trees inside the insulation. Water trees are very harmful for solid insulation because they may turn into electrical trees. Eventually electrical trees will lead to failure. To prevent and slow down the growth of water trees different additives are added into the insulation material. From the insulation materials mentioned earlier TR-XLPE material has shown to be the most resistant to water treeing. [15] The growth rate of a water tree is typically < 1 mm/year which means that it takes about five to ten years from a water tree to grow across the whole insulation layer. [16]

2.1.3. Semiconducting layers

Semiconducting layers are used on both sides of insulation. The inner layer is called the conductor screen and its purpose is to create a smooth cylinder-shaped surface on top of the conductor. This smoothens the radial electric field and prevents partial discharge ignition between the conductor and the insulation. Semiconducting material is usually based on the same material as the insulation.

The outer layer is called the insulation screen. Its function is to homogenize the radial electric field and work as a path to charge and leakage currents. The insulation screen also prevents partial discharges on top of insulation. It is usually made from the same material as the conductor screen. [14]

Most of the high frequency attenuation of partial discharge pulses in cables is due to semiconducting layers. This imposes a major limitation to the length of the cable that can be monitored with a partial discharge measurement system. This is discussed in detail in Chapter 4.

2.1.4. Metallic shield and jacket

The metallic shield is an important safety factor in medium voltage cables. It enables a quick switch off of electricity and offers a low impedance route for fault current when a cable is mechanically damaged. Metallic shield is also needed as a low resistance path to the charging current to flow to ground. Charging current is produced by capacitor formed between the conductor and the metallic shield. [14] Copper and aluminum are typical materials for the metallic shield because of their good electric conductivity and resistance against corrosion. The fact that partial discharges propagate through the metallic shield makes this cable part especially interesting.

The cable jacket protects the cable from mechanical or chemical damage. Nowadays the materials used in cable jackets are based on polyethylene (PE) because of its small moisture permeability. There are many possible PE based compounds which have different properties so it is important to choose the right kind of material for the intended application. If extra protection is needed, the cable jacket can contain additional metallic armor.

2.1.5. Moisture proofing

Moisture has a negative effect on cables lifetime. This is why water tight structures are used in extruded cables. Radial water tightness can be achieved by using e.g. laminated aluminum foil attached to the inner surface of a jacket. At the same time, this kind of layer can work as a metallic shield. Semi-conductive swelling tapes, powders or strings inside the cable structure are used as longitudinal water blocks.

A cable is aged in different ways because of moisture. Corrosion damages the metallic shield and in the worst case it might break its continuity. Moisture with electric field forms water trees inside the insulation which may turn into electrical trees. Electrical trees are formed by partial discharges inside insulation and they will eventually lead into a breakdown of the insulation. Electrical trees are discussed more in Chapter 3.1.4.

2.2. Cable accessories

Cable accessories are an important part of a cable system. Different kinds of accessories are needed to connect cables together and into other electrical equipment. High electric fields in medium voltage level make the designing of these accessories a challenging task. In this chapter different medium voltage cable accessories and their structures are introduced. Only accessories made for extruded shielded cables are considered.

There are two different types of accessories, joints and terminations. Joints sometimes called splices are used to connect cables together. The main purpose of a joint is to preserve the cable structure at a point where cables are connected to each other. Terminations are needed to connect cables into other electrical equipment. The main purpose of a termination is to prevent harmful electric field concentrations at the end of a cable.

2.2.1. Joints

Cables are connected together with a joint. This task must be done with great care to ensure a reliable operation of a joint during its lifetime. Joints are usually made from materials of the same kind as extruded cables. Due to this, joints are facing the same degradation problems as cables.

A joint consists of a connector that connects the conductors together and carries current, a conductive electrode layer on top of the connector that forms a smooth interface between the insulation and the connector, the main insulation layer, a semi-conductive insulation screen that is connected into the insulation screens of the cables and necessary shielding and jacketing layers. Figure 2.6 presents a layout of a typical single phase joint and its main parts. Mostly used joint types are premolded rubber joints, heat- and cold shrink joints.

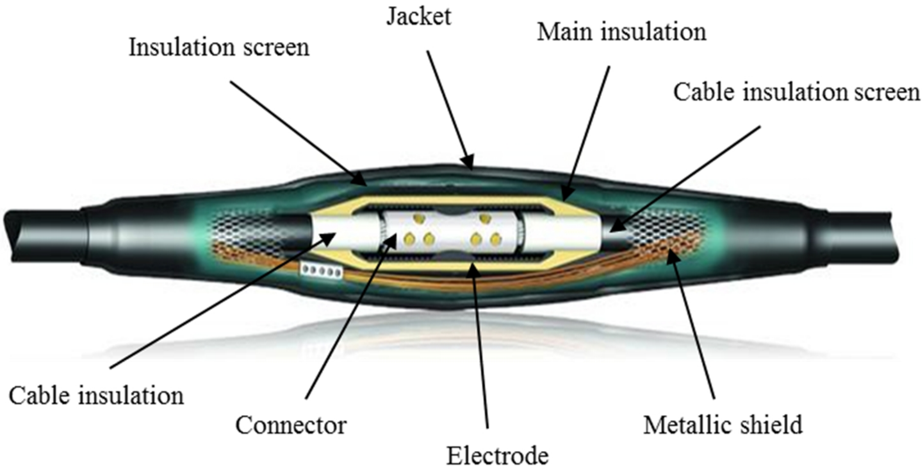


Figure 2.6. *Structure of single phase joint [17]*

Before any joints can be installed, the cable ends must be prepared as it is said in the manufactures instructions. Premolded rubber joint usually has one piece molded body that consists of an electrode and main insulation covered by an insulation screen. This piece is pulled over the connection and grease is used to fill the step in the insulation screen of the cable. The cable's metallic shield must be extended over the joint and it must be in contact with the insulation screen on top of the joint. A cable jacket is installed on top of everything to provide mechanical-, chemical- and moisture protection to the joint. A heat shrink joint usually consists of a stress control mastic applied over the connector and cable insulation, a heat shrinkable stress control tube and an insulation tube which is covered by a semiconducting layer. These parts are shrunk on the cable one by one and after that shielding and jacketing are performed at the same way as with the premolded joint. The structure of a cold shrink joint is much like the structure of the premolded joint. Cold shrink joints are stretched and loaded over a removable core. The step in the insulation screen of the cable is filled with grease, a cold shrink joint is positioned over the prepared cable, the core is removed and the joint shrinks into place. After that cable metallic shield is extended over the joint and jacket is installed like in previous cases.

2.2.2. Terminations

Terminations are needed when shielded power cables are connected to other electrical equipment. To be able to make the connection the insulation screen must be removed at the end of the shielded cable. The place where insulation screen ends is problematic because the electric field is highly concentrated at that place. The termination must be designed in a way that this stress is controlled by using stress cones or stress grading materials. Figure 2.8 shows the typical structure of termination. [18]

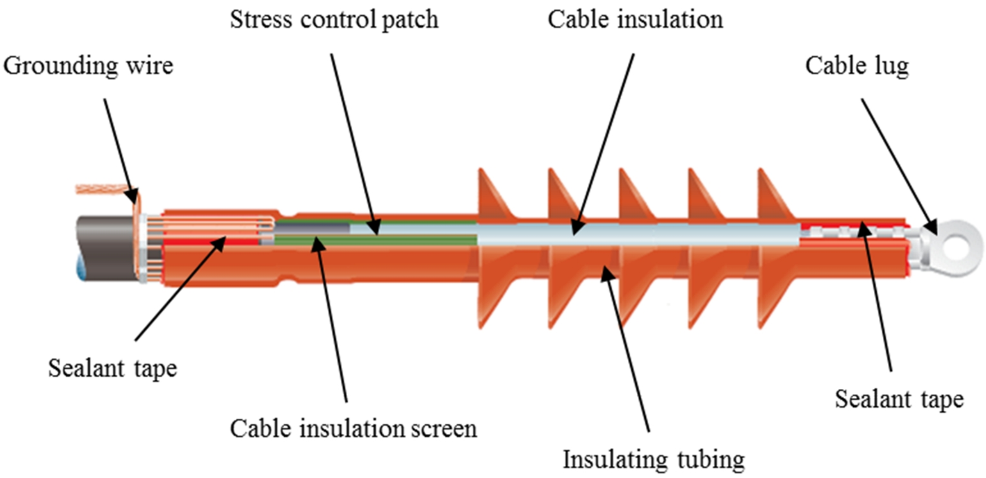


Figure 2.8. *Structure of termination [19]*

Three different construction methods (premolded, heat- and cold shrink) are used in terminations. The cable end needs to be prepared before termination can be installed. Premolded structure consists of every necessary layer and it is pulled over the prepared cable end. Grease is used to fill the semi-conductive step of the cable. Heat shrink terminations consist of one or more different heat shrinkable layers which are shrunk on the cable end. Cold shrink terminations are stretched and loaded on a removable core which makes them very easy to install. The advantage of cold shrink terminations over premolded- and heat shrink terminations is that the force which presses the termination against the cable is much bigger. This reduces the risk for cavity formation between termination interfaces. [18]

In modern compact electrical equipment, the clearances between phases are very small. To be able to install terminations in this kind of equipment special adapters need to be used. The other advantage is that once adapters are used it is easy to disconnect the terminations if necessary. Figure 2.9 introduces one type of adapter. The adapter consists of insulating material and necessary connections.

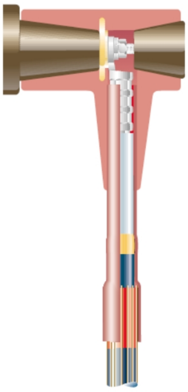


Figure 2.9. *Insulated adapter termination system for SF6-insulated switchgear RICS 24 kV [19]*

2.2.3. Screened connectors

Screened connectors are the latest type of terminations. The outer layer of this kind of termination consists of semiconducting material and it is grounded. This way the cable shielding is never fully cut out and in theory there is no need for clearances between the phases because the outer layer is grounded. This grounding is the biggest difference between adapters and screened connectors. Figure 2.10 presents a screened connector.

Figure 2.10. *Cross-sectional view of non-extensible and extensible screened connectors RSTI [20]*

3. PARTIAL DISCHARGE THEORY

Partial discharge is defined in IEC 60270:2000 as “a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor” [21]. Basic theory behind partial discharges is presented in this chapter. Different signals produced by partial discharges, different discharge types, and partial discharges in cables and its accessories will be discussed.

The severity of a deteriorated spot producing partial discharges is not directly related to the magnitude of the discharges. It is proved that the amount of deterioration in dielectric depends on the energy dissipated per unit volume of the dielectric rather than the energy dissipated in the discharge. It is impossible to determine the energy density from the measurements made at the terminals of a high voltage component. This imposes a major limitation on the efficiency of a partial discharge measurement system to predict the rate of degradation or the remaining life. [22] Different discharge types have their own discharge characteristics and thus they can be identified. The harmfulness and time to the breakdown of partial discharges highly depend on the discharge type.

3.1. Partial discharge types

There are a lot of different kinds of definitions used for partial discharge phenomena [23]. In this text partial discharges are classified in four different types based on the discharge properties and place of occurrence. These types are internal discharges, surface discharges, corona and electrical treeing. Internal discharges take place inside the insulation in small gas filled cavities. Surface discharges take place along the surface of dielectric material or along the interface between two dielectric materials. The latter is also called surface tracking. Corona discharges usually happen around sharp edges in the interface between metal and air. Electrical treeing forms a growing tree like structures inside the insulation and is caused by multiple micro scale internal discharges. [24]

The harmfulness of partial discharges depends on the discharge type and location. Different discharge types can be recognized because they all have their own characteristics. The only place in a cable where corona discharges are likely to take place is at the metallic contacts at the cable end. This means that corona discharges are not harmful when cables are concerned. The harmfulness of surface discharges on the surface of terminations depends on the initial reason behind the discharges. Surface discharges caused by moisture and dirt are less harmful than discharges caused by insufficient distance between cables. Surface tracking is very harmful because it erodes the insulation surface which in time will lead to failure [25]. Internal discharges deteriorate insulation directly and are thus usually very harmful. Electrical treeing has the highest impact on insulation deterioration and it is often the final cause for the dielectric breakdown.

3.1.1. Internal discharges

Internal discharges take place inside the insulation in gas-filled cavities, between insulation interfaces or near contaminants. Strength of the electric field inside a cavity depends on the voltage across the insulation, size and shape of the cavity, the gas content of the cavity and the difference between the permittivities of the gas inside the cavity and the dielectric surrounding the cavity. An electrical breakdown takes place in a cavity once the voltage stress in the cavity exceeds the breakdown voltage. The composition and pressure of a gas inside a cavity, the cavity wall conditions and static charges from the previous discharges all affect the breakdown voltage level in the cavity. The breakdown strength of the gas is also much lower than the solid's. That is why partial discharges occur in cavities at lower voltages than the breakdown voltage of the solid insulation. Change in internal pressure within the cavity combined with an increase in the conductivity of the cavity walls may cause self-extinction of partial discharges [22]. This also explains some of the random nature of partial discharges. Besides in cavities, internal discharges might also ignite near contaminants which could be for example small metal particles. Contaminants may have sharp edges around where partial discharges ignite because of the concentration of the electric field. These sharp edges might also occur at the interfaces.

The degradation process in solid dielectrics is accompanied by intricate chemical processes. Gaseous, liquid and solid byproducts are formed during these chemical processes. Internal discharges deteriorate solid dielectrics with the following process. Polymer chains break and oxidate, leading to a formation of short chain fragments. These fragments are dissolved in water and form clusters on the surface of the dielectric. The water originates from the gas atmosphere or from chemical processes taking place on the surface of the dielectric. The formed clusters are crystallized when subjected to discharges. In time the edges of these crystals are eroded by the discharges leading to a formation of craters. Usually the final breakdown process (electrical treeing) starts at such a crater. [26]

3.1.2. Surface discharges

Surface discharges take place on the surface of the insulation in points where the electric field is concentrated. The high electric field ionizes the surrounding air, therefore causing it to become conductive. In cable systems, one possible place for this type of discharges is at the point where the insulation screen is removed from insulation. This is done at cable joints and terminations. [24] This type of discharges may also occur anywhere in the system where outer layers of the cable are damaged.

Surface discharges produce surface tracking where carbonized conductive tracks are formed. Surface discharges at the interface between solid insulation and air results from the following process. Strong electric fields are created around irregular or sharp points at the end of each potential gradient. The strong electric field ionizes the surrounding air, therefore causing the air to become conductive. Some partial discharges may occur in this region. Additional surface contamination and moisture create a leakage current path to the ground. The leakage current creates heat which evaporates the moisture, leading to the creation of tiny islands or very small voids. These tiny island voids prevent the flow of the leakage current. Since all the remaining surface is still conductive, most of the voltage drop will be applied over these tiny island voids creating an arc across it. Partial discharges in a form of arcing burns the insulation creating permanent carbonized paths. These carbon tracks are conductive and they form new sharp points from where the process continues across the insulation until failure results. [27] Figure 3.1 shows an example of carbonized tracks on top of insulation, created by surface tracking.

Figure 3.1. *Surface tracking on top of insulation [25]*

3.1.3. Corona

The term “Corona” refers to discharges that happen around sharp edges in the interface between metal and air. There are many different types of corona discharges but they are not discussed in this work. Corona discharges produce ozone which can be harmful for the nearby dielectric materials due to the chemical reactions it causes in dielectrics. The only place in a cable where corona discharges are likely to take place is at the metallic contacts at the cable end. In many cases corona discharges detected from the cable are harmless and they are produced outside the cable. The current signals produced by the corona look the same as the current signals from other type of partial discharges and thus they disturb the measurements. Due to this it is important to be able to distinguish corona discharges from other more harmful types of discharges. [28]

Corona discharges have some unique characteristics that make it quite easy to distinguish them from discharges taking place in solid dielectrics. Corona discharges usually take place near the peak of the negative or positive voltage. When the point electrode is at high voltage side then the discharges are first ignited at negative voltage. In case the point electrode is at earth side then the discharges are first ignited at positive voltage. The discharge magnitude is lower at negative voltage than in positive voltage. Thus it might be possible that corona discharges are detected only after they have ignited at positive voltage.

3.1.4. Electrical treeing

Electrical trees are one type of internal discharges where treelike channels are formed inside the insulation. Electrical treeing is in many cases the final step before the insulation breakdown. Electrical treeing can be divided into three phases which are tree initiation where degradation leads into formation of the first channel, tree growth where the channels extend and the final breakdown which takes place after one or more channels have bridged the electrodes. [29]

There are basically two shapes of electrical trees bush- and branch-like and it depends on the average voltage stress which shape forms. If the average voltage stress is <3 to 5 kV/mm, then forming trees will be branch-like. When voltage stress is >3 to 5 kV/mm bush-like electrical trees are formed. Usually electrical trees spotted from medium voltage extruded cables are branch-like but also bush-like trees can be found. The transition between branch- and bush-like trees is not sharp. At intermediate voltages, the tree starts off as a bush-like and then converts to a branch-like. [30] Figures 3.2 and 3.3 presents an example of a bush-like -and a branch-like electrical tree.

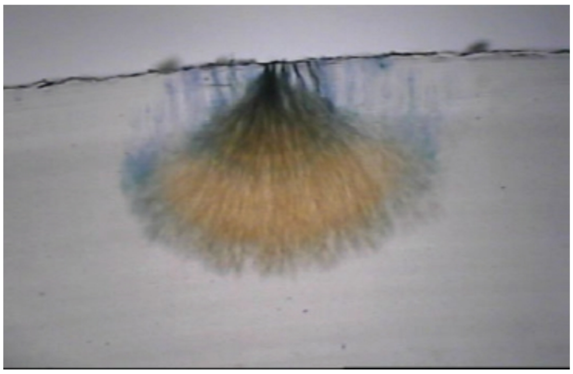


Figure 3.2. *Bush-like electrical tree [31]*

Figure 3.3. *Branch-like electrical tree [32]*

Electrical trees are usually ignited by over voltages. After ignition partial discharges can take place in an electrical tree and progress the tree growth during normal operating voltage or only during sufficient amount of overvoltage. If continuous partial discharges take place at normal operating voltage in an electrical tree, it will grow through insulation and lead to a breakdown quite fast. Usually, the breakdown will happen in a few hours. [30] If the overvoltage transient, like a surge pulse from lightning, has enough energy, it is possible that the ignited electrical tree grows through the insulation and causes breakdown during the voltage transient. The exact physical and chemical processes behind electrical treeing are not yet fully understood. However, the current understanding about partial discharges in electrical treeing is enough to estimate the condition of the insulation.

3.2. Signals from partial discharges

The presence of partial discharges is indicated by chemical transformation, gas pressure, light, heat, sound and electrical signals. Only the last four has practical importance while detecting partial discharges in cable systems. Light from partial discharges can be detected with optical sensors. In current cables light can be measured only from external or corona discharges taking place at cable terminations. Heat produced by partial discharges can be detected with heat cameras. The problem here is that the amount of heat generated is usually quite small and only quite severe discharges can be detected. Ultrasonic sensors can detect partial discharges from corona and surface discharges quite well but the accuracy to detect internal discharges is not that good. In this work, only electrical discharge detection is discussed.

3.2.1. Partial discharge pulse shape

Partial discharge pulse shape depends on many factors. Some of them are: voltage level, void size, shape and location, and the type of gas in the void and its pressure. Basically there are two kinds of pulses: pulses with fast rise- and decay time and pulses with fast rise time and long decay time. The discharge pulse we can measure is actually created by the movement of electrons and ions at the discharge site. The physical discharge mechanism dealing with the movement of charges actually determines the discharge pulse shape. Typical rise times for partial discharge pulses are between 0,5 – 5 ns and decay times between 1 – 100 ns. In general it can be concluded that the shorter the discharge path and higher the voltage level the faster the rise- and decay time. Also the discharge type affects the pulse shape as an example in case of a flat cavity numerous discharges occur almost simultaneously forming a combined discharge pulse with longer duration and multiple peaks. [33]

The actual measured partial discharge pulse differs from the original discharge pulse due to attenuation and distortion during pulse propagation, sensor properties and disturbing noise. All these effects are discussed in detail later. Also the sampling rate during analog-to-digital conversion affects the measured pulse shape.

3.2.2. Partial discharge coupling mechanisms in cable

Partial discharge coupling is a complex phenomenon that involves different mechanisms depending on the physical position of the discharge. Partial discharges can couple to the cable through inductive or capacitive coupling. In internal discharges, the partial discharge pulse flows through the internal conductor and return through the cable shield. Internal discharges couples with the cable through the electric field established between the partial discharge site and the conductor of the cable. The electron movement at the internal discharge source is usually orthogonal to the conductor of the cable and thus inductive coupling between the conductor and the partial discharge current or the cable shield and the partial discharge current is not very effective. [34]

Surface discharges take place on the surface of the insulation and the discharge current flows in a loop made by the discharge itself and part of the cable shield. This current loop is parallel to the conductor of the cable and thus it couples magnetically with the loop made by the cable core and shield. A model for partial discharge coupling based on mentioned coupling mechanisms has been postulated and validated by Tozzi. It is noticed that at frequencies above some tens of MHz surface discharges couple more effectively with the cable system than internal discharges. [34]

The magnitude of currents induced or coupled in the conductors depends on the partial discharge direction and the position of the discharging defect within the dielectrics. For example, if we place the same size cavity in the same relative position in a 15 and 35 kV cable, one of which has twice the insulation thickness as the other, the partial discharge magnitude measured for 35 kV cable will be half that for 15 kV cable. The reason for this is basically because of the reduced capacitive coupling to the electrodes. However, the physical phenomenon that leads to the discharge depends on the local electric field strength which must be the same in both cases. [35] Because it is impossible to know the exact physical position where the partial discharge takes place, the measured discharge magnitudes are always something else than in reality.

3.3. Partial discharges in polymeric cables and accessories

Basic structure for a polymeric cable consists of a conductor, insulation, a metallic shield and jacket. Insulation itself has three layers: the conductor screen, the main insulation and the insulation screen. Partial discharges are very harmful in these cables and will lead to the breakdown of the cable. It is shown that cable loading has an influence on partial discharge intensity and magnitude from interfacial cavity type defects in polymeric cables. The main factors for this are the temperature rise and mechanical stresses that are caused by cable loading. It is believed that more cavities are formed at elevated temperatures due to differences in the thermal expansion coefficients of different cable materials. [36]

Cable joints and terminations cause most of the faults in a cable system. [11; 12; 37] They have thicker insulation than in the cable so it usually takes somewhat longer time for partial discharges to cause a breakdown. The insulation screen must be cut off to make a joint or termination this causes an uneven distribution of the electric field which means more stress to the insulation. This is one reason why partial discharges are more common in joints and terminations than along the cable itself.

There are many defects which can induce partial discharges and many different degradation processes that can result. Most defects that induce partial discharges at normal operating voltage will lead in formation of an electrical tree which will eventually grow to failure.

3.3.1. Discharges in cables

Partial discharges are very harmful in solid insulated cables. In most cases, discharges that are detected during normal operation will lead to a breakdown. The time from partial discharge ignition to the final breakdown depends on the discharge type and place in the cable. A partial discharge phenomenon is random and there is always some statistical variation between the times to the breakdown. Depending on the discharge's type and place the time to the breakdown varies from a few hours to a few years. [38; 39] In extruded medium voltage cables there are many places where partial discharges may ignite. Partial discharges might appear in voids or cavities within the insulation or at interfaces between insulation and semi-conductive screens, in broken neutral or in electrical trees initiated from protrusions, contaminants, voids or water trees. [39] Figure 3.4 presents typical defects in solid insulation.

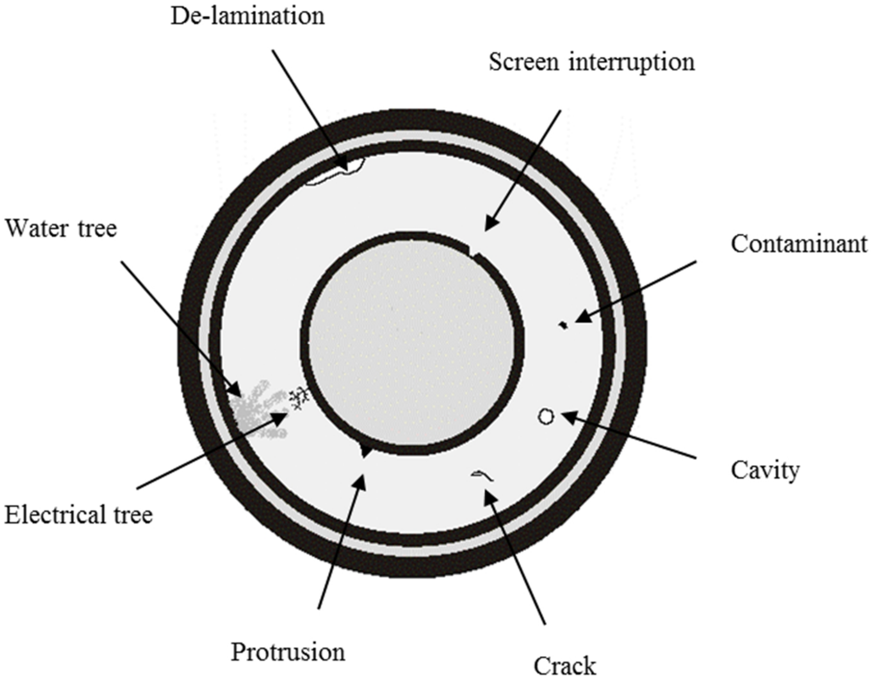


Figure 3.4. Typical defects in solid insulation.

Cavities, protrusions, contaminants, screen interruptions and de-laminations are all defects that may form during cable manufacture. De-lamination may also form due to external pressure which strangles the cable. Water trees are formed due to the ingress of moisture in cable insulation. Cracks might form when insulation is subjected to extreme temperature conditions. The metallic shield might break due to excessive fault currents or corrosion. Rough handling during installation may damage the outer protective layers, insulation or insulation screen and thus speed up the aging process. Today an acceptance test for medium voltage cables is conducted after manufacturing. To pass this test the partial discharge magnitude in the cable should be less than 5 pC at 1,5U_0 [40]. There is some variation in this threshold value and measurement voltage between different standards. As an example the IEC 60502_2 threshold is 10 pC at 2,0/1,7U_0. [41] When cable manufacturing and testing is properly conducted new cables should not contain any harmful defects.

Resent article written by Mashikian and Szatkowski describes the most typical cable defects found while testing over 9000 km of medium voltage XLPE insulated cable with an off-line partial discharge test. In most case partial discharges were generated by electrical trees at the defect sites. Electrical trees where found especially near water trees but also near contaminants and interface stress concentration areas. It should be noted that water trees itself doesn't produce partial discharge signals. Water trees enhance the electric stress inside the insulation because the insulation containing water trees has a higher permittivity and a higher conductivity. Figure 3.5 presents the effect of a water tree on electric stress. It has also found out that water trees decrease the growth rate of an electrical tree as long as it hasn't bridged the entire insulation. The reason for this is the lower electric stress inside the water tree. In many cases electrical trees near water trees were detected 3 - 4 years before the sites were dug out and identified in laboratory examinations.

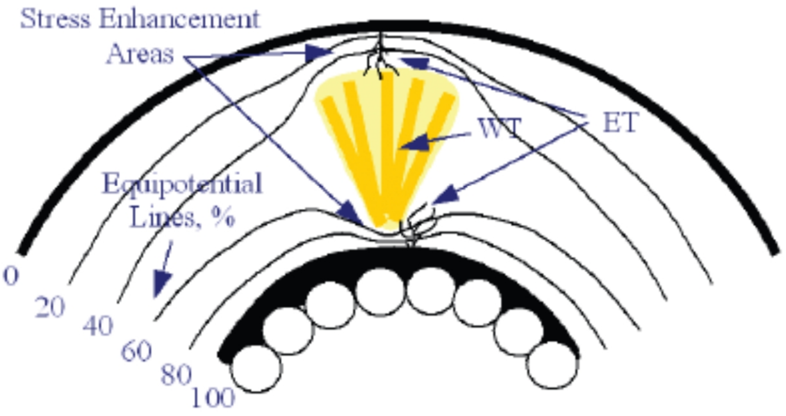


Figure 3.5. *Electrical trees growing from electric stress enhancement areas produced by a water tree [31]*

Other than electrical treeing types of partial discharges were spotted from delaminations between the screens and the insulation and from spots where the insulation or its screen had been physically injured during manufacturing, transportation or installation. Partial discharges from voids in the insulation where not spotted. In rare cases, when the insulation had been subjected to excessively high temperatures, voids have been found in the insulation. It should be noted that these measurements where done for service aged cables. Within these measurements, the discharge magnitude in case of electrical treeing was typically <40 pC at 2,5 p.u. voltage. [31] Electrical trees are much easier to be spot in time when higher than nominal voltages can be used during measurements. With on-line partial discharge measurements, electrical trees can be spotted only with extremely high measurement sensitivity (<5 pC).

Partial discharges may also take place in the cable's metallic shield if it is harmed. The type of discharges in those cases is spark discharges that take place between metallic connections. It has been shown that the discharge magnitude in these kinds of defects is in a range of hundreds of pC [42]. This type of partial discharges seldom results in cable failure [43]. However, it is important that the continuity of the cable shield is preserved for safety reasons.

Today it is common to install cables with fully watertight structure, which in theory should decrease water treeing. Faults related to manufacturing mistakes have been reduced due to improved manufacturing techniques and quality control. Cable plowing has become more and more common also at medium voltage level. It is important to control how this affects the amount of damages caused to the cables during installation. [44]

3.3.2. Discharges in joints and terminations

Joints and terminations are the most fault prone components in cable systems. Many faults in joints and terminations generate partial discharges before the final breakdown. These accessories are installed in field conditions and their quality also depends on workmanship. Electric fields are not homogenous in these accessories due to their structure. Places where the electric field is concentrated are prone to partial discharges.

Typical defects causing partial discharges in joints are cavities, surface tracking at the interface between the cable insulation and the joint insulation, cuts made in the cable insulation during preparation and irregular cut at the end of the insulation screen. Cavities are the most likely to occur due to the improper shrinkage of accessory components or poorly shrunk heat shrink or cold shrink layers. [39] Figure 3.6 introduces typical places for partial discharges in a joint.

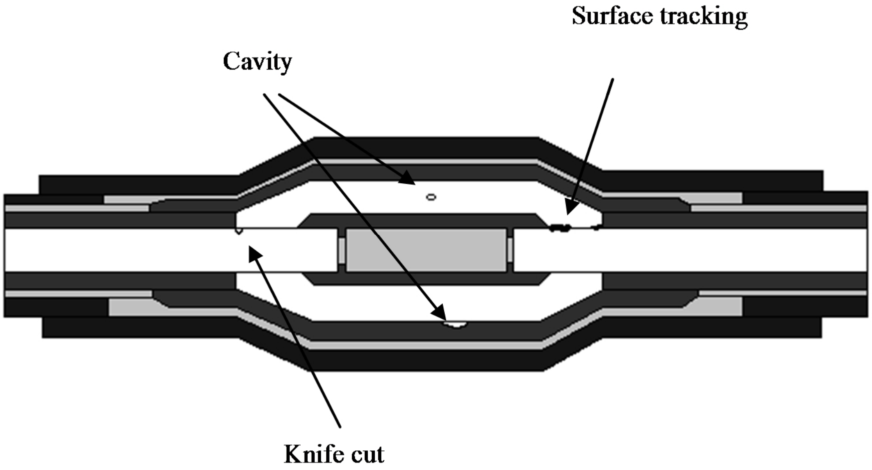


Figure 3.6. *Typical PD producing defects in a joint*

Many defects in terminations that cause partial discharges are there because of workmanship errors. Usually, the best results are achieved with good training. The most problematic part in termination is the point where the insulation screen is cut and stopped. Without proper stress relief, the high electric field concentration in this point quickly ages the insulation and short circuits the cable end. Every irregularity in this area will affect the concentration of the electric field and thus might ignite partial discharges. These kinds of irregularities are voids left between the cable insulation and layers above it, rough insulation screen ends or cuts made in cable insulation while removing insulation screen. Terminations might also suffer from manufacturing faults so it is important to know that proper testing has been conducted during manufacturing. Other factors causing partial discharges in terminations are humidity, dirt, too short distance between other cables and bad cable lug contact. Sharp edges at the surface of the cable lug can lead to corona discharges and humidity, dirt and too short distance ignite external surface discharges. [25] Figure 3.7 shows some typical places where partial discharges might appear in termination. Figure 3.8 introduces the examples of termination defects.

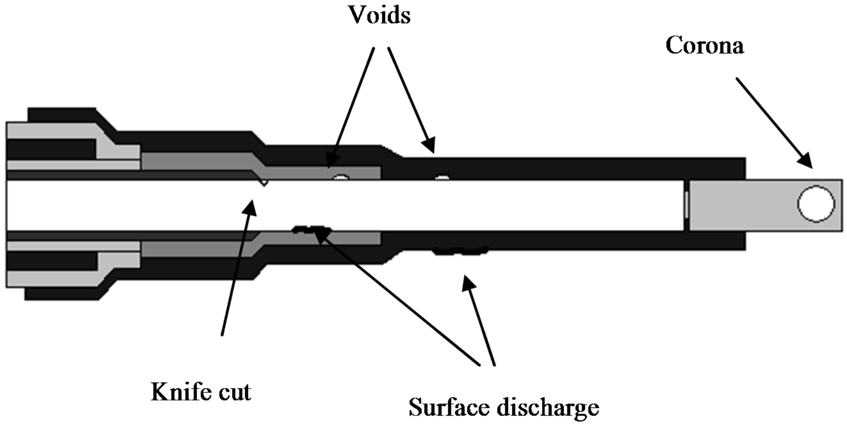


Figure 3.7. *Typical partial discharges producing defects in a termination*

Figure 3.8. *Surface discharge ring on top of termination probably due humidity and dirt (left) and high impedance fault in termination (right) [25]*

Typical discharge types in cable joints are internal discharges and surface discharges. At medium voltage level these defect types produce rather strong discharges in a range of hundreds of pC:s. It is noticed that discharge magnitude and repetition rate increases before the actual breakdown. [45] In cable terminations typical discharge types are internal and external surface discharges and internal discharges. The discharge magnitude is rather strong (hundreds of pC) with these kinds of discharges. External surface discharges taking place on the outer surface of the termination are strongly dependent on environmental conditions (dirt, moisture level, etc.) and thus discharge activity varies to a great extent over time. The given typical discharge magnitude range hundreds of pC:s is based on the typical harmful discharge magnitude level that is given by many measurement system providers [46; 47; 48] and on the other hand on typical discharge magnitudes that can be found in reported on-line measurements made with PD-OL system developed in Netherlands [42; 49]. PD-OL stands for Partial Discharge testing On-line with Location. The indication about typical discharge magnitude range given in this work is based on the discharge magnitudes typically encountered in literature. There is a need for further study to find out the typical discharge properties for deteriorated in service joints and terminations.

4. PARTIAL DISCHARGE PULSE PROPAGATION

Partial discharge pulse propagation in the cable distribution network sets limitations to partial discharge measurement systems. Partial discharge pulses attenuate, disperse and reflect while propagating in the cable system. The propagation constant depends on frequency which causes distortion in partial discharge pulse shape. In this chapter it is discussed how partial discharge pulses propagate in different parts of the cable system.

The partial discharge pulse splits in half at the discharge site and starts to travel in both directions of the cable. The discharge pulses that are induced in cables are broadband signals with frequency content in a range of 10 kHz – 1 GHz. A Cable work as a low pass filter for the partial discharge signal which means that only lower frequencies (below 10 MHz) of the signal can be detected after some length (about 1 km) of traveling in the cable. [34]

4.1. Propagation in cables

The propagation of partial discharge pulses has to be dealt with as a traveling wave problem due to the short duration of the pulses ($10^{-9}-10^{-6}$ s) and long electrical length of the cable network ($10^{2}-10^{5}$ m). What this means is that the resistances, inductances, conductances and capacitances have to be considered as distributed along the length of the cable.

The way a power cable has been constructed has a big influence on how partial discharge pulses propagate in it. There are usually at least two semiconducting layers. One on top of the conductor called the conductor screen and other on top of the insulation called the insulation screen. These layers have a great impact on partial discharge pulse attenuation [50, 49].

4.1.1. Transmission line parameters

Transmission line parameters are series resistance, -inductance, parallel conductance and –capacitance. Resistance depends on the resistivity of the conductor as well as on skin- and proximity effects. Inductance is formed from mutual inductances between different lines and the self-inductances of each line. Conductance depends on the conductivity of the insulation. Capacitance depends on the permittivity of the insulation. Figure 4.1 presents per unit length transmission line parameters.

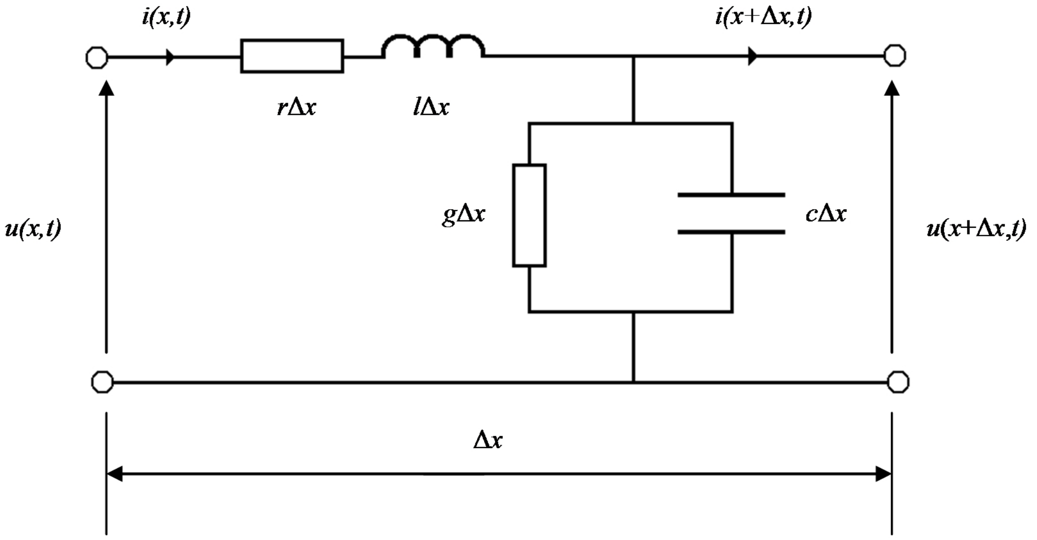


Figure 4.1. *Per unit length transmission line parameters*

Propagation constant γ determines the propagation properties of the partial discharge pulse in transmission line. For propagation constant we can write:

$$\gamma = \alpha + j\beta = \sqrt{(r + j\omega l)(g + j\omega c)} \tag{1}$$

, where α is attenuation constant, β is phase constant, r is resistance, l is inductance, g is conductance, c is capacitance and ω is the angular velocity. Both attenuation and phase constant are frequency dependent.

The characteristic impedance Z_0 of the cable can be calculated as:

$$Z_0 = \sqrt{\frac{r + j\omega l}{g + j\omega c}} \,. \tag{2}$$

The propagation velocity $v(\omega)$ of the electromagnetic wave is calculated as:

$$v(\omega) = \frac{\omega}{\beta(\omega)} \,. \tag{3}$$

4.1.2. Reflection and refraction of waves

Discontinuity points where the reflection and refraction of partial discharge pulses take place are formed by changes in the impedances and admittances along the propagation path of the partial discharge pulse. Some places in the cable system where partial discharge signals are reflected are substations, ring main units with multiple cable connections, joints where cable type is changed and cross-bonded cable joints.

Obviously, wave reflection affects partial discharge pulse measurements and especially when conducting on-line measurements.

The effects of straight cable joints to the propagation of partial discharge pulses are negligible due to their short length [5; 52]. In case of cross-bonding joints the situation is different and they have a major influence on the pulse propagation. However cross-bonding joints are not common at medium voltage level. This is not further discussed in this work but there are papers dealing with this issue. [53] The fact that partial discharge pulses reflect in a certain part of the cable system can be used in partial discharge source location this will be discussed in detail at Chapter 6.3.

4.1.3. Propagation in a single-phase cable

Analytical models have been developed to estimate partial discharge pulse propagation in single-phase cables. One commonly cited model has been developed by Boggs and Stone in 1982. This model is based on the calculation of longitudinal impedance and parallel admittance of the cable while taking into account the frequency dependency, skin effect and influence of semi-conductive screens. Figure 4.2 presents the equivalent circuit of Boggs's and Stone's model as it is introduced by Tozzi in [54].

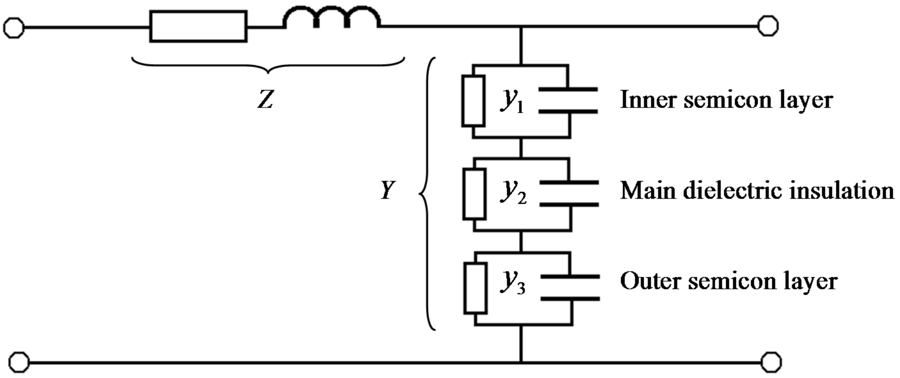


Figure 4.2. *Equivalent circuit for extruded power cable: the longitudinal impedance includes skin effect and all parameters are frequency dependent [54]*

From the Figure 4.2 parallel admittance Y can be calculated from equation

$$Y = \left(\sum_{k=1}^{3} y_k^{-1} \right)^{-1} \tag{4}$$

, where

$$y_k = j\omega C_{0k}\varepsilon_k^*(\omega) = j\omega C_{0k}(\varepsilon_k'(\omega) - j\varepsilon_k''(\omega)) . \tag{5}$$

Here C_{0k} is the geometrical capacitance, ε_k' is the real part of permittivity and ε_k'' is the imaginary part of permittivity. Usually the real- and imaginary parts of permittivity are unknown and they need to be measured to be able to use this model. The longitudinal impedance Z which includes the skin effect can be calculated as:

$$Z = \frac{1}{2\pi R_{\mathrm{in}}}\sqrt{j\omega\mu_0\rho_1} + \frac{1}{2\pi W R_{\mathrm{s}}}\sqrt{j\omega\mu_0\rho_{\mathrm{s}}} + \frac{j\omega\mu_0}{2\pi}\ln\frac{R_{\mathrm{out}}}{R_{\mathrm{in}}} \tag{6}$$

, where R_{in} and ρ_1 are the radius of center conductor and its resistivity, W is the total number of copper wires, R_{s} is the radius of each copper wire, ρ_{s} is the copper resistivity and R_{out} is the radius to the center of the metallic sheath. Now the propagation constant is evaluated as:

$$\gamma = \sqrt{\mathrm{ZY}} \tag{7}$$

Attenuation constant is frequency dependent and higher frequencies attenuate faster while propagating in the cable. Attenuation depends on the permittivity and loss factor of the insulation material these variables are affected by the temperature and cable ageing. Thus no generic theoretical or experimental permittivity can be assumed. Figure 4.3 presents the attenuation of different frequencies as function of distance propagated. Here 20 dB attenuation equals about 90 % attenuation. We see that in this case the component of 10 MHz travels 800 m, that at 50 MHz travels 100 m and the component of 100 MHz travels only 30 m.

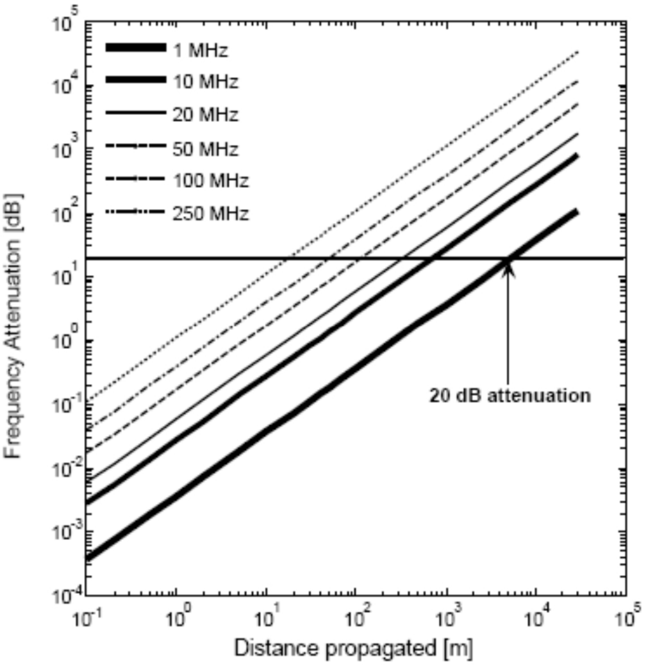


Figure 4.3. *Attenuation dB of the pulse frequency components as a function of the distance propagated in a medium voltage extruded cable, obtained by the analytical model described earlier. [34]*

The waveform of the discharge pulse changes while it propagates through the cable system. The change is caused by both signal attenuation and dispersion. The effect of attenuation has been studied by Oussalah in case where a discharge pulse has been modeled as an asymmetric pulse [55; 56]. Figure 4.4 presents how pulse propagation affects the waveform of an asymmetric pulse. Since the attenuation constant is higher for high frequencies the sharp peak of the pulse attenuates very fast and the rise time of the pulse increases.

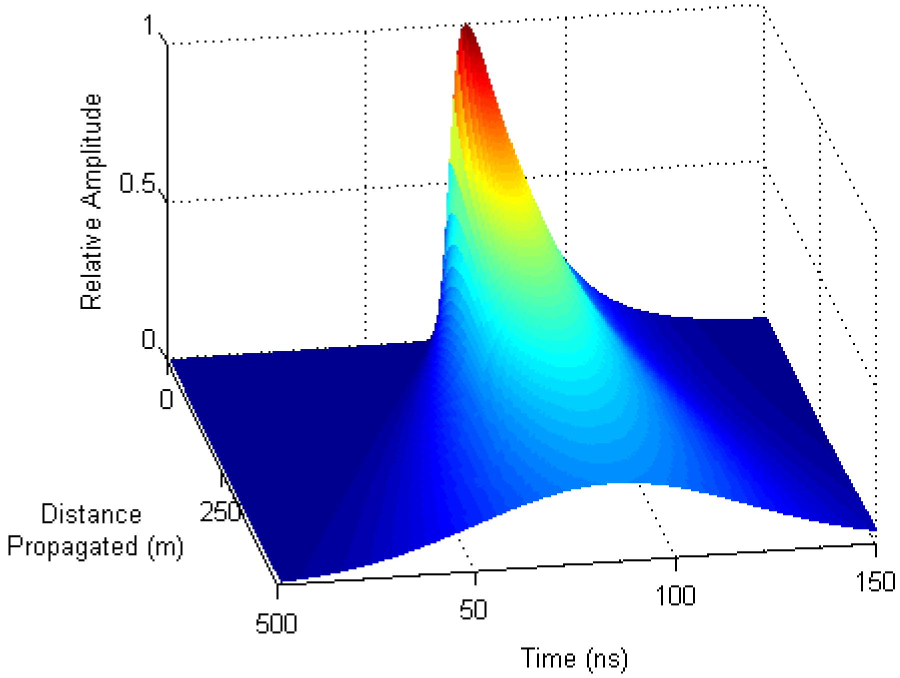


Figure 4.4. *The change in the waveform of an asymmetric pulse as it propagates along a cable (calculation is based on a model presented in [55]).*

From Figure 4.5, we see that at low frequencies attenuation is mainly caused by skin effect and at high frequencies dielectric losses, ground shield and neutral wires. It should be noted that the shown “loss budget” in Figure 4.5 cannot be considered universal for extruded power cables due to the fact that conductor and ground shield characteristics vary widely and the cable structures are different, these reasons can cause substantial differences in the distribution of loss among the cable components. In the scope of this work we are mainly interested in the total attenuation.

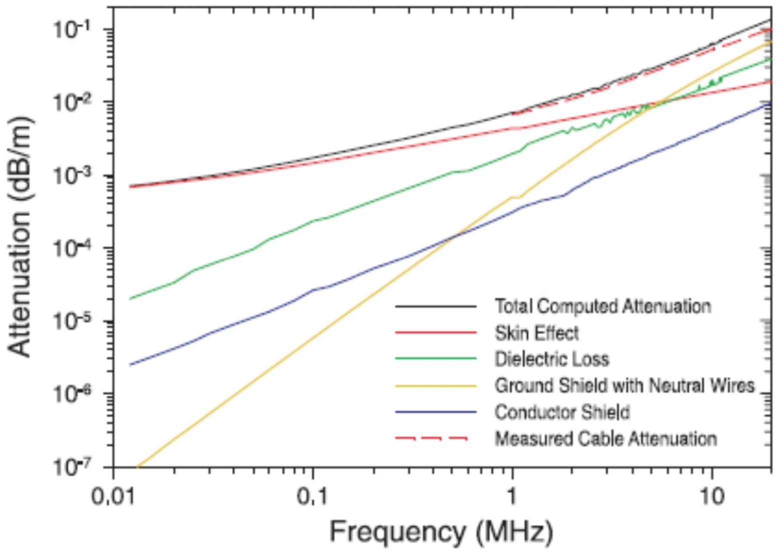


Figure 4.5. *Frequency dependent attenuation and its different components in extruded shielded single phase cable. [51]*

4.1.4. Propagation in a three-phase cable

Partial discharge pulse propagation in a three-phase cable can be modeled as three single-phase cables if each cable has its own metallic shield. Today it is common that three-phase cables are constructed with common earth screen. In this case multiple propagation modes exist and thus these cables need to be treated as multi transmission lines. The propagation modes can be decoupled into three modes: a shield-to-phase SP mode traveling between the conductors and earth screen and two phase-to-phase PP modes traveling between two conductors. Also in three-phase cables the semiconducting layers have a significant influence on the transmission line parameters. A detailed exposition of partial discharge propagation in three-phase cables with common earth screen can be found in [57; 58].

Three-phase cables with common earth screen decrease the partial discharge detection sensitivity due to the fact that the energy of the discharge pulse is spread in multiple propagation modes. The estimation of transmission line parameters is harder for three-phase cables due to more complex geometry but those can be measured quite easily as shown in [58].

4.2. Propagation through ring main units

The effect of ring main units (RMUs) on the propagation of partial discharge pulses has been studied in Netherlands [59; 60]. Partial discharge pulse shape and amplitude changes when it propagates through a RMU. The reason for this is that the load impedance for a partial discharge pulse arriving from a cable usually differs from the cable's characteristic impedance, and thus a part of the pulse will reflect and a part will transfer to continuing medium voltage cables. The number of connected cables plays a significant role because the transferred signal distributes its energy over the outgoing cables. Partial discharge detection sensitivity is significantly reduced if more than two cables are connected in a RMU. In case of multiple connected cables like in case of a substation a significant part of the partial discharge pulse is reflected back in the cable where it originally came from. [59] The total transfer function is defined as:

$$H_{\mathrm{rmu}}(\omega) = \tau_{\mathrm{c1}} H_{\mathrm{cn}}(\omega) = \frac{2Z_{\mathrm{c}}}{Z_{\mathrm{c}}+Z_{\mathrm{load}}} H_{\mathrm{cn}}(\omega) \tag{10}$$

, which is a combination of the current transmission coefficient τ_{c1} from cable under test to the load impedance Z_{load} and transfer function $H_{\mathrm{cn}}(\omega)$ that describes the distribution of current inside the RMU from incoming cable to the other connected cables. Current transmission coefficient τ_{c1} depends from the characteristic impedance of the cable Z_{c} and the load impedance Z_{load} for arriving partial discharge signal at the RMU.

Figure 4.6 presents the transfer functions $H_{\mathrm{rmu}}(\omega)$ from a study made in Netherlands for one, three and nine RMUs along the measured section which all have only two connected cables.

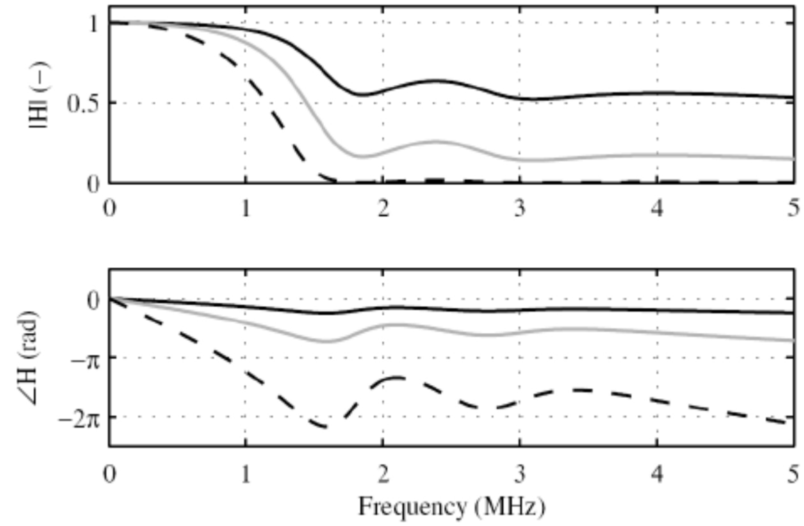


Figure 4.6. *Modeled total transfer function $H_{\mathrm{rmu}}(\omega)$ of a typical RMU (solid black line). The combined transfer functions of three (grey line) and nine (dashed black line) consecutive RMUs [59]*

From Figure 4.6, we can see that a RMU affects to frequencies above 1 MHz and nine RMUs to frequencies above 500 kHz. This means that the influence of RMUs decreases when the length of the measured cable system increases. This is due the fact that higher frequencies attenuate undetectable after travelling long enough in a medium voltage cable.

5. PARTIAL DISCHARGE SIGNAL DETECTION

Sensors are needed to measure partial discharges from the cable network. Noise and interference signals hamper on-line measurements and thus an advanced signal processing is needed to extract partial discharge pulses from measured data. Measuring partial discharges from long medium voltage cables is especially difficult because the measurable frequency range of discharge pulses is at the same range as most of the background noise [61]. The fundamental limitation to field testing is the external noise, which determines the detection sensitivity. The level of noise can vary to a great extent during a day and place [62].

In this text disturbance means all other signals except partial discharge signals from the cable under measurement. Disturbances are divided into noise and interference. Noise composes from disturbing signals that are continuously present during measurements and interference composes from disturbing signals of relatively short duration. The classification of disturbances mentioned above is used in a dissertation written by J. Veen [52].

5.1. Sources and types of disturbances in on-line measurements

On-line partial discharge measurements are hampered with external and internal disturbances, which decrease the sensitivity of the measurements. The power cables itself are well shielded and won’t pick up much disturbance but in other parts of the power grid there are many open structures that will pick up many disturbing signals. There are three common types of disturbances: narrowband interference, broadband noise and pulse-shaped interference. Figure 5.1 shows the typical form in time and frequency domain for all the different disturbance types mentioned.

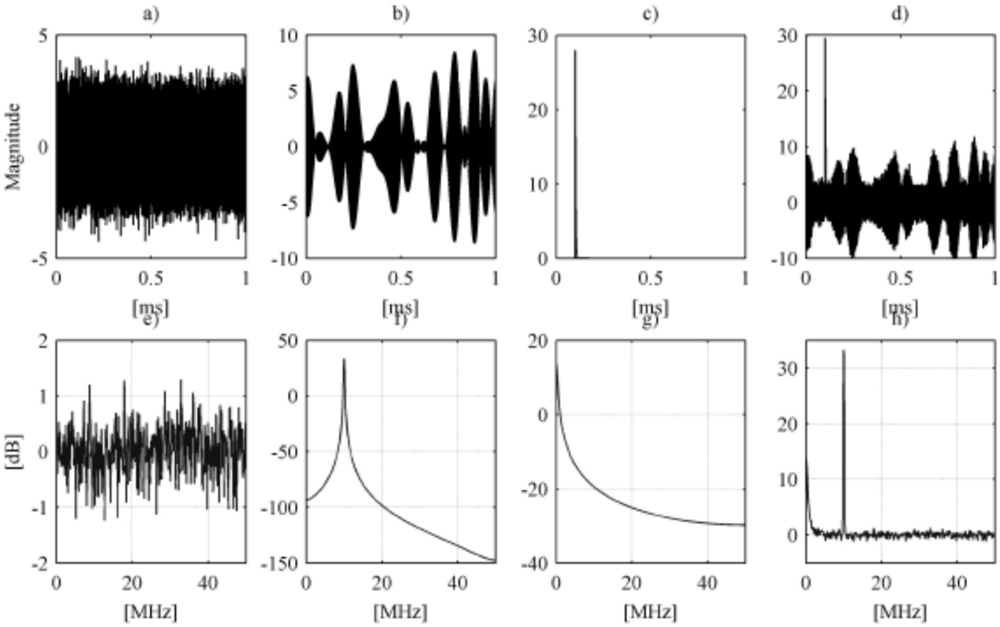


Figure 5.1. *Components of on-line partial discharge measurement signal in time and frequency domain. a),e) Broadband signal, b),f) Narrowband signal, c),g) pulse-shaped signal and d),h) example of measurement signal. [62]*

It can be seen from Figure 5.1 that a broadband signal is random in nature and its energy is equally spread along the whole frequency band. A narrowband signal is concentrated on a narrow frequency band and in time domain it is continuous and strongly oscillating. A pulse-shaped signal is discontinuous in time domain and in frequency domain its power is widespread and usually concentrated on lower frequencies.

5.1.1. Narrowband interference

Narrowband interference is usually the most dominant source of disturbance in on-line partial discharge measurements and thus increases the noise level. Its amplitude can be a lot higher than the amplitude of the partial discharge pulses. The main sources of narrowband interference are radio transmitters. Broadcasting stations, mobile phones, navigation systems and radio links all produce this type of interference. The level of these kinds of disturbances varies strongly as a function of time of day. During day time, the level of narrowband interference is only slightly over the level of broadband noise. During night time, the level of disturbance can be ten to fifty times higher. The main reason for this is that radio waves refracting from the ionosphere propagate more effectively during night time. [5; 52; 62]

Narrowband interference is picked up by the cable shield, overhead lines, badly shielded RMU components or the sensors themselves. Narrowband interference can be compressed by conventional notch filters or modern signal processing tools and through that the sensitivity of the measurement can be increased.

5.1.2. Broadband noise

Stochastic broadband noise signals result from numerous natural and artificial sources like thermal noise, lightning noise, measurement instrument noise or other man-made noise. Broadband noise is present within the entire frequency spectrum of the partial discharge signals and thus sets a fundamental limit for partial discharge detection. [52] Most of the broadband noise is concentrated on frequencies below 30 MHz. [61]

5.1.3. Pulse-shaped interference

Pulse-shaped interference frequently occurs during partial discharge measurements. Examples of pulse-shaped interference are thyristor pulses, switching transients and partial discharges from adjacent systems. The pulse shape of this kind of interference can be identical to the partial discharge pulses from the tested cable. Thus this type of interference can lead into false results if proper discrimination between the partial discharge pulses from the measured cable part and adjacent pulse-shaped interference is not made. [52]

5.2. Sensors

Sensors are very important parts of the partial discharge measurement system. They are needed to catch the electrical signals produced by partial discharges in the cable. A good sensor is accurate, safe and easy to use. Both capacitive and inductive sensors can be used. Capacitive sensors are more sensitive but their risk of failure is higher. That is why inductive sensors are preferred. Both the sensor type and positioning have a significant influence on the measured signal. It is also important to realize which signals are being measured. In case of on-line measurements are done for three-phase cables there are two different propagation paths for partial discharge signals (phase-to-phase) PP and (shield-to-phase) SP. [63] In this chapter different sensor types and places for sensor installation are discussed.

Required sensor properties depend on the place where the sensor is installed. For example, the frequency range where the sensor must be able to work depends on how close to possible partial discharge sources the sensor is installed. Development of an optimal sensor requires the knowledge of the wanted frequency range and information about the installation site. The price of sensors that can be used in on-line partial discharge measurements is still high because of small manufacturing volumes and markets. In many cases the installation of on-line partial discharge measurement systems without an interruption is not possible because cable terminations can’t be accessed while the power is on due to Finnish safety regulations.

Partial discharge pulses traveling in cables have a frequency range between 10 kHz - 1 GHz. Frequencies above 100 MHz are attenuated after short propagation in a cable usually only a few meters depending on the cable structure. In cases where it is possible to install the sensors very close to the potential partial discharge source UHF sensors can be used. This is the case when partial discharge measurements are made for single components which in case of a cable system could be cable terminations or joints. The advantage of UHF measurements is that due to the short propagation of the partial discharge pulses the discrimination between internal discharge pulses and external interfering pulses is easy. UHF partial discharge measurements are usually used to monitor the condition of expensive high voltage equipment and systems. At higher frequencies (above 30 MHz) (signal-to-noise ratio) SNR is increased due to the fact that most of the background noise is usually spread in the lower frequency range (below 30 MHz). [61]

5.2.1. Sensor types

The main sensor types used in partial discharge measurements are capacitive and inductive sensors. These types of sensors can be used to measure the current or voltage signal produced by partial discharge, which propagates through the cable system. Also sensors that use both capacitive and inductive coupling can be used. In this chapter capacitive and inductive sensing is discussed at general level and some examples of sensors generally used in on-line partial discharge measurements are shown.

Capacitive sensors can be used to measure the voltage pulse caused by partial discharge. There are basically three main categories for capacitive sensors: capacitors connected directly to a phase conductor of the cable, electrodes which form capacitors through capacitive coupling when installed in the vicinity of a phase conductor and capacitors that are integrated in the cable system for example in the switchgear. High voltage capacitors can be connected directly into a phase conductor. In this case partial discharges are measured over resistive impedance that is connected in series with the capacitor. This is a common method used in off-line partial discharge measurements. However in case of on-line measurements there are two main disadvantages. The installation of the high voltage capacitor can be done only when the cable is de-energized thus an interruption is needed. Secondly, the reliability of high voltage capacitors is often not very good on long-term and thus they can become a cause of a fault themselves. Long measuring time is needed in case of continuous on-line partial discharge measurements and thus the reliability of the sensors is crucial. The problem with electrodes is that the obtained capacitance is highly dependent on the installation details of the substation, cable termination and electrode positioning. Also the obtained capacitance is usually relatively low which decreases the sensitivity of the sensor. In modern substations sometimes capacitive sensors are integrated into the switchgear to detect the phase voltages. These capacitive sensors could be used for partial discharge detection but in practice it is hard due to their small capacitance value. The other problem is that this kind of technique could be used only in the presence of particular type switchgears. [63]

Inductive sensors can be used to measure the current pulses caused by partial discharges through the magnetic field. There is no galvanic connection between the sensor and the measured system and thus there is no risk for the sensor to cause a fault in the network. Other benefit of an inductive sensor is that it can be installed without an interruption. Typical inductive sensors are a Rogowski coil and a high frequency current transformer (HFCT). The sensitivity of HFCT is better due to the ferromagnetic core material. The ferromagnetic core material might saturate in the presence of high energy power frequency and thus HFCT sensors can't usually be used around energized cable conductors.

Antenna type sensors might offer a cheap alternative compared with conventional sensors. Resent paper written by Kwang-Jin Lim introduces a planer loop sensor, based on microstrip technology, which has sensitivity comparable to commercial HFCTs [64]. It should be noted that antenna type sensors are in general more sensitive to external interferences.

5.2.2. Sensor placement

There are many factors which affect the placement of partial discharge sensors. The most important factors are: sensor type, cable system accessibility and installation safety. In on-line measurements, disturbances play a decisive role when sensitivity is considered. The amount of disturbance radiated or conducted to a sensor depends on its placement within the ring main unit. Here the sensor placement is considered only for inductive sensors because they are usually preferred in on-line partial discharge measurements.

Two main current circuits can be defined when considering currents related to cables. The differential mode (DM) current flows through the phase conductor, load impedance and cable shield. This current includes the partial discharge signals we want to measure. The common mode (CM) current flows through the cable shield and back via several other earth paths. This circuit is actually a large antenna that picks up noise and disturbance and does not contribute to partial discharge signal detection. [63] Figure 5.2 presents these two current circuits.

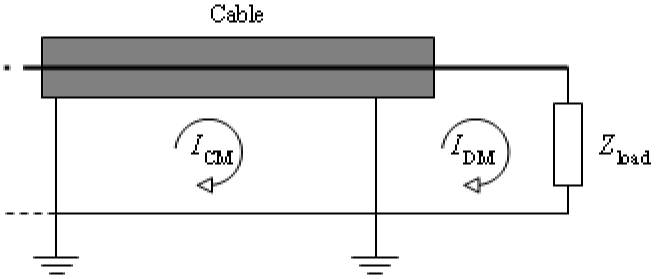


Figure 5.2. *Common mode and differential mode currents*

Figure 5.3 shows the possible sensor positions at the ring-main-unit. Each position has its own advantages and disadvantages which are described below:

1. The earth connection between the earth and the cable shield offers a partial discharge measurement point where a sensor can be safely installed without an

interruption. However, the safe installation without an interruption is only possible if this part can be safely accessed while the power is on. The disadvantage is that also the common mode current is measured at this place which increases the disturbance level thus decreasing measurement sensitivity.

2. There are different opinions about the possibility of using this place to measure partial discharges from the cable. In his dissertation P.C.J.M. van der Wielen concludes that both the forward and returning currents of a partial discharge pulse travel through this location resulting in a total current of zero. This means that partial discharges pulses can't be detected from this position. However he also mentions that, in the case of a cable with a helically-wired screen this location can be used to detect pulses inside the cable. The helical wires cause a magnetic field with a component in the direction of the cable which can be measured. This magnetic field is measurable only when a partial discharge pulse contains high frequencies (> 100 MHz). [3] On the other hand, in a paper written by N.H. Ahmed and N.N. Srinivas this place is used for partial discharge detection. The reason why partial discharge detection is possible from this place is explained below. In the vicinity of the partial discharge source, the discharge pulses are carried by a small portion of the cable shield. These pulses distribute uniformly along the circumference of the shield after some distance of propagation. This distance depends on the wavelength of the discharge pulses and the structure of the cable shield. Pulses in very high frequency (VHF: 30 – 300 MHz) range can travel a few hundred meters before they are distributed around the entire circumference of the cable shield. The traveling distance is reduced only to a few meters in case of pulses in ultra-high frequency (UHF: 300 – 3000 MHz) range. Cable shield structure affects in a way that in case of a solid shield structure the distance after pulse currents are uniformly distributed is roughly a half from what it is in case of a concentric wire shield. The unbalanced current distribution in the shield will result in a magnetic field outside the cable. Cable shields are normally made of diamagnetic materials which will contribute to a small leakage of the magnetic field outside the cable even when the discharge current is uniformly carried by the cable shield. The mechanisms described above enable partial discharge detection around the cable with inductive sensors. [65] There is at least one commercial on-line partial discharge measurement provider that uses this approach and their electrical system condition assessment process is called CableWISE® [66].
3. The insulated cable termination after the cable shield to the earth connection is preferred location for a sensor since only signals from the cable are measured and the safe installation of the sensor is possible.
4. The partial discharge current from the cable conductor will be distributed over the several impedances in the RMU. If transformer cables are shielded partial discharge current can be safely measured around them.
5. Transformer cables are relatively short and usually grounded only from one end. This is why they can be considered as lumped-circuit capacitors and the partial

discharge current through these capacitors can be measured at this location. Basically the measured current at this point is proportional to the partial discharge voltage. When, both partial discharge current and voltage are measured it is possible to determine the propagation direction of the pulse. This can be used to discriminate between the pulses from the cable under test and pulses from other sources.

6. This location is not very attractive when partial discharges form the cables are being measured. There are multiple paths to high frequency partial discharges in this location.

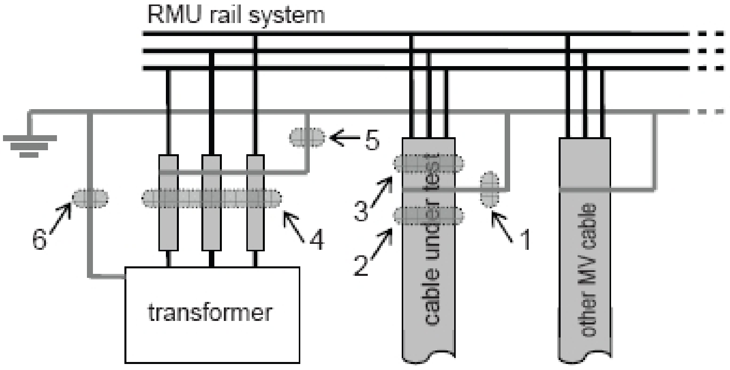


Figure 5.3. *Possible places for sensor installation at RMU [67]*

5.3. Partial discharge signal extraction

The original amplified signal gained from the sensor contains noise and interference and thus it is hard to extract the small partial discharge signals from the original signal. To do this modern signal processing is needed. Without signal processing, the detecting sensitivity of a partial discharge measurement system is greatly reduced. Some methods for noise suppression to help the extraction of partial discharge signals are introduced in this chapter. The use of analogical filters is a conventional way and matched filtering is an example of more advanced digital signal processing requiring computing power.

To allow state of the art signal processing the analogical signal from the sensor must be digitized. This can be done with analog to digital (A/D) converters. The sampling frequency must be high enough to provide sufficient accuracy in measured signal waveform. The Nyquist sampling theorem says that to be able to perfectly reconstruct the sampled signal the sampling frequency must be at least two times higher than the highest measured frequency. Partial discharge current signals propagating in cables have maximum frequencies between 10 MHz – 1 GHz depending on the propagated length. This means that the sampling frequency of A/D converters must between 20 MS/s – 2 GS/s. The problem with high sampling frequencies is that they produce a huge amount of data in a short time.

5.3.1. Analogical filters

Analogical filters are needed to filter out the unwanted frequencies. A high pass filter is used to cut off the low frequencies including the power frequency. Low pass filters can be used to limit the highest measured frequency. Specially tuned notch filters can be used to suppress the narrowband interferences. The cable itself works as a low pass filter as mentioned before.

The advantage of analogical filters is that they work fast. In case of notch filters the problem is that they need to be tuned separately for every measurement place depending on the narrowband interferences encountered. Narrowband interference can also be suppressed with modern signal processing like matched filtering.

5.3.2. Matched filtering

The characteristics of a partial discharge propagation channel in a cable are generally constant during measurements, thus a partial discharge signal can be regarded as being deterministic. Matched filtering is a standard technique for the detection of deterministic signals in the presence of noise. The transfer function $H(f)$ of a matched filter can be expressed as:

$$H(f) = C\frac{S^*(f)}{P_\mathrm{N}(f)}. \tag{11}$$

In the equation above C is a constant, $S^*(f)$ is the complex conjugate of the PD signal's Fourier transform and $P_\mathrm{N}(f)$ is the power spectral density function (psdf) of the noise.

A matched filter for a partial discharge signal can be obtained only if an accurate knowledge about the discharge pulse shape is available. The pulse shape can be estimated by using cable propagation models. Chapter 4 contains detailed discussion about the propagation of partial discharge signals in cables. First a partial discharge propagation model is formed based on the properties of the measured circuit and measurements. Second the shape of a partial discharge signal induced from the source needs to be approximated. Third the shape of the partial discharge signal after propagation is estimated for different propagation distances. This knowledge can be used to form a matched filter bank for the partial discharge signals that have propagated different distances in the cable. The closer the estimated partial discharge signal shape is with the measured partial discharge signal shape the better is the overall SNR. A rough estimate for the location of a partial discharge source can be formed by finding out which filter gives the maximum output to a certain time interval around the partial discharge signal. [68]

Figure 5.4 explains how matched filtering works. The frequencies where the SNR is high are amplified and frequencies with low SNR are suppressed. This way the total SNR of the partial discharge signal is maximized and noise is effectively suppressed with the matched filter. Figure 5.5 shows an example of a measured signal hampered with broadband noise and the signal after matched filtering is adapted.

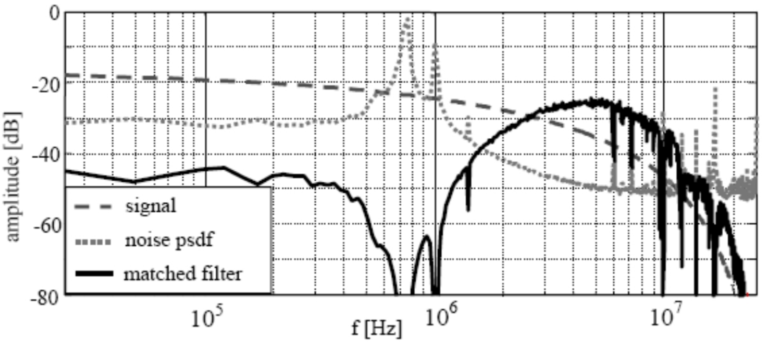


***Figure 5.4.** Example of a matched filter amplitude spectrum [68]*

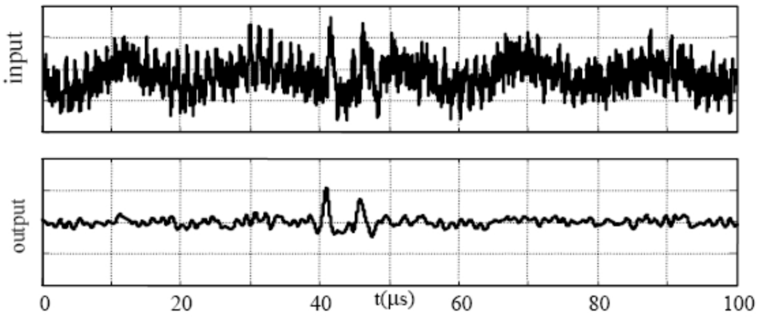


***Figure 5.5.** A noisy partial discharge signal from on-line measurement and signal after matched filtering [68]*

5.4. Measurement data collection

Measurement data forms the base for the partial discharge analysis. When, partial discharge activity is measured the things we are interested in are the location of the discharge source and the behavior of the discharges in that spot. Thus the data must be collected in a way that the discharge source location is possible and sufficient measurement sensitivity is achieved. The accurate location of the partial discharges requires that the time of arrival (TOA) of the partial discharge pulses are recorded. There are also other ways that can be used to give an approximate discharge source location. Chapter 6 contains detailed discussion about partial discharge source location. The way measurement data is saved determines which types of analyzing methods can be used to estimate the harmfulness of the discharges.

The discharge pulse waveform, the relations between consecutive discharges, the statistical distribution of the discharges as the function of the voltage phase or the time trends in continuous long term measurements can be used to analyze the harmfulness of the discharges. Time-resolved analysis (TRA) requires that the waveforms of the discharge pulses are recorded as $i(t)$. In depth analysis based on discharge waveform are usually not possible due to the high level of noise added to the signal and distortion caused by signal propagation in the cable. To be able to perform a phase resolved pulse-sequence analysis (PRPSA) the discharge magnitude needs to be recorded as $q_s(t_s, u(t_s))$, where q_s is the discharge magnitude, t_s time of occurrence and $u(t_s)$ phase voltage at time of occurrence of s:th discharge. Discharge magnitude is usually presented as apparent charge, which is the time integral of the induced partial discharge pulse at the discharge site $Q_{\text{app}} = \int i_{\text{ind}}(t)\,dt$. We can estimate the real apparent charge from the measured one with the help of the transfer functions in the path of the signal. The transfer functions are based on signal propagation models and the parameters can be measured during the discharge magnitude normalization process. [52] In PRPSA every consecutive discharge pulse needs to be recorded. This is problematic because to achieve sufficient accuracy, time spending digital signal processing is needed. In case of phase-resolved partial discharge analysis (PRPDA) only the discharge magnitude and phase of occurrence needs to be recorded as $q_s(\varphi_s)$. Since in here the information between consecutive pulses is not needed it is enough to record only some of the partial discharge pulses and the time needed for signal processing is not a problem anymore. [69] In case of time trend studies discharge magnitude and frequency are the most commonly used parameters. These analyzing methods are discussed in detail in Chapter 6.

5.5. Partial discharge magnitude normalization

When partial discharge measurements are used, it is important that they are normalized so that comparison can be made between different measurements. The quantity which is normalized is the apparent charge. The term “calibration” is also often used for this procedure but it is somewhat misleading because it is not possible to carry out absolute measurements on charge produced by the partial discharge. The normalization procedure can also be used to check the sensitivity of the system and to verify that the test equipment is functioning normally.

The normalization methods that are used in the factory tests are defined in test and measurement standards like IEC 60270:2000 and IEEE Std 400.3-2006. The described methods are valid for low or narrow bandwidth measurements, but wideband measurements are not addressed [21; 39]. Normalization is also possible for wideband measurements when the lower cut off frequency is low enough [70]. In normalization procedure first a current pulse which waveform and duration are comparable to usually occurring partial discharge pulses and which magnitude is known (pC) is injected (inductive coupling) into the measured cable at the remote end. Then the reading of the measurement system installed in the near end is adjusted to until the magnitude (pC) obtained is the same as that of the injected pulse. The sensitivity of the system can be tested by finding out the magnitude of the smallest detectable injected pulse.

5.6. Limitations in on-line partial discharge detection

The major limiting factor in on-line partial discharge measurements is the measurement sensitivity. As it is mentioned before, discharge magnitude depends on the defect type. Depending on the defect's type the magnitude of harmful discharges is at the range of (1 - 10^3 pC) for extruded medium voltage cables [71]. Thus the detection sensitivity of the measurement system determines which type of defects can be spotted.

The physics behind partial discharge measurements, including the discharge coupling to the cable system, forms the fundamental limitations to discharge detection. The quality of the sensor, the level of the disturbances encountered, the length of the cable between the measurement site and the discharge source and the effectiveness of the signal processing on disturbance removal are the main factors that determine the detection sensitivity. One can't determine universal detection sensitivity to on-line partial discharge measurements, because it depends on the measured circuit and prevailing measurement conditions. Other limiting factors are reliability and structural aspects. In this context with reliability it is meant that the measurement system doesn't become a reason for a fault by itself. Basically, this limits the use of certain type of sensors. Structural aspects address the actual physical accessibility of the system like where the sensors could be installed and the structure of the components. Accessibility of the system limits the minimum length between the sensors. This sets a limit for the highest frequencies that can be measured. Partial discharge pulse propagation properties depend on the cable structure. It has been shown in [5] that for cable lengths between 0,3 – 5 km the achievable sensitivity is about two times better for a single-core XLPE cable than a three-core XLPE cable. The main reason for this is that in case of a three-core cable there are multiple propagation paths where the signal is spread. Figure 5.6 shows how the disturbance level and distance from partial discharge source to the measurement point affect to the measurement sensitivity. Figure 5.6 is not based on measurements it is just an ideal presentation based on a sophisticated guess how things are.

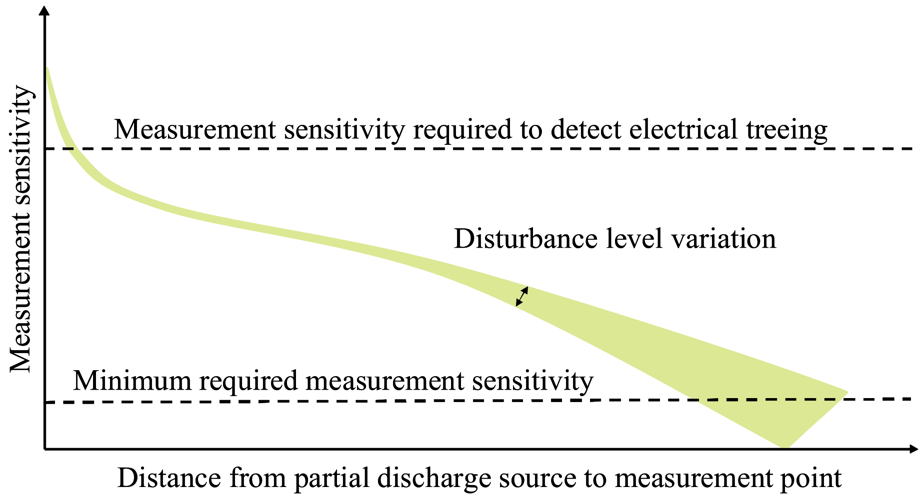


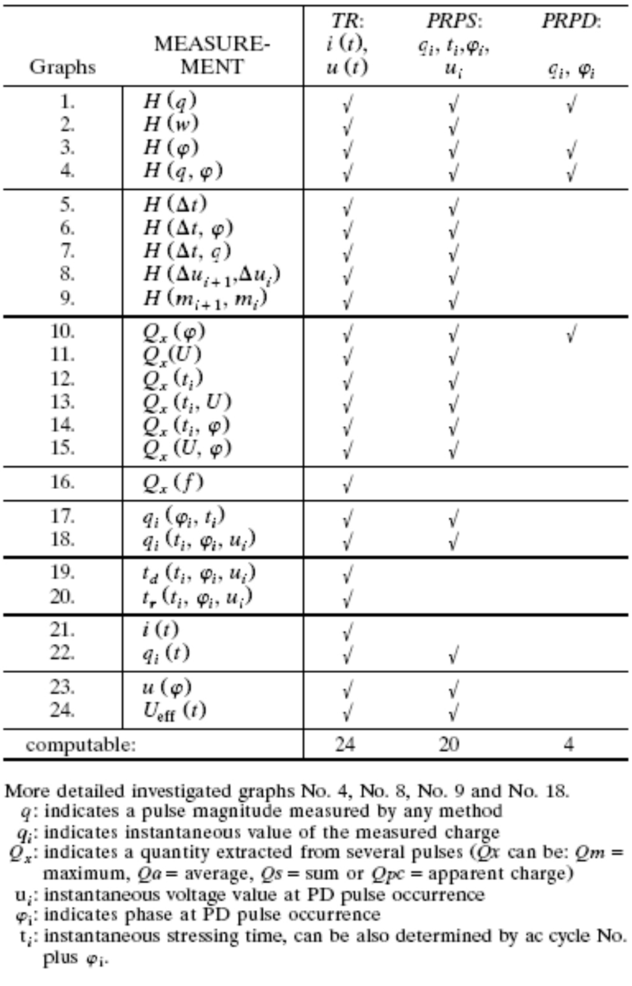
Figure 5.6. *Measurement sensitivity as a function of the distance from the discharge source*

The attenuation of the peak value of the partial discharge pulse during propagation in the cable is exponential thus the sensitivity of the measurement decreases exponentially. Most of the background noise is distributed on the lower frequencies (below 30 MHz). This is why the sensitivity starts to increase more rapidly after the point where there are only lower frequencies left in the discharge pulse due to long enough propagation. Disturbance level has a significant influence on the measurement sensitivity. This influence is shown in Figure 5.6 by the width of the curve. Rough estimates for required sensitivities are ~5 pC for the minimum sensitivity to detect electrical treeing and ~200 pC for minimum required sensitivity. This means that with current on-line partial discharge measurement systems electrical treeing can be detected closer than ~150 m [66] from the discharge source and maximum measurement distance is ~4 km [5] (requires double sided measurement). These estimates are based on measurement results found in the literature and harmful discharge magnitude levels set by commercial partial discharge measurement providers.

To give some kind of idea about the sensitivity of today's measurement systems the sensitivity of two commercial systems is given below. The first system is suitable for measuring long cables with a single measurement set-up. This On-line partial discharge monitoring system is called Smart Cable Guard SCG previously PD-OL and it has been developed in Netherlands by KEMA. The system uses matched filters and double-sided measurement. The measurement sensitivity of this system in case of average noise level encountered in Netherlands is for short cables around 30 pC and for 2 km length cables between 100 – 200 pC depending on the cable structure [5]. These sensitivities are probably measured for 10 kV cables because the distribution network in Netherland is mostly operated at 10 kV. Thus these results can't be directly compared with measurements at 20 kV cables. Another example is called CableWISE® that is developed in the USA. This electrical system condition assessment process uses a measurement system that makes the measurements in the frequency domain, and it is developed to measure only a short part of the cable at single measurement. In case of longer cables several measurements at different points of the cable needs to be done. The achievable measurement sensitivity depends on the cable structure and the distance between consecutive measurement points. When the distance between consecutive measurement points is kept below 150 m very high measurement sensitivities (about 1 pC) can be achieved [66]. Obviously the downside is the short measurement length with a single measurement.

6. ANALYSIS OF MEASURED DATA

Data analysis is carried out after partial discharge measurements. There are three major steps in partial discharge analysis: partial discharge source location, partial discharge type recognition and evaluation of the criticality of the identified partial discharge defects. In the cable system the location of the discharge source can be considered as the most informative information [42]. When the location of the discharge source is known it is easier to recognize the discharge type and evaluate the criticality of the discharges. Partial discharges are analyzed with the help of different graphs which are formed from the saved data. Table 6.1 introduces different graphs that can be used in partial discharge analysis. We can see that the amount of possible graphs that can be used depends on the way the data is collected.



Graphs	MEASUREMENT	*TR*: $i(t)$, $u(t)$	*PRPS*: q_i, t_i, φ_i, u_i	*PRPD*: q_i, φ_i
1.	$H(q)$	√	√	√
2.	$H(w)$	√	√	
3.	$H(\varphi)$	√	√	√
4.	$H(q, \varphi)$	√	√	√
5.	$H(\Delta t)$	√	√	
6.	$H(\Delta t, \varphi)$	√	√	
7.	$H(\Delta t, q)$	√	√	
8.	$H(\Delta u_{i+1}, \Delta u_i)$	√	√	
9.	$H(m_{i+1}, m_i)$	√	√	
10.	$Q_x(\varphi)$	√	√	√
11.	$Q_x(U)$	√	√	
12.	$Q_x(t_i)$	√	√	
13.	$Q_x(t_i, U)$	√	√	
14.	$Q_x(t_i, \varphi)$	√	√	
15.	$Q_x(U, \varphi)$	√	√	
16.	$Q_x(f)$	√		
17.	$q_i(\varphi_i, t_i)$	√	√	
18.	$q_i(t_i, \varphi_i, u_i)$	√	√	
19.	$t_d(t_i, \varphi_i, u_i)$	√		
20.	$t_r(t_i, \varphi_i, u_i)$	√		
21.	$i(t)$	√		
22.	$q_i(t)$	√	√	
23.	$u(\varphi)$	√	√	
24.	$U_{\mathrm{eff}}(t)$	√	√	
computable:		24	20	4

More detailed investigated graphs No. 4, No. 8, No. 9 and No. 18.
q: indicates a pulse magnitude measured by any method
q_i: indicates instantaneous value of the measured charge
Q_x: indicates a quantity extracted from several pulses (Qx can be: Qm = maximum, Qa = average, Qs = sum or Qpc = apparent charge)
u_i: instantaneous voltage value at PD pulse occurrence
φ_i: indicates phase at PD pulse occurrence
t_i: instantaneous stressing time, can be also determined by ac cycle No. plus φ_i.

Table 6.1. *Partial discharge data acquisition (measurement) and evaluation tools (graphs) subjected to different acquisition procedures [72]*

6.1. Location of partial discharge source

Degradation which takes place because of partial discharges is a local phenomenon. The fact that these local discharge sources can be localized makes partial discharge measurements such a good diagnosis tool. When on-line measurements are done it is even more important to be able to locate the discharge sources. The cable that is being tested is connected into other cables and equipment and thus without discharge location it is not possible to tell if the discharges originate from the cable or from other equipment. Location is difficult in on-line measurements because of the high amount of disturbance and usually the discharge pulses won't reflect properly. Partial discharge location systems developed for high voltage transmission cables require multiple distributed sensors which increase their cost.

Time-domain reflectometry (TDR) is the most common method used in off-line discharge source location, but a good reflection is needed to be able to use this method. Thus TDR can only be used in some special on-line measurement cases. The way to overcome the lack of reflection is to measure from both ends of the cable. This method has many benefits compared with TDR and it is the most suitable method for on-line partial discharge location in long cables. Because the propagation properties of a discharge pulse in the cable are well known and modeled the information about pulse attenuation can be used to evaluate discharge source location. Discharges can also be located based on their frequency content. [3]

6.1.1. Time-domain reflectometry

Time-domain reflectometry is the most commonly used method in order to locate partial discharge sources during off-line measurements. The idea is to measure the difference in the time of arrival (TOA) between the direct and reflected pulse. Now when the propagation velocity of the discharge pulse is known the location of the discharge source can be calculated. If the propagation velocity is unknown we can still calculate the location if we are also able to measure the time difference between the first and second reflected pulses. Figure 6.1 explains the principle of time-domain reflectometry.

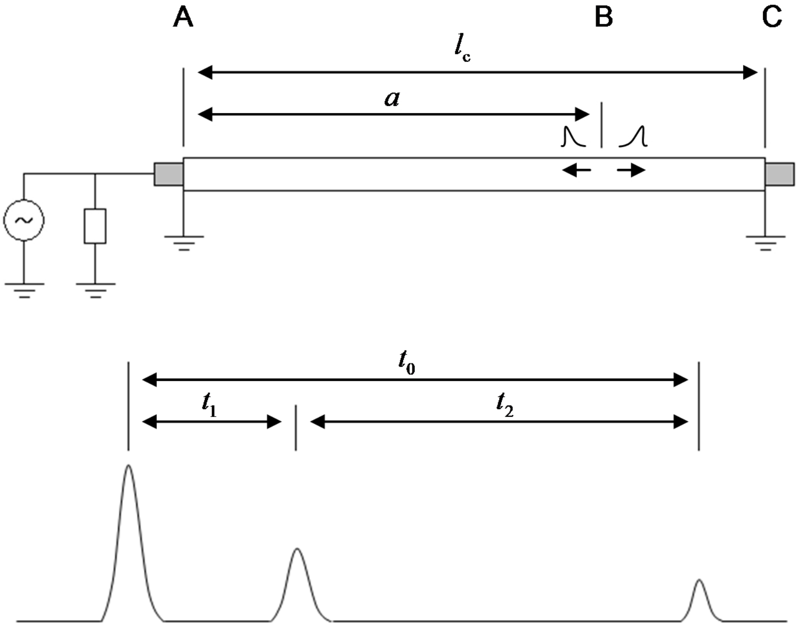


Figure 6.1. *Principle of time-domain reflectometry [73]*

When the propagation velocity of the partial discharge pulse is known distance *x* can be calculated from the following equation.

$$a = l_c - \frac{vt_1}{2} \tag{13}$$

If the propagation velocity is not known, the distance *a* can be calculated if also the three-times reflected pulse can be detected. In this case, the following equation is valid for the distance *a*.

$$a = \frac{t_2}{t_0} l_c . \tag{14}$$

In both of cases mentioned above it is assumed that the pulse propagation velocity is constant along the whole measured cable. This is usually not the case when the measured cable consists of multiple segments of different types of cables.

The following conditions have to be met before TDR can be applied:

a) Proper discharge pulse reflection at the other end of the measured cable is needed. In on-line measurements there is a ring-main-unit or a substation connected to the other end and thus usually the discharge pulse is not fully reflected.
b) The total attenuation and dispersion can't be too large. In case the discharge location is made with TDR the maximum length for a cable is around 4 km, depending on the noise level and required sensitivity.

If the cable network is branched, TDR can't be used in practice because of multiple reflection points. When other power cables and other possible partial discharge sources are connected to the cable under test the use of TDR becomes almost impossible. For instance, it is possible that in this case two successive pulses originate from somewhere else in the adjacent grid leading into a false location of discharge source. [3]

6.1.2. Double-sided measurement

Double-sided measurement is based on the same principle as TDR. However most of the problems involved in TDR are solved. The total propagation distance is smaller in comparison with TDR which increases the sensitivity of pulse detection and accuracy of TOA estimation. There is no need for a reflection at the far cable end. Also branched networks can be measured when the measurement unit is placed at each branch end. Noise has the same impact but double-sided measurement offers a way to reject pulse-shaped disturbances. [3]

Measurement units are placed in both cable ends and the difference between the arrival times is measured. If the partial discharges originate from the cable under test the time difference is between 0 - t_{c}, where t_{c} is the time it takes from a partial discharge pulse to travel through the whole cable length under test. If the time difference is t_{c}, it means that the measured discharge pulse originates outside the cable. This offers a possibility for a pulse shaped disturbance rejection in on-line partial discharge measurement. The difference in TOA is determined by:

$$\Delta t_{\mathrm{oa}} = t_{\mathrm{oa2}} - t_{\mathrm{oa1}} \tag{15}$$

, where t_{oa1} and t_{oa2} are the pulse arrival times at measurement units 1 and 2. Now the distance x from measurement unit 1 to the discharge source can be calculated as:

$$x = \frac{1}{2}\left(1 - \frac{\Delta t_{\mathrm{oa}}}{t_{\mathrm{c}}}\right) l_{\mathrm{c}} . \tag{16}$$

, where l_{c} is the length of the measured cable section. [3]

To be able to measure the difference in TOA the time bases of the measurement units, in both cable ends, must be extremely well aligned. The reason for this is that the location error is half the error in Δt_{oa} times v_{c} (which is large). In order to locate partial discharges within 10 to 20 m, the time bases of the measurement units have to be aligned within a margin in order of 100 ns. Some methods that can be used for time base alignment are: stable independent clocks, GPS signal or pulse injection. Atomic clocks can be used as stable independent clocks, but they must be calibrated on regular basis to maintain the required accuracy. For the most accurate atomic clocks, the calibration is needed only ones in a year, but in general atomic clocks are very expensive. The normal accuracy of GPS based time alignment is around 100 ns. This can be even improved when using a differential GPS receiver which has accuracy of 5 – 20 ns. In the third method pulses are injected through the cable under test itself. This can be done by using inductive Rogowski coils around the earth connection or cable conductor. With this method even higher accuracy than with GPS can be achieved. It also needs less expensive equipment than the other mentioned methods. [3]

Besides double-sided measurement partial discharges can be located in on-line measurements with only one measurement unit and a transponder unit which is placed at the other end of the cable under test. The transponder unit injects a pulse into the cable itself every time it detects a partial discharge pulse. This makes it possible to locate the discharges in the same way as in TDR without the need for pulse reflection. However, this system is very sensitive to noise and the use of this system is problematic in case of intensive partial discharge activity due to the large amount of pulses that is being injected. [3]

6.1.3. Pulse-shape based location

The shape of a current signal induced by partial discharge can be approximated to be a delta pulse on considered frequencies. Current signals attenuate and disperse while they propagate along a cable. Both effects increase with increasing distance. The transfer properties of a cable can be modeled very accurately and with the help of these models the shape of the current signal can be modeled and approximated on different distances. The location of the partial discharge source can be estimated by comparing the shape of the measured current signal on the approximated shapes of current signals with different distances propagated. [3] The accuracy of this method is determined by the level of pulse shape variation as a function of the propagation distance. When noise is introduced only small (tens of meters) total propagation distances can be distinguished.

On the other hand partial discharge pulses can be examined also in the frequency domain. As we know attenuation is frequency dependent and high frequencies attenuate faster than low frequencies. For short measurement lengths the accurate location of partial discharge sources can be made by examining the frequency content of the partial discharge pulse. [36; 74] Amplitude-frequency map is one way to perform approximate discharge source location and it is based on discharge pulse attenuation and dispersion. In this method, the peak amplitude, equivalent bandwidth F and equivalent time length T of the discharge pulse are measured at different locations along the cable. Figure 6.2 presents pulse peak amplitude, F and T as a function of distance from discharge source to the sensor. Near the discharge source, the T has a low value and F has a high value. On the contrary when the sensor is positioned far from the discharge source the T has a high value and the F has a low value. Different discharge sources can be separated from each other as they form clusters in a graph where T is plotted as a function of F. Once the different discharge sources have been separated it is possible to locate these sources by comparing the average F value and the high probability percentile of the magnitude distribution on different measurement points. The measurement point corresponding the highest *F* value and amplitude value is likely the site of the PD source. [36]

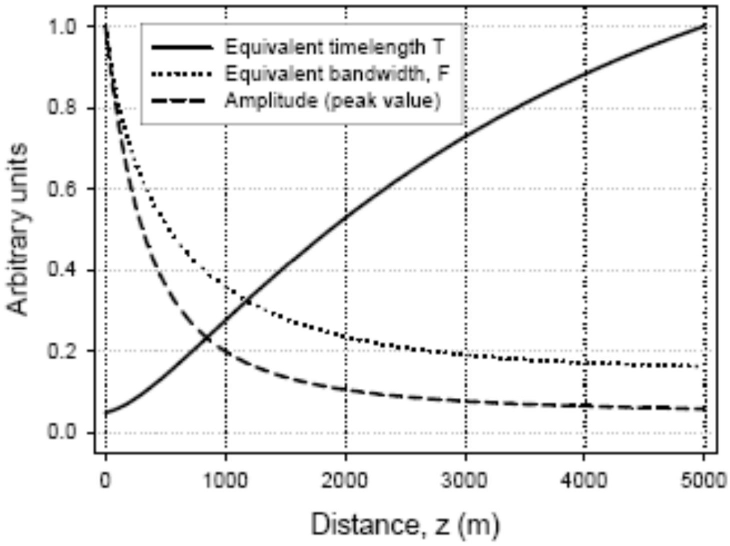


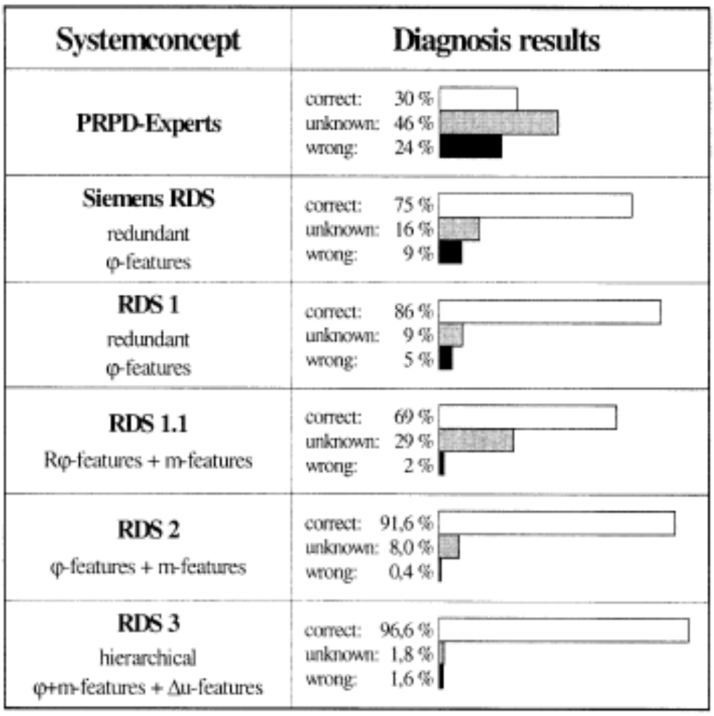
Figure 6.2. *Pulse peak amplitude, F and T as a function of distance from the discharge source to the sensor [36]*

6.2. Recognition of partial discharge type

It is very important to be able to distinguish the discharge type because the harmfulness of partial discharges highly depends on it. As mentioned before there are four different types of discharges: corona discharges, internal discharges, surface discharges and electrical treeing. There are three different methods to be used for partial discharge type recognition: phase-resolved partial discharge pattern analysis (PRPDA), phase-resolved pulse-sequence analysis (PRPSA) and time-resolved analysis (TRA). Next each of these analysis methods is discussed in more detail.

It is more common that the final partial discharge type recognition is made by a human expert. Automatic partial discharge type recognition is also possible today and a lot of research has been conducted in this area at recent years. High quality reference data is the key component in every discharge type recognition method. The importance of the quality of the reference data is even greater when automatic computer-based discharge type recognition is used. Automatic partial discharge type recognition includes two main steps: feature extraction and type classification. In feature extraction it is crucial that the extracted features (fingerprints) show significant differences in case of diverse partial discharge defects and a clear consistence when the same defects are evaluated. This must be fulfilled even under non-ideal data acquisition conditions. Feature extraction can be based on statistical tools, signal processing tools or image processing tools. More detailed description of these tools can be found in a paper written by N.C. Sahoo and M.M.A. Salama [75]. In that paper also different type classifiers are introduced. Type classifiers can be break down into distance classifiers, statistical classifiers, artificial neural networks based classifiers and fuzzy logic based classifiers.

Figure 6.3 introduces the accuracy of partial discharge diagnostics made by experts and by computer. It can be noticed that computer based diagnostics are a lot more reliable than human experts. Human experts have used only PRPDA which is also used in Siemens redundant diagnosis system (RDS) and RDS 1 automated recognition procedures. RDS 1.1, RDS 2 and RDS 3 use also PRPSA. It can be seen that by utilizing both PRPDA and PRPSA highly accurate and reliable automatic discharge type recognition is possible. It must be remembered that the quality of the reference database has a big influence on the achievable results. [72] In the shown case the partial discharge measurements were done in gas insulated system (GIS). Examples of automated discharge type recognition in cable systems were not found.



Systemconcept	Diagnosis results
PRPD-Experts	correct: 30 % unknown: 46 % wrong: 24 %
Siemens RDS redundant φ-features	correct: 75 % unknown: 16 % wrong: 9 %
RDS 1 redundant φ-features	correct: 86 % unknown: 9 % wrong: 5 %
RDS 1.1 Rφ-features + m-features	correct: 69 % unknown: 29 % wrong: 2 %
RDS 2 φ-features + m-features	correct: 91,6 % unknown: 8,0 % wrong: 0,4 %
RDS 3 hierarchical φ+m-features + Δu-features	correct: 96,6 % unknown: 1,8 % wrong: 1,6 %

Figure 6.3. *Example of diagnosis results attained with different methods described in [72; 76]*

6.2.1. Phase-resolved partial discharge analysis

It has been shown that observation of the discharge magnitude as a function of the phase angle offers a good way to discriminate different discharge types from each other. To be able to perform PRPDA partial discharge magnitudes and their phase of occurrence over some time needs to be recorded. From this information, different phase-resolved patterns can be obtained. Phase-resolved partial discharge analysis is based on discharge magnitude and thus the measurements needs to be standardized so that the measurement results can be compared. The problem with phase-resolved partial discharge analysis is that the phase-resolved patterns are highly dependent on the measurement system and its properties (sensor linearity, measurement range pC, measurement voltage) and on the measurement conditions (the amount of disturbances). The patterns also change during time. This means that there are multiple patterns describing the same type of defects. The situation gets even trickier when multiple defects produce partial discharges at the same time. Thus type recognition is a very difficult task for a human expert. On-line measurements are done with constant ac voltage (operating voltage) which reduces the amount of patterns but this also reduces the analyzing potential of the system. When measurement is done at constant voltage important information such as inception and extinction voltage of the partial discharges can't be measured. Actually partial discharge type recognition is especially difficult when constant measurement voltage is used. [72; 77]

The so called φ-q-N pattern (graph number 4 in Table 6.1) is a widely spread tool for partial discharge expert evaluation. This plot features the number of discharges N with a certain phase position φ and the apparent charge q of a partial discharge event. [69; 72] Figure 6.4 shows the ideal partial discharge patterns for four different defect types (corona discharge, internal discharge, surface discharge and electrical treeing) here the length of the pole describes the discharge magnitude.

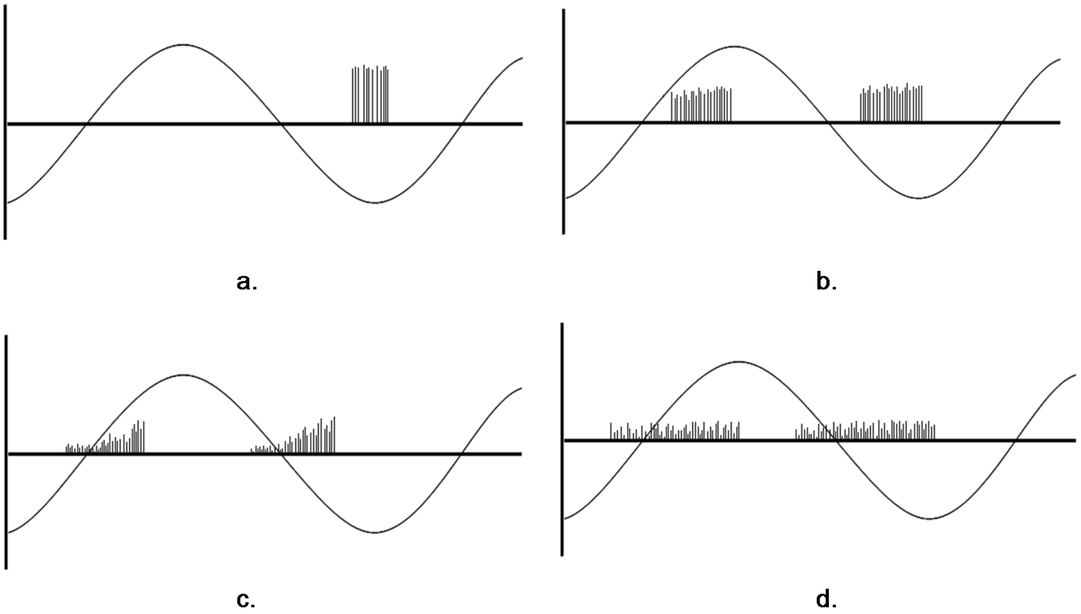


Figure 6.4. Typical phase-resolved partial discharge pulse magnitude patterns for different partial discharge types a) corona discharge, b) internal discharges, c) surface discharges and d) electrical treeing. [78]

Corona discharges occur near sharp edges which can be found either from the high voltage side or the earth side. When the sharp points are on the high voltage side, which is usually the case, discharges take place near the peak of the negative half cycle of the operation voltage. In case of sharp points are at the earth side discharges take place at the positive half cycle of the operation voltage. It is also common for corona discharges that their magnitude have a little variation. Figure 6.4a presents the typical corona discharge pattern. As we can see from the Figure 6.4b internal discharges take place on both positive and negative half-cycles and the discharge magnitude is steady. There might be differences between the discharge magnitudes on positive and negative cycle depending on the geometrical location of the cavity. Also the geometrical shape of the cavity has a significant effect on the PRPD pattern. Figure 6.4c illustrates that the magnitude of surface discharges varies and they occur around the zero crossings of the operating voltage. For surface discharges, it is also common that the magnitude of the discharges is different on the negative and positive half cycle. Figure 6.4d shows pattern from electrical treeing discharges from electrical treeing have small varying magnitude. [79] Real partial discharge patterns are far from the ideal ones shown in here and thus a lot of experience is needed to be able to determine the defect type from the measured discharge pattern. To overcome the need for skilled professional an automated discharge analyzer is needed.

To make automatic PRPDA possible features must be extracted from the PRPD patterns where the measurement results are saved. This can be done by using statistical tools, signal processing tools or image processing tools. [77] As an example the following statistical operators can be used for automated discharge type recognition when PRPD is used: skewness (S_{k}), kurtosis (K_{u}), number of peaks, cross-correlation factor, asymmetry and phase factor. Skewness describes the asymmetry of the distribution with respect to a normal distribution. Kurtosis represents the sharpness of the distribution with respect to the normal distribution.

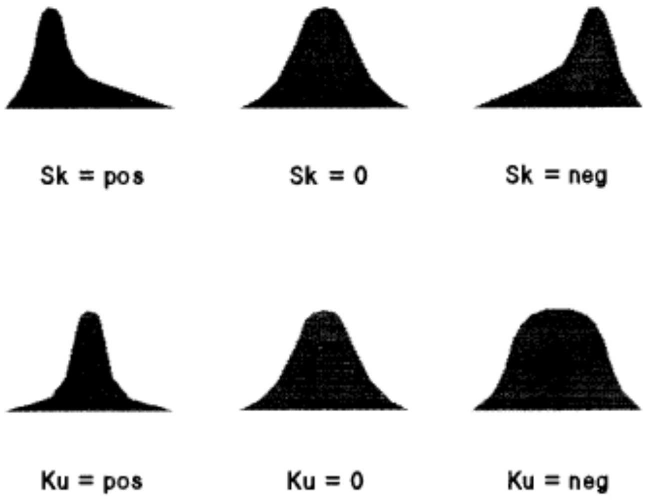


Figure 6.5. *Examples of shapes of patterns and their resulting operators [75]*

The number of peaks is used to distinguish between distributions with a single and those with several tops. The cross-correlation factor describes the difference in shape between $H^{+}_{\mathrm{qmax}}(\varphi)$ and $H^{-}_{\mathrm{qmax}}(\varphi)$, $H^{+}_{\mathrm{qn}}(\varphi)$ and $H^{-}_{\mathrm{qn}}(\varphi)$, and $H^{+}_{\mathrm{n}}(\varphi)$and $H^{-}_{\mathrm{n}}(\varphi)$ distributions of the positive and negative half of the voltage cycle. The asymmetry is the quotient of the mean level in the negative and in the positive half of the voltage cycle of the

$H_{\mathrm{qmax}}(\varphi)$, $H_{\mathrm{qn}}(\varphi)$ and $H_{\mathrm{n}}(\varphi)$ distributions. The phase factor is the difference in the inception voltage in the negative and positive half of the voltage cycle. These statistical operators form the so called fingerprints which are used in discharge type recognition where they are compared with the fingerprints of known defects. [75; 79]

6.2.2. Phase-resolved pulse-sequence analysis

PRPSA examines the correlations between consecutive pulses, which are directly related to the physics of partial discharge phenomena. Space charges from previous discharges that remain near the discharge site affect the ignition conditions of the following pulse, which explains the strong correlation. [80] It has been shown that PRPSA offers more reliable results than phase-resolved pattern analysis in on-site partial discharge defect identification [72]. The biggest advantage is that no calibration is needed and sensor properties don't have as big influence as they have in case of PRPDA. This method is especially effective in the early stages of insulation degradation where space charges play a decisive role [80].

To be able to use PRPSA multiple consecutive pulses which all originate from the same discharge source need to be measured. This is problematic in case of long cables. Frequencies over 10 MHz are basically completely attenuated in long cables. This limits the measurable frequency below 10 MHz which on the other hand means that noise and interference level is high. In these conditions modern signal processing is required to achieve sufficient sensitivity. Signal processing requires time which means that partial discharge magnitudes and phase of occurrence can't be recorded in real time. It is a challenge to handle the huge amount of data that this kind of measurement creates. Figure 6.6 presents different variables used in PRPSA.

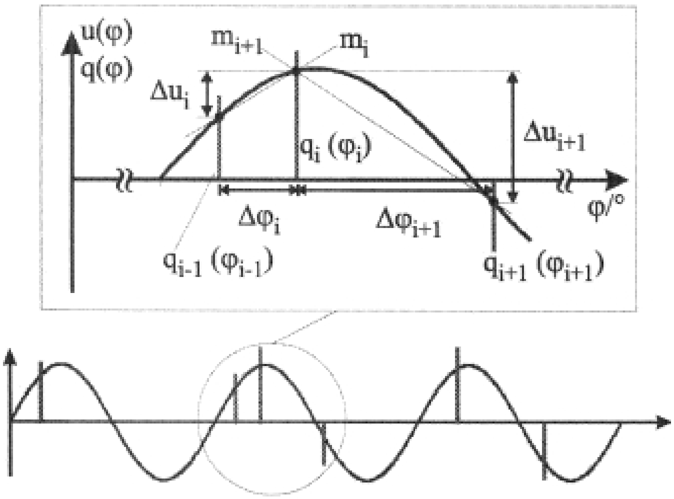
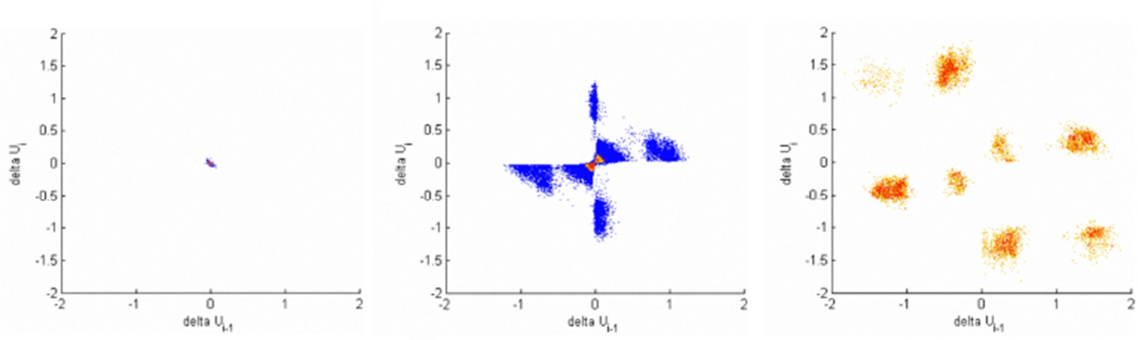


__Figure 6.6.__ Presentation of different variables used in PRPSA [72].

In Figure 6.6 Δu_i is the voltage difference (operating voltage) between two consecutive discharge pulses, $\Delta\varphi_i$ is the phase angle difference between consecutive discharge pulses, $m_i = \frac{u(\varphi_{i+1}) - u(\varphi_i)}{\varphi_{i+1} - \varphi_i}$ it approximates the voltage gradient which is necessary to excite a consecutive partial discharge pulse and q_i is the partial discharge magnitude.

There are multiple graphs that can be created from PRPS data as it was shown in Table 6.1. Figure 6.7 shows examples of Δu-patterns. As we can see there is clear difference between the Δu-patterns describing different discharge types. This pattern evaluates the frequency of the voltage differences of a sequence of partial discharge pulses showing the voltage range necessary to evoke consecutive partial discharge pulses. This is a powerful evaluation tool for a large number of defects. It is noticed that the partial discharge re-ignition activity depends strongly on the voltage gradient and not on the absolute voltage itself. The $\Delta u/\Delta\varphi$-pattern, where m_{i+1} is presented as the function of m_i, evaluates the voltage gradient of consecutive partial discharge pulses.



a. b. c.

Figure 6.7. *The Δu-patterns $(\Delta u_i - \Delta u_{i-1})$ of artificial partial discharge defects, a) corona discharge, b) surface discharge and c) internal discharge [81]*

6.2.3. Time-resolved analysis

The shape of the current pulse induced by a partial discharge can be used to identify the discharge type and stage of deterioration. However, this technique can't be used for long cables due to partial discharge pulse deformation during its propagation along the cable. If only cable terminations are being measured, this might be used. Pulse-shape based analysis is mostly used when partial discharges take place in gas. This type of partial discharge analysis is typically used in gas insulated systems (GIS). Figure 6.8 shows how the gas composition affects the partial discharge pulse waveform. Pulse-shape features can be created from the parameters which characterize the partial discharge pulse. These parameters are the rise time, decay time, pulse width, pulse maximum amplitude, area under the pulse and the applied voltage.

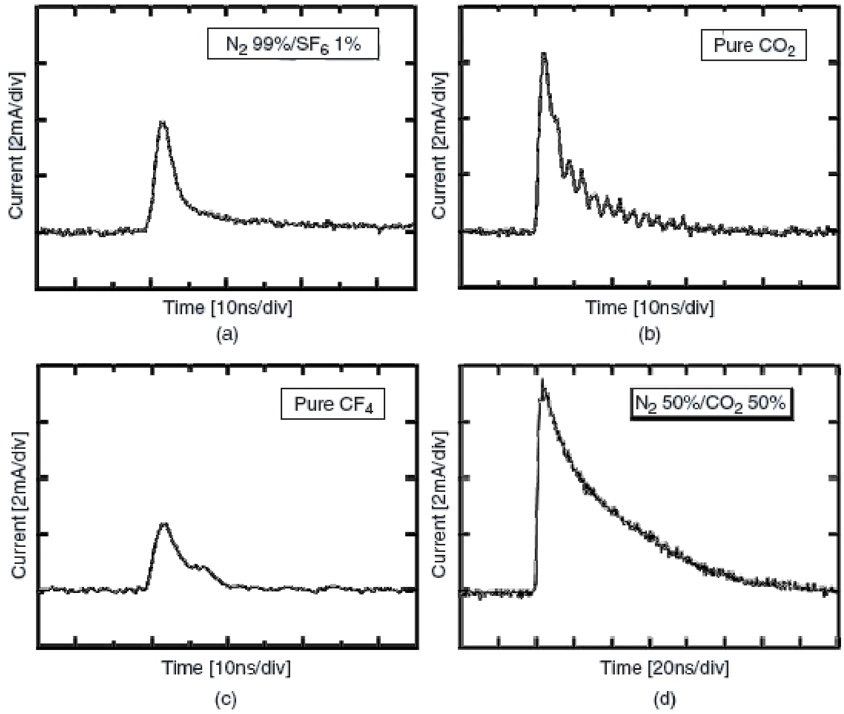


Figure 6.8. *Partial discharge current pulse waveforms in different gas compositions [82]*

6.3. Time trends in on-line partial discharge measurements

On-line partial discharge measurements offer the possibility to follow the development of partial discharges in a cable system during normal operation. It is known that cable operational conditions affect to the partial discharge activity and thus a more realistic picture of the cable condition can be created when the cable is continuously measured over a time period of weeks, months or even years. Polymeric cables and its accessories have found to be very sensitive towards partial discharges. The time to a breakdown depends on the defect type and the root cause which is creating the discharges. Measurement sensitivity has a major effect on how partial discharge development is seen. When measurement sensitivity is decreased only the very harmful defects producing partial discharge can be detected. An exception to this is defects related to electrical treeing which are known extremely harmful and produce only low levels of partial discharges. Electrical treeing taking place at normal operating voltage leads to a breakdown in matter of a few hours. This kind of defect is extremely hard to detect because of the small discharge magnitude [22; 30]. It should be possible to detect electrical treeing type defects before a breakdown with a continuous on-line partial discharge measurement system that has very high sensitivity. With very high measurement sensitivity it might be possible to detect partial discharges that are not harmful at all during the expected lifetime of the cable.

Partial discharge time trends can be found by following the evolution of different parameters from partial discharge inception to a breakdown. Some of the parameters used are discharge magnitude, repetition rate and PRPD patterns. The behavior of these parameters depends on the defect type and root cause which is producing the partial discharges. Usually partial discharge magnitude and repetition rate increases before a breakdown. This can also be seen from the PRPD patterns. Most significant changes in time trends take place very close, a few days or weeks depending on the defect type, before the breakdown. Thus time trend analysis is most effective when partial discharges in a cable are continuously monitored. The measurement time in periodic measurements is a lot shorter in comparison with continuous measurements. Thus the changes noticed in partial discharge activity during periodic measurements are more likely caused by changes in local conditions than because of imminent breakdown. For instance local temperature which has an effect on partial discharge activity varies depending on the network loading. The nature of time trends caused by changes in local conditions is a bit different in comparison with the time trends caused by imminent breakdown. Time trends caused by changes in local conditions can have both upward and downward trend and basically these trends only make partial discharge analysis more difficult. In practice this means that to be able to compare consecutive periodic measurements the environmental conditions should be about the same at the time of measurements and the measurement time should be long enough so that the effect of network loading could be noticed.

Partial discharge time trends in a real medium voltage cable network is a relatively new research area. The measurement system already mentioned in Chapter 5.6 called SCG and developed by KEMA is able to perform semi-continuous on-line measurements with maximum sensitivity around 30 pC. Here semi-continuous measurement means that partial discharges are measured during one cycle time in each minute. Real time measurements would decrease the measurement sensitivity because matched filtering could not be used for noise removal anymore. From the measurements done with SCG it is learned already that usually a breakdown will take place in a time period from a few days to a few months after the partial discharges have been detected. One should remember that the partial discharge detection sensitivity of this system is limited. The network where these measurements where done consist from both paper insulated lead covered (PILC) cable and XLPE cable. So far in 16 % of the fault cases no partial discharges have been detected before the fault. However, it is not said what is the number for XLPE cables only. In all the cases where partial discharge activity was detected, there was enough time to take repair actions. It has been concluded that partial discharges taking place due to a bad conductor connector usually lead into a breakdown in a few days. The root cause here is the thermal degradation caused by an unsuitable conductor connector. It is also concluded that surface discharges along the XLPE cable give partial discharges several weeks before a breakdown. So far, only a small amount of continuous on-line partial discharge measurement data is available and thus more data is needed to confirm the findings. The results gained so far look promising and the reliability and accuracy of the life time estimations made with continuous on-line measurements are far better than with any other methods used in cable networks before. [42; 45; 49; 83]

Another on-line partial discharge measurement system, mentioned already in Chapter 5.6, called CableWISE® is capable of achieving measurement sensitivities around 1 pC. This system is not developed for continuous measurements so it can’t be used to measure continuous time trends. However, from the measurements made with this system we are able to see that small levels of partial discharges can be active in XLPE cables for many years without leading into a breakdown. It is also shown that the number of partial discharge sites detected in cables increases as a function of cable age. This result is not a surprise because it is well known that partial discharge activity is closely related to cable aging. [84] Partial discharges with high magnitude and which are active during normal operating voltage lead into a breakdown quite fast. This means that the detection of harmful defects producing partial discharges with a single shot periodic on-line measurement is highly unlikely without sufficient measurement sensitivity. Even when the periodic measurements are done with sufficient sensitivity it is very difficult to predict which discharges will lead to a failure and how fast.

6.4. Knowledge rules

After measuring and analyzing the partial discharge activity decisions about the insulation condition needs to be made. All the knowledge from the different analyzing methods is put together and so called knowledge rules are created. The end result of the partial discharge measurement should be a proposal about what should be done. This could mean a proposal for repair or replacement actions. If no partial discharges where found the network is in good condition as long as defects which produce partial discharges are considered and no further actions are needed. In case some small but not yet harmful partial discharge activities have been measured the measurement should be repeated after some time. When harmful partial discharges are spotted repair or replacement actions should be taken depending on the situation.

The exact aging processes related to partial discharge activity are still not accurately known. However, it is possible to find statistical similarities from the measurements which make it possible to evaluate the condition of the measured network. The knowledge rules are created to help this evaluation process. Knowledge rules are based on past experience and theoretical understanding. The biggest problem on creating these rules is that the amount of faults in XLPE insulated cable network is quite low. Thus it is hard to collect relevant measurement data which would reveal how the measurable quantities develop before the actual fault. The situation becomes even trickier due to the fact that electrical breakdown phenomenon is random in nature. Thus statistical evaluation is needed to extract certain limiting values. However, this requires a reasonable amount of accurate measurement data which as mentioned before is hard to collect. In knowledge rules statistical values for allowed discharge levels for cables, joints and terminations are created. In case of on-line partial discharge measurements, the usable discharge properties are discharge magnitude, frequency and change in those during time. The structure and materials used in a cable, joint or termination affects to the critical discharge properties. In on-line measurements which are done at the normal operating voltage the XLPE insulated cable should be discharge free. Cable joints and terminations can withstand small levels of partial discharges for some time. Thus it is very important to be able to locate the discharge source in the cable network.

Knowledge rules are an important part in asset condition diagnostics. Figure 6.9 shows where knowledge rules are placed in asset condition diagnostics and how the rules are generated. This example is for off-line partial discharge measurements, but the same goes also in case of on-line measurements. As we can see, the results achieved are evaluated and used as an input to further improvement.

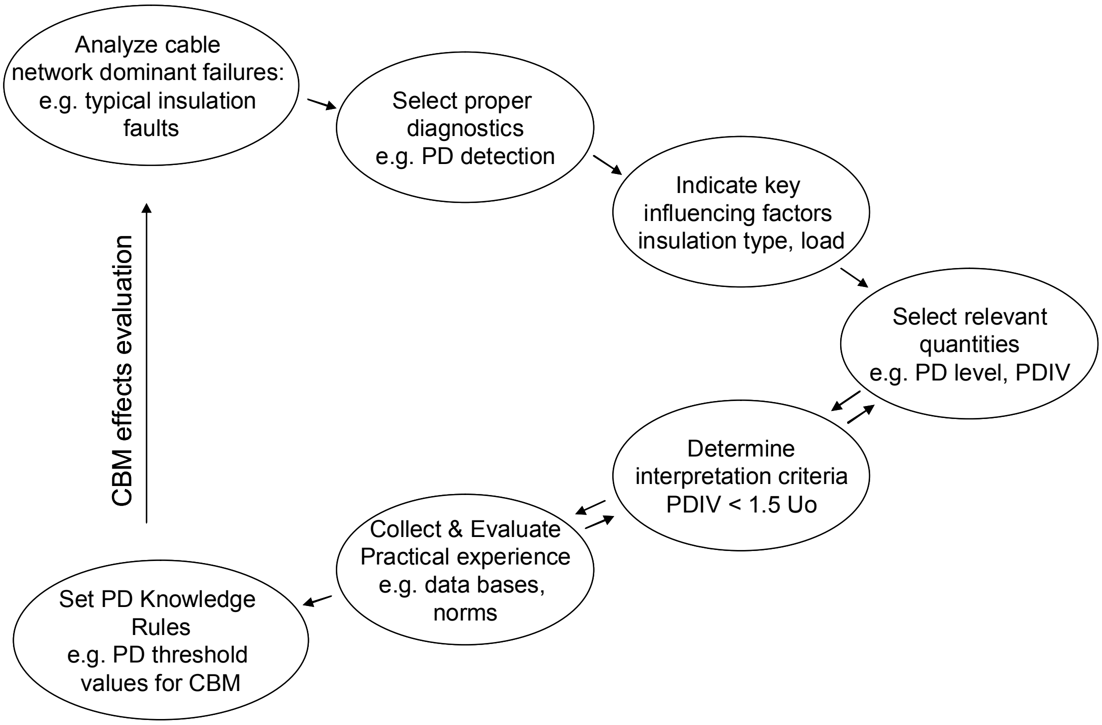


Figure 6.9. *Generation process for partial discharge knowledge rules to support condition based maintenance (CBM) [37]*

The following decision diagram in Figure 6.10 presents one possible way to categorize the insulation condition by using the knowledge rules. The knowledge that is known about partial discharge activity and its harmfulness is built in the diagram. If there is no discharge activity, the cable section is ok. If there are discharges, the next important thing is to find out whether they come from accessories or the cable itself. This is important because the critical partial discharge levels are different for discharges in the accessories than in the cable. If the discharges are not from accessories, it is important to know if they are concentrated on certain spot in the cable. This is important because if there is no concentration it is possible that the measured discharges are false readings or the measurement sensitivity is not high enough. The final decision about the condition of the measured cable section is made based on partial discharge levels and the phase resolved patterns.

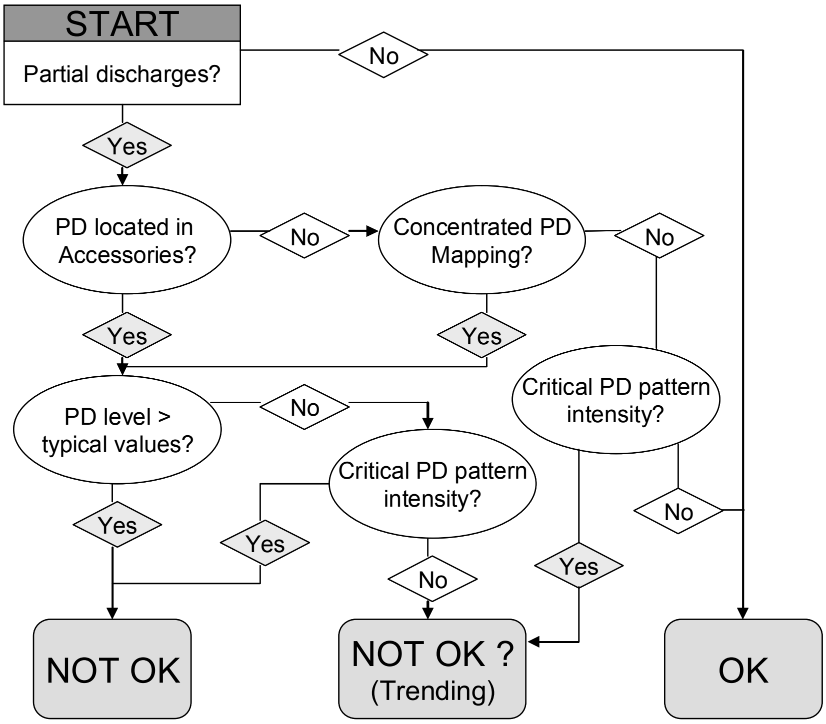


Figure 6.10. *Decision diagram for insulation condition categorization (this diagram is based on a diagram presented by Gulski in [48])*

7. IMPLEMENTATION OF ON-LINE PARTIAL DISCHARGE MEASUREMENTS

From the previous chapters it has become clear that on-line partial discharge measurements can be used to assess the current condition of a cable system. On the other hand, it is quite challenging to predict the future performance of the cable system based on these measurements. On-line partial discharge measurements can be used to detect defects caused during installation due to rough handling or bad workmanship, to make preventive maintenance possible and through that increase the general network reliability or to help allocating reconstruction investments. However, it is worth to mention that special knowledge is required to be able to analyze the measurement results.

The biggest advantage of an on-line partial discharge measurement compared with other measurements is its ability to locate highly deteriorated spots from the cable system. It is known that cables don’t age uniformly. It is possible that only a small section of a cable is highly deteriorated and the other parts of the cable are in good condition. Obviously, this small deteriorated section has a major influence on the reliability of the whole cable. It is easy to understand that replacement of the deteriorated section would have a major effect on the reliability of the whole cable. Obviously, the replacement of the whole cable would have at least the same effect on the reliability but that would be a lot more expensive. Partial discharge measurement can detect localized defects in a cable system. When, partial discharge measurements are used it is possible to replace only the highly deteriorated part of the cable. In this way it is possible to get the most out of the replacement budget when reliability is considered. This is one of the reasons why there is such an interest towards partial discharge measurements. The best results at the moment are achieved with continuous on-line measurements.

One of the main benefits of on-line measurements is that they can be done without an interruption to the electric supply. In theory on-line partial discharge measurement systems can be installed without an interruption to electric supply. In reality often a short interruption is required due to the safety regulations and system structure. In cases where cable ends can be reached while the voltage is on sensors could be installed without an interruption. Currently there are no Finnish instructions how to make this safely. This is an area where further investigation is needed to find out possible methods and suitable sensors to be used in on-line partial discharge measurements.

Measurements can be done in continuous or periodic way. In continuous on-line measurement, the cable under test is monitored continuously for a certain time of months to years or even as long as the cable stays in service. However, with current technology it is not possible to monitor the real time situation of the cable under test because it is not possible to process the measured signal in real time. The measured signal needs to be digitized and then modern signal processing algorithms are used to extract the hidden partial discharges. With current commercially available technology partial discharge activity can be checked every once in a minute. Basically, it would make more sense to talk about semi-continuous measurements. However, in this work the term continuous measurement is used. Periodic measurements are repeated after a certain time which depends on the earlier measurement results. In periodic measurements the future condition of the cable under test needs to be predicted. To be able to detect harmful future defects the measurement sensitivity needs to be higher than in continuous measurements.

The defects that can be detected with an on-line partial discharge test are limited to those defects that produce partial discharges at normal operating voltage. When continuous measurements are done it would be possible to make measurements during fault situations taking place somewhere in the network. In some cases, this would offer the possibility to do on-line partial discharge measurements at elevated voltages. This requires that the on-line partial discharge measurement unit is somehow triggered to measure when a network fault has occurred and before the power is shut down. This is one possible development idea for on-line partial discharge measurements.

In London EDF Energy have been using on-line partial discharge measurements to target the replacement of their cables to the ones which are actual in bad condition. Their network mainly consists of 33kV and 6,6/11 kV PILC cables. Thus the used measurement program can’t be directly applied to a cable network consisting of XLPE cables. In PILC cables harmful partial discharge magnitude is usually higher than in XLPE cables. Thus the sensitivity requirements for partial discharge measurements in PILC cables are not as high as they are for XLPE cables. The failure mechanisms are also different since oil paper insulation can heal itself because the insulation is partly liquid. The measurement devices are bought from HVPD Ltd. A British company specialized in partial discharge measurements. The system uses three types of test equipment: on-line partial discharge cable tester, on-line partial discharge mapping system and on-line partial discharge monitor. The portable cable tester is used to detect those parts of the network that are producing partial discharges. Partial discharge monitors are placed in critical substations where partial discharge activity has been detected with a cable tester. The feeders which are showing critical partial discharge activity are further investigated with an on-line partial discharge mapping system. The data analysis at the partial discharge monitor is fully automated and the results can be viewed through and web-based application. In 2009 EDF Energy already had over 1000 MV feeders monitored with web-enabled remote-access on-line partial discharge monitors. The data provided by these systems are used to support the condition based asset management decision by EDF Energy. [85; 86]

7.1. On-line partial discharge diagnostic system

In this chapter, a model structure for an on-line partial discharge measurement system is proposed. The model is based on a system developed in Netherlands called SCG [84]. The model is introduced in Figure 7.1. The model consists of a database, measurement units and a discharge analysis unit. The synchronization of the measurement units is needed for accurate partial discharge source location. With this type of structure the analysis can be separated from the actual measurements and it can be done in a single place. One reason why the measurements and data collection are made separately is that in this way the measurements can be done by a trained electrician rather than a qualified expert. Another reason is that in this way it is easier to develop and improve the analysis. Analysis should be as much automated as possible so that human expert would be needed only in rare cases. Once the analysis is completed the results are sent to customers. The same structure works for both continuous and periodic measurements. However, the collected and transferred partial discharge data might be different depending on the measurement situation. If the automated expert systems develop enough to give reliable and clear results about the condition of the cable under test, partial discharge analysis could be integrated into the measurement units.

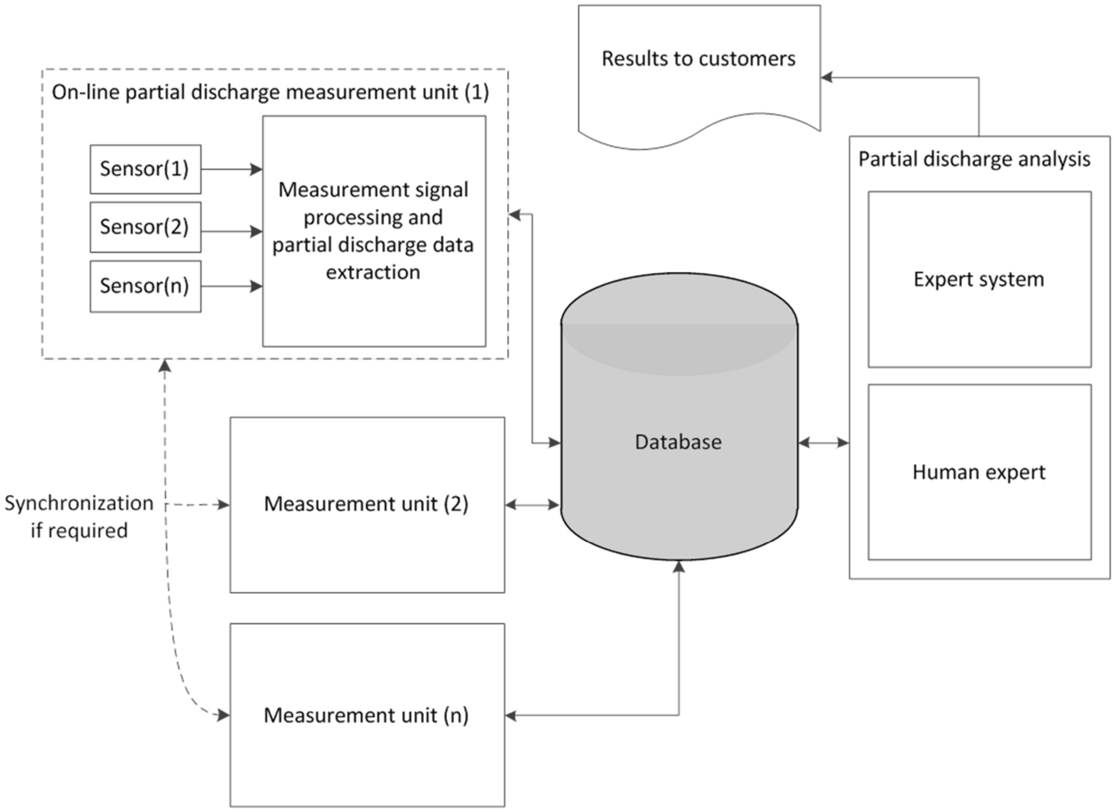


__Figure 7.1.__ Structure of an on-line partial discharge diagnostic system

Signal processing is a vital part of the measurement unit. Without proper signal processing it is not possible to achieve sufficient measurement sensitivity. Once the partial discharge signals have been extracted, we can collect the relevant data. This has to be done at the measurement unit to keep the amount of transferred data between the measurement unit and database at reasonable level. The methods that can be used at partial discharge analysis depend on how the measured data is collected. The amount of raw data that the measurements create is huge. Thus only relevant data should be collected. This is even more important when the measurements are continuous in nature and the cable is monitored for years. Partial discharge signals contain high frequencies and thus very high sampling rate is needed when the measured signals are digitized. As an example 75 MB is needed to save the measured signal over just one voltage cycle (20ms) with a 12 bit A/D converter which has a sampling rate of 50 Ms/s. Partial discharge activity needs to be recorded over hundreds or even thousands voltage cycles depending on the method used for analysis. During one voltage cycle usually only a few partial discharges take place. The information from these discharges can be stored with only a few values. This means that once the relevant partial discharge information is extracted it needs only a fraction of the memory that is needed when the measurement signal is digitized. If more detailed information is needed, it is possible to save just the parts of the digitized signal where interesting partial discharge activities take place. However, the wave shape of these signals is heavily distorted because of propagation in the cable, sensor properties and signal processing and thus it might not provide that much more relevant information.

In continuous measurements, the most promising analysis is time trend analysis combined with partial discharge source location. The time trends which can be seen short before the breakdown usually have a clear upward trend at least at some point and the change is significant. These time trends offer much to the analysis. In addition PRPDA can be used to identify the discharge type. To be able to make these analyses the TOA, magnitude and phase of occurrence of the partial discharges needs to be collected. In periodic measurements, PRPDA combined with partial discharge source location and the development of discharge activity over consecutive regular measurements can be used. It is important that the possible effects of environmental and operational conditions on partial discharge activity during periodic measurements are taken into account. To be able to do these analyses the same information that in case of continuous measurements must be recorded. When, only single components like cable terminations are measured PRPSA could be used. The advantage of pulse sequence analysis is that it doesn’t require calibration and the results are easier to analyze. The reason why PRPSA is not suitable for long cables is explained below. PRPSA requires that every consecutive partial discharge pulse from certain specific spot is recorded as $q_s\left(t_s,u\left(t_s\right)\right)$, where q_s is the discharge magnitude, t_s time of occurrence and $u\left(t_s\right)$ phase voltage at time of occurrence of s:th discharge. This is very difficult if not even impossible to do when long cables are measured. The reason for this is the time taking modern signal processing that is required to achieve sufficient measurement sensitivity and the fact that partial discharges can take place at several sites along the cable at the same time and the source location might not be accurate enough.

7.1.1. System properties

The properties which are needed from a partial discharge measurement system depend on many different factors. The three main topics we need to consider are partial discharge behavior, measurement environment and the measurement process. Partial discharge behavior depends on components' structure and on the used materials. The structure and materials also have an impact on the typical discharge types. The considerations about the measurement environment are mainly focused on cable accessibility and prevailing disturbances. The measurement process itself sets demands on the system properties depending on which types of analysis are used and whether continuous or periodic measurements are done.

The harmfulness of partial discharges can't be analyzed directly from measurable quantities. It is also very important to be able to locate the discharge source because polymeric cable insulation tolerates much less discharges than polymeric cable joints or terminations. When the discharge source is known, it is also easier to identify the discharge type. Discharge type identification is important because the harmful discharge magnitude level depends on the discharge type. Table 7.1 describes the typical discharge levels in different polymeric components and with different discharge types. There are no exact numbers presented, just a scale. It is important to remember that with on-line partial discharge measurements it is not possible to measure the exact discharge magnitude values.

Cable	
Spark discharges	10^{2} pC
Cavity discharges	10^{0} pC
Electrical treeing	10^{0} pC
Joints and terminations	
Spark discharges	10^{2} pC
Cavity discharges	10^{1} pC
Electrical treeing	10^{0} pC
Surface tracking	10^{2} pC
External discharges	10^{2} pC
Corona (terminations)	10^{3} pC

Table 7.1. *Typical discharge levels in different components and with different discharge types*

Measurement environment plays a decisive role when maximum measurement sensitivity is concerned. The length between the access points to the cable under test determines the minimum distance between the measurement points. The longer this minimum distance is the lower the maximum measurement sensitivity is. The measurement environment also determines which types of sensors can be used. The sensor type also has an effect on the achievable sensitivity. However, the most dominant factor affecting the maximum measurement sensitivity is the amount of disturbances around and inside the cable under test. Thus modern signal analyzing tools are needed in every measurement unit to achieve required measurement sensitivity.

The required measurement sensitivity depends on the measurement process which defines whether the measurements are done continuously or periodically and whether the cables with joints and terminations or only for instance cable terminations are measured. Periodic measurements should be able to predict the condition of the cable system as far in the future as possible. Thus higher measurement sensitivity than in continuous measurements is needed because in many defect cases higher levels of partial discharges are present only a short time before the breakdown. Table 7.2 presents the required measurement sensitivity in case of continuous or periodic on-line partial discharge measurements. These figures are based on typical discharge levels found in the literature [31; 40; 42; 46; 47; 48; 49]. When looking the figures in Table 7.2, it is important to remember all the factors affecting the measurement sensitivity. As an example, the required measurement sensitivity of 200 pC for continuous on-line partial discharge measurements means that the maximum measurement length is from 2 to 4 km depending on the amount of disturbances encountered.

Cable insulation	
Measurement type	Required measurement sensitivity
Continuous on-line	<5 pC
Periodic on-line	<1 pC
Cable terminations, joints and metallic shield	
Measurement type	Required measurement sensitivity
Continuous on-line	<200 pC
Periodic on-line	<20 pC

Table 7.2. *Required measurement system properties for different measurement scenarios*

The currently available commercial on-line partial discharge measurement systems can easily achieve the required measurement sensitivities to cable terminations, joints and metallic shield. However, the required measurement sensitivities to cable insulation are at the level of maximum measurement sensitivities achieved so far. These sensitivities can be achieved only when the disturbance levels are low and the cable sections under test are short. Currently, no commercial on-line partial discharge measurement system exists that performs continuous measurements and is capable of achieving the high measurement sensitivity required for cable insulation.

7.1.2. Possible use of on-line partial discharge measurements

The theory related to partial discharges, measurement sensitivity and time to fault estimation accuracy all set limitations to the use of on-line partial discharge measurements. Most defects produce partial discharges before the actual breakdown. However, the measurement sensitivity determines which types of defects can be detected and how long before the breakdown this is possible. The time to fault estimation accuracy depends on how close the actual breakdown is. The closer the breakdown is the better the estimation accuracy. Water treeing is one major cable aging related phenomena. An on-line partial discharge test can only detect a water tree which has ignited an electrical tree that produces partial discharges at normal operating voltage. When this kind of situation exists the breakdown usually happens after only a few hours. To be able to analyze the cable condition it is important to know if the cable is aged by severe water treeing this can’t be evaluated with the help of on-line partial discharge measurements. Thus an on-line partial discharge test alone can only tell for sure how many highly deteriorated spots can be found along the cable. The tested cable can be in bad condition even when no defects are found during the on-line partial discharge measurement. Such a case could be a cable which is highly deteriorated by water treeing. In case only cable terminations are measured it is highly likely that the termination is in good condition if no partial discharges are spotted during the on-line partial discharge test. The reason for this is that the most common degradation mechanisms in cable terminations produce partial discharges already at the early stages of deterioration.

An on-line partial discharge test can locate deteriorated joints, terminations and cable shield sections, detect a cable insulation section near failure or work as a quality assurance test for the installed cable. However, an off-line test is a better alternative during commissioning because in laboratory tests it has been noticed that some of the workmanship errors require a voltage two times higher than the operation voltage to show up during commissioning [87]. Off-line test basically repeats the factory test so it is easy to compare the results of these two tests. Continuous cable monitoring can be used to decrease the amount of unplanned outages caused by cable failures in important cable sections or in old cable sections waiting for replacement. The importance of a cable section is based on how much the interruption costs and how many customers are affected. The replacement of certain joint or termination types noticed to suffer from premature failures can be prioritized with on-line partial discharge measurements. The problematic component types should be spotted from fault statistics. An unacceptable high failure rate of certain component type doesn’t necessary mean that all these components need to be replaced. However, if it is not possible to check the condition of each of these components the only way to remove the problem is to replace them all. With on-line partial discharge measurements, it is possible to find the components that really need to be replaced. Now money is saved when only the components that are really in bad condition are changed. Some sort of cable replacement prioritizing might be possible based on the amount of deteriorated spots found during periodic on-line measurements. However, more research needs to be done before the benefits of periodic on-line measurements are truly revealed.

Figure 7.2 shows which types of partial discharge measurements should be used in each stage of cable system life cycle. Continuous on-line partial discharge measurements could be used at every stage of cable life if it is economical. This means that the profit obtained outsources the price paid or in some cases the reduction of risk is worth the price. Models to estimate the profitability of on-line partial discharge measurements have been created in some recent works [88; 89]. As mentioned earlier more research is needed in case of periodic on-line partial discharge measurements and thus there is a question mark. Periodic on-line measurements are cheaper in comparison with long term continuous measurements. Thus periodic measurements can be used to diagnose large networks and to pin point the most problematic areas where continuous measurements for instance could be used.

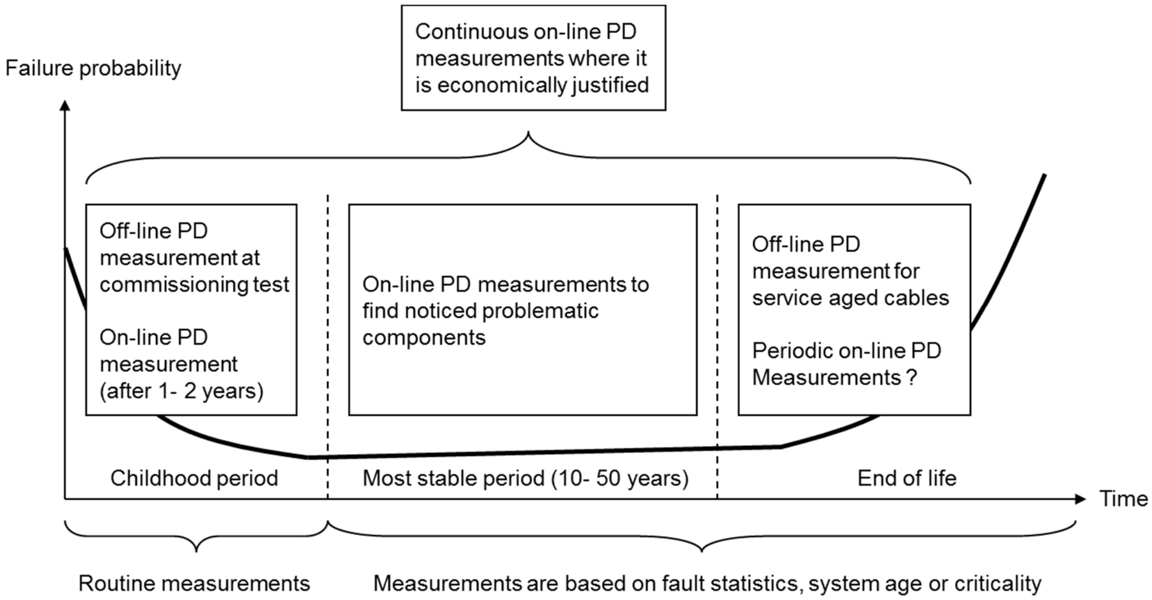


Figure 7.2. *The use of partial discharge measurements during the life cycle of a cable system*

Continuous on-line partial discharge measurements should be made with the highest achievable measurement sensitivity to learn more about the degradation caused by partial discharges. More information is needed about the average time to failure after partial discharges have been noticed by on-line measurements. Without this information it is impossible to say how often periodic on-line measurements should be conducted and it is also hard to estimate how many percent of the sites near failure could be detected.

There is some variation in literature between results achieved with on-line partial discharge measurements. In a research made by DTE Energy Technologies Inc. [90] it seems like they have been able to detect every highly deteriorated spot from the network. The measurements are done in a periodic way with ultra-high-frequency sensors and with very high accuracy (at its best around 1 pC). The number of highly deteriorated sites (remaining life under 2 years) found in XLPE cables under 20 years of age is reported being in average 0,0059 sites/km. Because all of these sites are assumed to fail during the next two years this assumes an interruption frequency of 0,30 faults a year/100 km as these types of faults cause about 30 % of all faults this means that the total interruption frequency would be 0,90 faults a year/100 km. The calculated interruption frequency is about the same as the normal interruption frequency for such network. In this research 7500 km of PILC, EPR and XLPE cable have been measured. The measured cables are classified into five levels depending on their condition. Table 7.3 introduces the failure probability in each level one and two years after measurements. The failure probabilities shown are based on failures encountered in PILC, EPR and XLPE cables that had been left in service after measurements. The results show that the classification works well. However, the results don't distinguish the situation between different cable types. It would be interesting to see how Table 7.3 would look like, if only XLPE cables where included.

Classification level	Number of PD sites found	Failure probability after:	
		1 year	2 years
1	*This level means that PDs have not been detected during the measurement*	0 %	0 %
2	400 000	0 %	0 %
3	250 000	0,0028 %	0,0068 %
4	4 000[1]	0,7 %	2,7 %
5	500[2]	14 %	37 %

[1] The calculated failure probability is based on the amount of faults encountered in 1000 sites that had been left in service after measurements

[2] The calculated failure probability is based on the amount of faults encountered in 100 sites that had been left in service after measurements

Table 7.3.*Failure probabilities of different classification levels in a research made by DTE Energy Technologies Inc. [90]*

In another research made in Netherlands the results are somewhat different. The measurements are continuous and they are done in high frequency range with rather high accuracy (at its best around 30 pC). The continuous on-line partial discharge measurements indicate that partial discharge appearance varies in time and higher levels (hundreds of pCs) can be recognized only a few days to a few weeks before failure. Time trends enable very accurate time to breakdown estimation in a short time frame and defects are noticed early enough to enable repair before the breakdown. [49]

In a research made in Taiwan the application of on-line partial discharge measurements on in-service medium voltage cable terminations was investigated. The measurements were made in the frequency range above the background noise to be able to eliminate this noise. The results show that from the 5,000 cable terminations measured 140 showed partial discharge activity. It was also noted that 20 of these terminations had clear marks from external discharges. So all in all partial discharges were wound at 3,2 % of the measured terminations. The disqualified terminations were dissected and the reason behind the partial discharges where examined. It was concluded that the major reason for partial discharges was bad workmanship. [25]

7.2. Cable system life cycle management

Extensive cabling increases the need for effective preventive maintenance. This can only be realized when reliable information about the current condition of the cable system is available. The key factors on producing this kind of information are the measurements conducted in the cable system. With preventive maintenance unplanned outages can be reduced and on the other hand condition information can be used to optimize the life time of a cable system, thus minimizing the total life time costs. Five different stages can be separated from the life cycle of a cable system: construction, commissioning test, operation, faults and end of life. Figure 7.3 shows a cable system life cycle management process and its main tasks on each stage. This should be a constantly progressive process and feedback from other stages should be used in the first stage to construct even more reliable and cost effective systems.

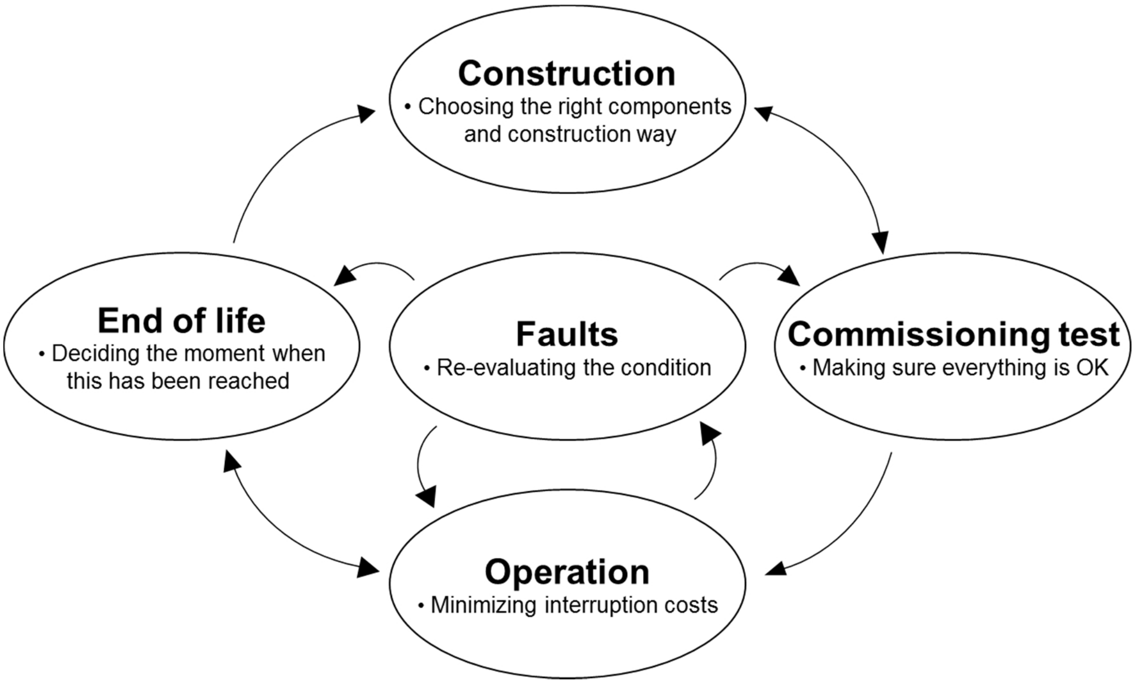


Figure 7.3. *Cable system life cycle management process*

Partial discharge measurements can be used in every stage of cable system life cycle. At construction stage it is important to use only cables that have passed partial discharge tests after manufacturing. In the commissioning test, an off-line partial discharge measurement is recommended. During cable operation interruption costs can be minimized and cable replacement can be optimized with the help of continuous and periodic on-line partial discharge measurements. When, a fault occurs this opens the possibility for off-line partial discharge measurements which are also beneficial in deciding when a cable system has reached its end of life stage. The commissioning test is an important part of cable life cycle. The idea of commissioning testing is to minimize the faults taking place during the childhood period of the cable due to bad workmanship or installation errors. The measurement results from the commissioning test can be used as reference in later measurements. For partial discharge measurements, these references are not needed since the cables should be partial discharge free during the commissioning test. The failure rate is generally very low during the stable period of cables' life cycle. This is also seen in Figure 7.2. Thus diagnostic measurements aren't economical for most of the network during this period. Once a cable has faulted Figure 7.3 shows three different options. It depends from the cable age and installation way which option is used. If the fault was caused by a faulty operation of protection equipment and there is no actual fault in the cable, the cable can be returned to service immediately. If the cable is old, in bad condition and easily replaceable it is replaced after a fault. In case the cable is critical and its replacement requires significant work, the cable is repaired and the commissioning test is repeated.

The starting point for condition based maintenance should be the history and the importance of the cable circuits. This means the failure statistics, operational and the laying conditions and technical information of the cable circuit in the network. With this information, the circuits for diagnosis can be determined. This step is very important when an on-line partial discharge test is used to diagnose the condition of a circuit. An on-line partial discharge test is best suited to detect highly deteriorated cable accessories or spots along the cable. Thus it is more likely that a defect is found when measurements are done in cable circuits with a high level of failures. On the other hand the importance of the system directs measurements to those circuits which have the highest interruption costs and biggest influence on customers.

To make most of the on-line partial discharge measurements there must be some kind of system to select the circuits which should be measured. The idea of this system is to determine when the circuits are moved into a condition based maintenance program which includes partial discharge measurements. One way to do this is to classify the cables based on their importance and failure risk. As defined earlier the importance of a cable section is based on how much the interruption costs and how many customers are affected. The importance is based mostly on the actual cost because the cost of cable diagnostics needs to be covered somehow. If the cost of diagnostics is not covered by interruption costs, it will show up in increased network tariffs. The failure risk is defined by cable sections age, component information, cable loading data and failure statistics. Failure statistics should be used to define how the mentioned variables affect on failure risk. Cable age is the most important variable. After the condition based maintenance program has started the measurement results take its own role when failure risk is defined.

The importance of a cable is calculated as:

$$S_1 = w_1 C_{\mathrm{avg}} + w_2 N_{\mathrm{C30}}$$

, where w_1 and w_2 are weighting coefficients, C_{avg} average cost of interruption and N_{C30} the number of customers that are left without power for longer than 30 minutes because of a cable fault. This second component of importance is here to add the aspect of customer satisfaction into the calculation. The average cost of interruption C_{avg} is calculated based on the disadvantage caused by outages (DCO) calculation. The DCO composes from a direct and a time dependent coefficient. Each customer groups (cg) have their own coefficients. The formula for the average cost of interruption is:

$$C_{\mathrm{avg}} = \sum_{\mathrm{cg}=1}^{\text{Number of cg:s}} \left[\frac{W_{\mathrm{mp}}(\mathrm{cg})}{8760} \times \left(k_{\mathrm{v}}(\mathrm{cg}) \times t_{\mathrm{i}} + k_{\mathrm{vm}}(\mathrm{cg})\right) \right] N_{\mathrm{C}}(\mathrm{cg})$$

, where $W_{\mathrm{mp}}(\mathrm{cg})$ is the amount of energy transferred to the user of certain customer group from the network in a year (kWh), $k_{\mathrm{v}}(\mathrm{cg})$ is the price of disadvantage caused by unexpected outages to a certain customer group (€/kWh), t_{i} is the outage time, $k_{\mathrm{vm}}(\mathrm{cg})$ is the price of disadvantage caused by unexpected outages to a certain customer group (€/kW) and $N_{\mathrm{C}}(\mathrm{cg})$ is the number of customers in a certain customer group. [91] The failure risk is calculated as:

$$S_2 = n_1 J + n_2 A + n_3 N_{\mathrm{F}} + n_4 L_{\mathrm{data}}$$

, where n_1, n_2, n_3 and n_4 are weighting coefficients, J number of joints over the allowed limit, A cable installation age, N_{F} number of faults experienced and L_{data} cable loading data. The failure risk is calculated at the same way as the selection criterion introduced by Simon Sing Ming Young and Lawrence Kin Keong Sun in [10]. Network company defines how big risk of failure is tolerable by defining the point when actions to lower the failure risk are started. After this defined point, the advantages that a cable diagnostics offer should be worth its price. The idea here is that the reliability requirements are higher for network sections with high importance. When cables are aging and their failure risk starts to increase on-line partial discharge measurements are used to maintain the failure risk at acceptable level. Figure 7.4 describes an action matrix for on-line partial discharge measurements, where the importance of a cable and the failure risk are each divided into four levels. There are totally 16 boxes which action is indicated by a color. If there are two colors in one box, it means that both of the actions are in use. Periodic and continuous on-line partial discharge measurements can be used to optimize the cable replacement and control the failure risk. The worst performing important cables are the ones that are replaced first.

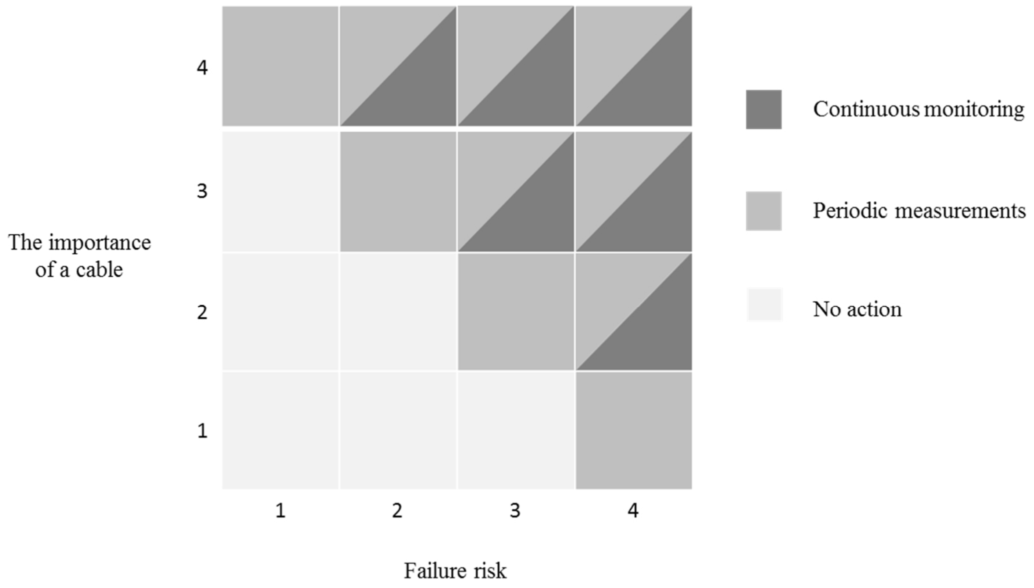


Figure 7.4. *Action matrix for on-line partial discharge measurements*

8. CONCLUSIONS AND RECOMMENDATIONS

In this work, a study has been made about the use of on-line partial discharge measurements as a part of a medium voltage cable life cycle management process. The theory behind partial discharges, their measurement in XLPE cable systems and experiences from laboratory and real life measurements have been studied. Based on these studies the following conclusions and recommendations are drawn.

Cable failure probability usually follows the so called bathtub curve where the failure probability is high at the beginning and at the end of cable life. The main reasons for failures on newly installed cables are damage during manufacture, transportation or installation and bad workmanship. The rise of failure probability at the end of cable life is mainly caused by cable aging. Cable aging depends on many internal and external factors and thus the aging is not universal even in a single cable. The temperature, voltage stress and moisture are shown to be the main factors affecting the speed of insulation degradation. Thus overloading should be avoided, overvoltage stresses should be minimized and water proof structures should be used. The quality of installation and installation conditions has a big influence on the lifetime of the cable and its joints and terminations. Partial discharges are a sign of insulation deterioration. The harmfulness of partial discharges depends on the discharge source location, defect type and discharge trend over time. Internal discharges are the most damaging types of discharges. Electrical trees are formed at the last stage before the breakdown.

Partial discharge pulses attenuate and disperse during their traveling through cables. The attenuation is frequency dependent and higher frequencies attenuate faster. Partial discharge pulse attenuation means that the pulse’s width broadens and the peak value decreases. This makes it more difficult to measure small magnitude partial discharges from long cables. On the other hand frequency dependent attenuation can be used for discharge source location for short measurement lengths. Measuring partial discharges from medium voltage cable ends of a long cable is difficult because the measurable frequency range of discharge pulses is at the same range as most of the background noise. For shorter cable lengths more sensitive measurements can be made when measurements can be done at higher frequencies where noise level is lower. With on-line partial discharge measurements damaged parts of the cable can be found but with current knowledge it is hard to make precise predictions about the general condition of the cable system based on those measurements. Discharge source location is one of the most useful information that an on-line partial discharge measurement provides. Discharge source location is important because e.g. joints and terminations tolerate higher partial discharge magnitudes than the cable insulation.

During the work, it came clear that it wouldn’t be possible to achieve all of the ambitious goals that were set for this work. On-line partial discharge measurements in a medium voltage cable network are not yet widely used. Thus there is not enough experience and reliable measurement result available to give definite numbers about the reliability of the measurement and its ability to estimate the remaining life time of a cable. At the moment, only the time to the next breakdown can be estimated quite reliably with continuous partial discharge measurement. More research needs to be done to be able to form reliable knowledge rules. Continuous on-line partial discharge measurements open new possibilities for measurement data analysis when discharge trends can be monitored along time. The research of these time trends is still in progress. Continuous on-line partial discharge measurements have proofed to be rather reliable, but the measurement systems available today are not yet fully developed. There is still a need for more effective measurement data analysis. On the other hand, there is not enough reliable and detailed failure statistics of XLPE cable systems through their entire life cycle. One reason for this is that the types of XLPE cables that are mostly installed today have been available only for 20 years. The structure and manufacturing techniques of XLPE cables have greatly improved from the first generation cables which had extensive problems with water treeing. Without a reliable knowledge about the most common failure causes in new XLPE cable systems it is hard to estimate the possible benefits that could be achieved with partial discharge measurements.

In the last Chapter, the use of on-line partial discharge measurements as a part of a medium voltage cable life cycle management process is discussed. Due to the nature of partial discharge measurements and its request for an expert analyst, the structure of a partial discharge diagnostic system should be such that analysis can be centralized. The requirement for measurement sensitivity depends on the defect type and whether continuous or periodic measurements are used. Each measurement has its limitations and these limitations have a significant effect on the way the measurement might be used. On-line partial discharge measurements are the most suitable for detecting problems in the cable terminations, joints or metallic shield. In these cases harmful levels of partial discharges can be detected well before a breakdown. With continuous measurements, reliable estimations about the time to the next breakdown can be made. In case of cable insulation, electrical treeing is usually the reason for partial discharges. When, measurements are done with operation voltage defects related to electrical treeing can be detected only a few hours before a breakdown with current measurement sensitivity. Water treeing, which is the main deterioration mechanism in aged cable insulations, doesn’t produce partial discharges and thus it can’t be detected with partial discharge measurements before it has ignited an electrical tree. Thus an on-line partial discharge test alone can’t be used to estimate the overall condition of the cable insulation. Partial discharge measurements can be used in every stage of cable system life cycle. At construction stage it is important to use only cables that have passed partial discharge tests after manufacturing. In the commissioning test, an off-line partial discharge measurement is recommended. During cable operation interruption costs can be minimized and cable replacement can be optimized with the help of continuous and periodic on-line partial discharge measurements. When, a fault occurs this opens the possibility for off-line partial discharge measurements which are also beneficial in deciding when a cable system has reached its end of life stage. One important question is how the cable sections for measurements should be selected. In this work, a selection criterion is proposed based on the importance of a cable and its failure risk. Partial discharges can be spotted in a cable during normal operation only if the cable has some clearly deteriorated spots. Thus discharges are more likely to be found in cables that have higher failure risk. Interruption costs play a significant role when cable importance is calculated. Thus there is more economical justification to do the measurements in cables with higher importance.

There are also many other open questions related to the overall medium voltage cable life cycle management where further research is needed. These questions are: What information should be documented when the cables are installed and how this information could be used in the cable asset management? What types of measurements should be made in cable commissioning tests and how to store the results and utilize later? Which diagnostic measurements should be used in each stage of the cable system’s life?

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