POWER CABLE DIAGNOSTIC REVIEW

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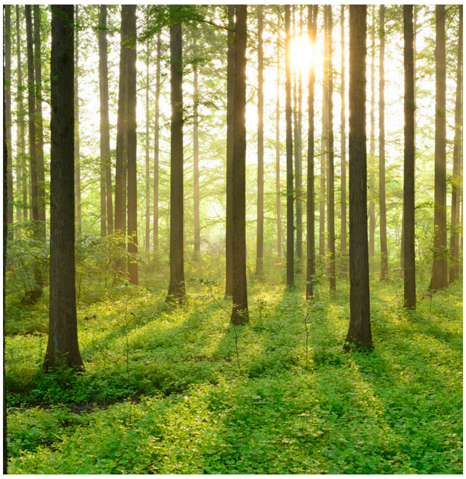

UNDERHÅLL AV ELNÄT

Energiforsk

Power Cable Diagnostic Review

XIANGDONG XU

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Foreword

There are several techniques for evaluating the status of power cables, and with a power system where the components are aging, the have become increasingly important. This project was initiated to give a comprehensible overview of the different techniques and to provide valuable insights to grid owners who wants to optimize the maintenance strategy for cables in their grid.

This project is part of the industrial research program Maintenace of power grids (Underhåll av elnät).

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Lennart Kjellman,
Program manager Underhåll av elnät
Stockholm, november 2022

Summary

The project reviewed the 9 different major power cable diagnostic technique categories that are available in the market for a comprehensive understanding of their pros and cons with consideration of practical aspect of power grid companies' maintenances activities.

The reviewed main techniques details were obtained from three major standards organizations: including 12 standards from IEC, 13 technical brochures from Cigre and 11 IEEE standards. In addition, numerous of literatures from both academic research and industrial reports were also studied to bridge between the technique principle and practical applications. To facilitate a deeper understanding of the reviewed diagnostic techniques, statistics of power cable failures and their fundamental causes are also elaborated in the report. Finally, the remaining power cable life-time evaluation and diagnostic technique procedures are also suggested with focus on practical and economic aspects of the maintenance strategies.

Keywords

Power cable, ageing, maintenance, diagnostic technique review.

Sammanfattning

Projektet har gått igenom de nio vanligaste teknikerna för att diagnostisera kraftkablar, och sammanfattat för- och nackdelar med dem. Målet är att ge praktiska riktlinjer till elnätsägare för att stötta deras underhållsarbete.

De tekniker som har analyserats kommer huvudsakligen från tre standardiseringsorganisationer: 12 standarder från IEC, 13 tekniska broschyrer från Cigre och 11 standarder från IEEE. Dessutom har både akademisk forskning och industriella rapporter använts som underlag för att överbrygga gapet mellan tekniska principer och praktisk användning. För att facilitera en djupare förståelse för de kartlagda teknikerna ingår även statistik för kabelfel och feltyper i rapporten. Slutligen beskrivs hur kvarvarande livslängd kan utvärderas, med fokus på praktiska och ekonomiska aspekter.

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1 Introduction

The Swedish medium voltage networks are made up of 103,000 km of underground cable and 90,000 km of overhead lines. Some 5.3 million electricity users are connected to the low voltage networks and 6,500 to the high voltage networks. The regional grids are mainly owned by DSOs and have a combined line length of around 30,000 km. The Swedish national grid with primarily of 400 kV and 220 kV lines with a total length of around 15,000 km is operated by Svenska Kraftnät. In total, the Swedish electricity grid contains over 543,000 km of power lines, including 339,000 km of underground cable. Adds up its total length over thirteen times around the earth. Delivery reliability on average 99.98 percent in the Swedish electricity networks.

The Swedish power grids are known for high reliability and constantly being improved through replacement of aged facilities and connection of new production. The increasing challenges for power grid companies in coming years are remains to determine the aging status and replacement of old, often oil-paper insulated, power cables to modern polymeric insulated cables. Meanwhile, to reduce the grid's weather dependence, with over 50,000 km of overhead lines need to be replaced by underground cables. Moreover, with increasingly demands on distributed renewable energy connection and repaid increase in electricity demands from transportation sectors, more distributed power cable networks need to be installed.

The goal of the work is to help power grid companies answering following critical questions in their decision makings:

- Determine the remaining lifetime of existing power cables.
- Dimensioning and selection of new cables to be installed.
- Criteria for installing, testing and documentation of newly installed cables for lifetime maintenances decisions.

In coming years, the needs for keeping reliable, and sufficient electric power for a sustainable economic recovery is essential. Diagnostics and testing with reliable technical methods play a critical role to ensure the reliability and forecasting the life of underground power cables. Thus, this study mainly reviews the available measurement techniques for distribution network medium voltage power cables maintenances. The focus is remaining on electrical measurement techniques but also with consideration of the other most practical methods.

The reviewed materials are selected from all available power cable related technical documents of three major intentional standard organizations, namely, IEC, Cigre and IEEE. The EPRI report "Diagnostic Techniques for Underground Cable Systems", service a guideline for sorting out existing and developmental diagnostic techniques for both oil-impregnated and polymeric cable systems.

In general, IEC standards more focus on specify requirements and testing methods for new cable, whereas Cigre and IEEE technical documents provide more practical guidance for field testing and diagnostics of power cables.

The earlier IEC standards 60055 and 60141 are dedicated for AC oil-paper insulation cable systems, thereafter, IEC 60183 provides a guidance of AC cable system selection, and its testing are specified in IEC 60502 and 61442 for 6kV–30kV, IEC 60840 for 30kV–150kV and IEC 62067 for 150kV–500kV systems. Later, IEC 61901, 62895 and 63026 gives recommendation for more special applications such as HVDC and submarine cables.

Major Cigre technical brochures are coming from study committee B1, insulated cable systems, which provides guidelines of more specific tasks, such as TB 182, 728 for partial discharge detections, TB 493 for water-tree detection and TB 773 for fault localization. Moreover, maintenance strategies and qualification procedures based on practical tests are suggested in TB 279, 379, 560 652 for cable system maintenance and operation. TB 303, 415, 722, 758 specified requirements for HV cable system and submarine cables qualifications.

Though large number of power cable related scientific research papers were published in IEEE, the practical use of these technical are largely limited within standards summarized by IEEE ICC published in IEEE Std 400 series Guide for Field Testing and Evaluation Power Cable Systems. In addition, more special guidelines such as IEEE Std 1406 for Gas-In-Fluid Analysis,

Std 1425 for remaining life evaluation of the of paper-insulated cable systems and IEEE Std C57 for general dielectric frequency response test were also reviewed in this study.

Fundamental cause of power cable aging is essential for understanding the maintenance measurement techniques principles and to interpret the obtained results, therefore, the report starts with a general introduction of fundamental causes of power cable aging.

Common practice of power cable diagnostics,

1. Overall insulation evaluations: VLF tan Delta and PDC measurements. If overall insulation evaluation excesses the thresholds level, step 2: defect localization is needed.
2. Localization of the defects: (in practices over 80% defects are at cable joints and terminations) PD and Broadband Impedance Spectroscopy (LIRA)
3. New installation with RFID localization signature at cable joints.

2 Power cables

Most of the medium and high voltage power cables can be classified into two major categories based on its insulation systems: oil-paper insulated and polymeric insulated. It can be considered as two generation of power cable systems, where oil-paper insulated cables were mainly installed before 1980s, whereas polymeric insulated cables were installed after introducing in 1970s and nearly exponentially increase in its length till now.

2.1 OIL-PAPER INSULATED CABLE SYSTEMS

Three common types of oil-paper insulated cable systems are often found in underground cable constructions, including: PILC, HPFF and SCFF cables. These cables share about 40 % total installation of the medium voltage power cables, and often installed before 1980s, and likely to be replaced by polymeric insulated cables in the coming years.

2.1.1 PILC cable

Paper-insulated lead covered (PILC) cables are manufactured by using layers of paper impregnated by a compound mineral oil as insulating system, both used in single core and overall insulation. A lead sheath is made as an outer core layer to provide a seal for the oil paper layers, for excellent corrosion protective properties, and to provide additional mechanical protection. PILC cables are generally used in medium voltage applications and shares about 20% market.

2.1.2 High-pressure fluid filled (HPFF)

High-pressure fluid-filled (HPFF) cable is made of a steel pipe that often contains 3-phase conductors and insulated by oil-impregnated kraft paper system; and covered with metal shielding (usually lead) and skid wires (for protection during construction). Inside steel pipes, conductors are surrounded by a dielectric oil which is maintained at high pressure (13-15 bar). This fluid acts as an insulator and heat exchanger.

2.1.3 Self-contained fluid filled (SCFF) cables

The self-contained, fluid-filled (SCFF) pipe-type cable is often used for underwater transmission construction. The conductors are hollow and filled with an insulating fluid that is pressurized to 1-1.5 bar. In addition, each phase cables are independent of each other constructed in separate pipes. Each cable consists of a fluid-filled conductor insulated by kraft paper and protected by a lead or aluminum sheath and a plastic jacket.

This type of construction reduces the risk of a total failure, but the construction costs are much higher than the single pipe used to construct the HPFF systems.

2.2 EXTRUDED POLYMERIC DIELECTRIC CABLES

Two types of solid dielectric cables are often used in power grids applications: EPR and XLPE. As XLPE cables becomes the dominate share of the power cable, this review will be mainly focus on the XLPE cables.

2.2.1 EPR cables

Ethylene Propylene Rubber (EPR) cables use a rubber-type elastomeric material for insulation to provide mainly greater flexibility as well as high corrosion resistance against harsh environmental conditions and ultraviolet radiation. In addition, EPR has a wide operational thermal range, typically in between -55°C to 150°C. Although, EPR does not offer a good resistance to oils, but it is resistant to a wide range of other chemicals including acids, alkalis, and organic solvents. Statistically, application of EPR cable only shares about 5% of the total medium voltage cables market.

Like XLPE cables, EPR insulation is suitable for many medium voltage applications though its dielectric properties are not as good as those of XLPE, however, it does offer some important advantages over XLPE including extra flexibility, reduced thermal expansion, and low sensitivity to water treeing. Which gives EPR cables in some special and lower voltage applications.

2.2.2 XLPE

XLPE cables uses cross-linked polyethylene as the main insulating materials. It is a thermosetting polymer meaning that polyethylene is cured under heating and degassing process to form bonds in a three-dimensional matrix. Due to its structure, XLPE is extremely resistant to abrasion and other wear and tear. It also highly resistance to E-filed, chemicals, and other hazardous materials. XLPE is also a more affordable material solution and shares about 60% of the total medium cable market, and continuously growing.

XLPE cables also contains two semiconductor layers and provide better interface between conductor and insulation as well as electrical stress relieving.

Before introduction of XLPE cables in 1970s, underground medium voltage cables were made of oil-paper insulated cable systems. The earliest manufactured XLPE cable insulation often contains moisture and other contaminants by-products in the insulation, resulting in water trees and premature failures. Later after 1980s, the improved manufacturing processes (dry nitrogen curing and degassing) largely purifies the by-products in the cable insulation system thus improves the quality and lifetime of the XLPE cables.

Major challenges for XLPE cable that relates to quality and operations are namely water trees, water ingress and insulation defects. These issues are to be covered in the section of fundamental causes of power cable failure.

3 Failure statistic of power cables

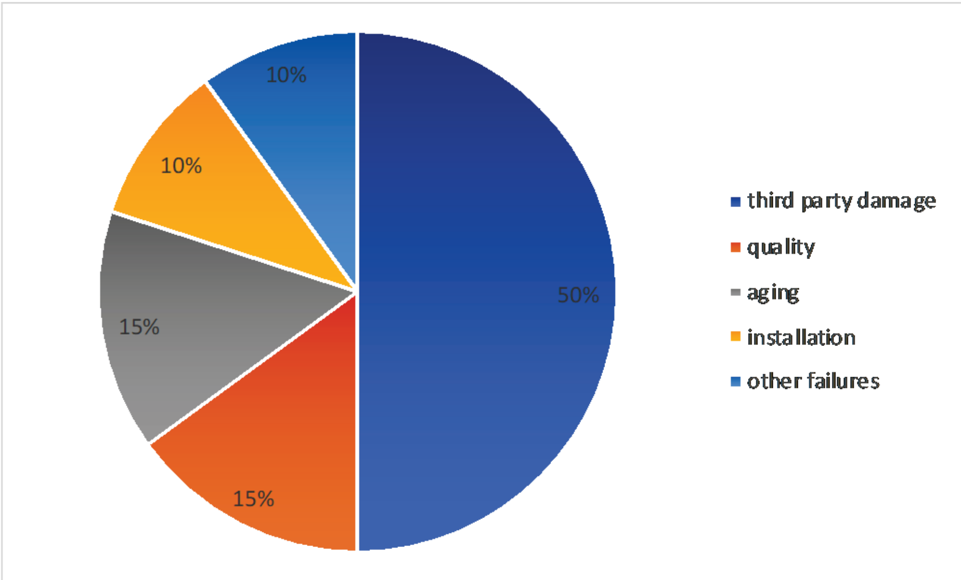
Power cable failure statistics not only provides an overview on probability of the different causes of the failure but also helps in decision making on maintenance strategies depending on its type as well as its technical maturity in time.

3.1 GENERAL CAUSES STATISTIC OF POWER CABLE FAILURE

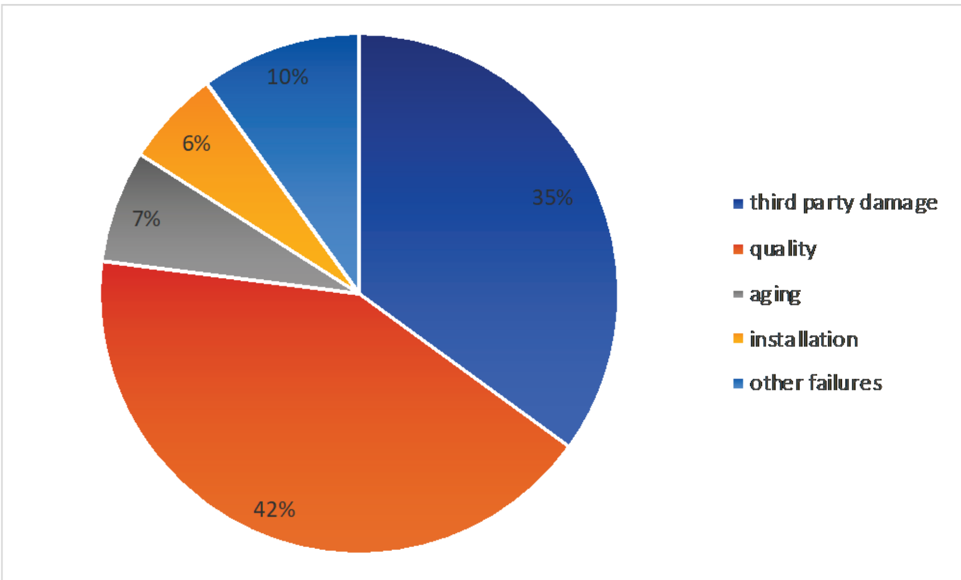
General failure statistic of medium voltage power cable data is generalized from field statistic data of different countries: including US, Denmark, UK, China and so on. In which, about 50% failure is due to the third-party damage, i.e., these damages were neither related to operation of power grid companies nor quality of the power cable itself, typical cases are excavation-caused failures. The other 50% failures that relate to cable quality and operation, can further be classified as following:

- 10-20%: aging related failures
- 10%: installation related failures
- 7-15%: manufacturing quality related failures
- 10%: other failures, including over-stresses, weather, operational failures etc.

Slightly different failure statistic data were found in high voltage power cable systems (35, 110, and 220 kV), indicating the handling and manufacturing maturity differences. Where quality related failures rise to 42% and installation and aging related failures were dropped to half of the medium voltage cable statistics. Two pie charts, Figure 1, are used to illustrate these failures in statistics: (a) medium voltage < 35kV power cables, (b) high voltage power cables > 35kV.



(a) General distribution of failure causes of medium voltage power cables (<35kV)



(b) General distribution of failure causes of high voltage power cables (35, 110 and 220 kV)

Figure 1 General distribution of failure causes of power cables [1, 2]

3.2 CABLE FAILURE RATE STATISTICS

With focus of XLPE cables, the failure rate can be studied as function of installation years, Figure 2. It shows high number of failures were found for the cables that installed before1980s regardless of its service time.

When studying the cable failure statistics as function of installation years, the development of manufacture's quality and technical maturity can be observed. In case of XLPE cable installed before 1980s, high failure probability alert needs to be assigned in defining their maintenance strategies [3].

Figure 3 further compares the failure rate of the Danish medium voltage XLPE cables installed before and after 1980s as function of service time. Results indicate significant higher failure rates (as much as 20 times) for the cables installed before 1980s than that installed after 1980s for the same period of service time. This is known as due to the manufacturing processes changes from steam-cured to dry cured XLPE cables in 1980s.

The higher failure rate after 30 years' service time for the cables installed after 1980s, could also be due to some steam-cured cables could have been installed around 1980 and be included in the statistic. However, it will be great value to follow the development in the failure rate in the coming years to, when a larger amount of the XLPE cable exceeds the service times of 30 years.

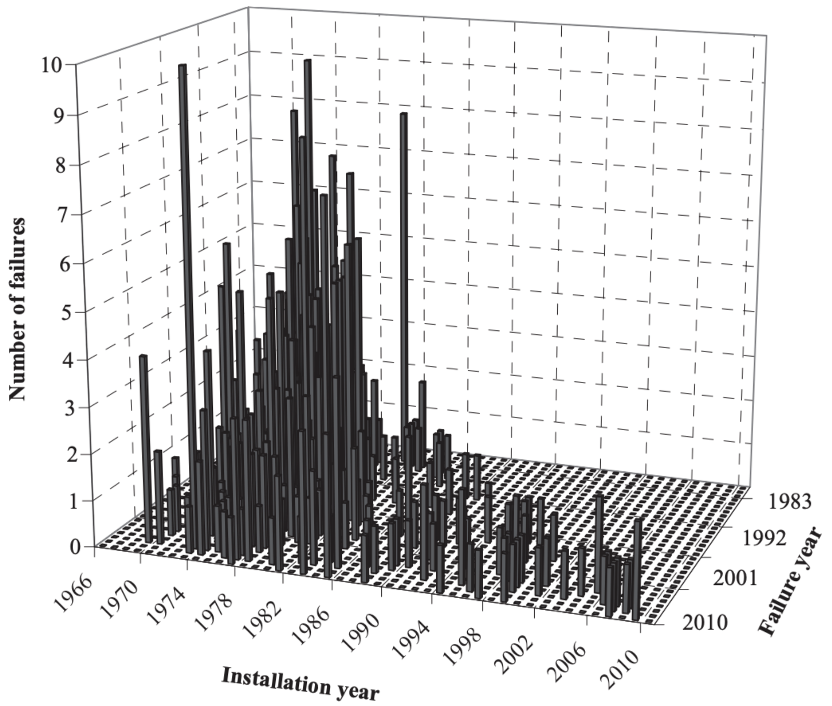


Figure 2 Danish MV XLPE power cable failure records as functional of installation year and failure years [3].

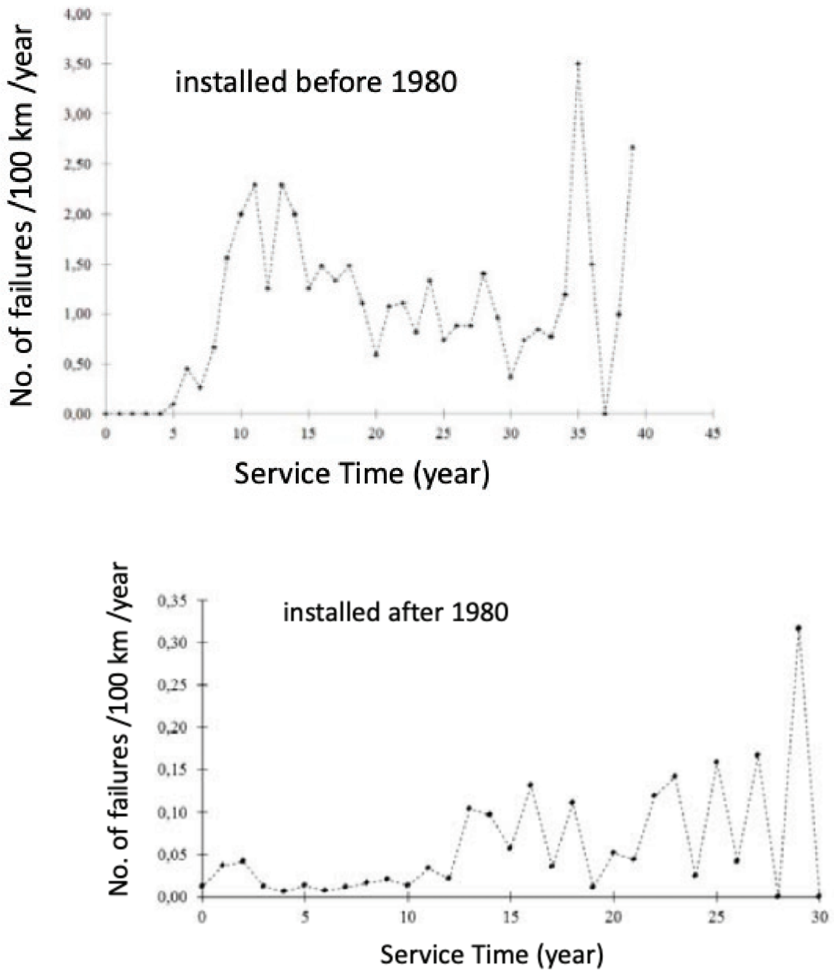


Figure 3 comparison of failure rate as a function of service time for XLPE cables installed before and after 1980s [3]

3.3 CABLE FAILURE LOCATION

Among failures due to cable quality and operation, statistic failure location provides valuable information for engineer to prioritize fault maintenance strategy and the optimize the fault localization and power restore efficiency. Based on the gathered report sampling, as illustrated in Figure 4, 70-80% of failures appear at cable accessories, i.e. joints, terminations, elbow, splice etc. only 20-30% were found at mid-cable body [4]. Clearly statistics suggests that large percentage of failures are likely link to the discontinuity of the cable parts as well as the act of technicians working in the field. The detailed causes of power cable failure are to be discussed in the next section 4.

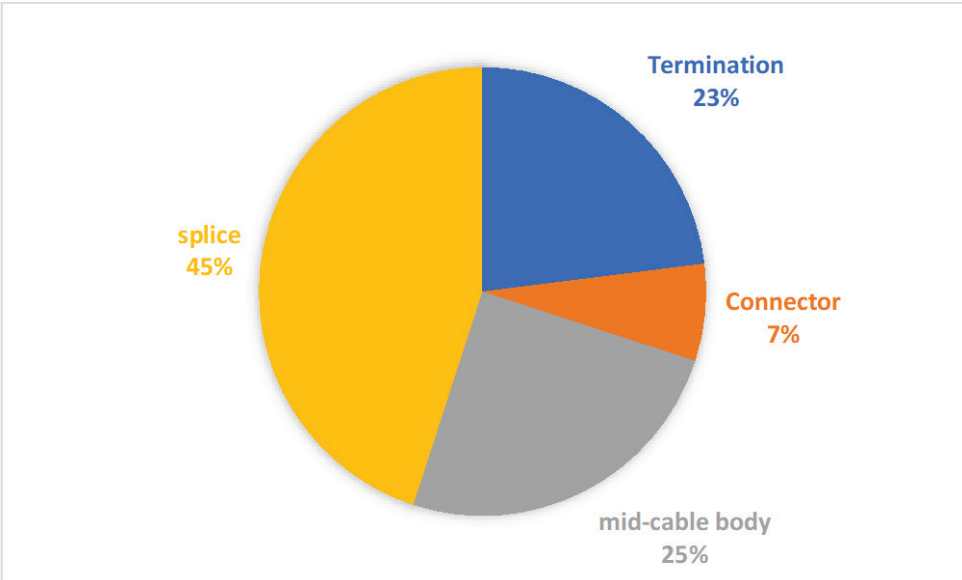


Figure 4 Cable fault location statistics [4].

4 Fundamental causes of power cable failure

Power cables are constantly subject to multi-physical stresses, namely: electrical, thermal, mechanical, and other environmental stresses. These stresses superimposed with each other and combined with artificial defects, accelerates the aging processes of the insulation system, and causes premature failures of the power cable system.

Though aging of the polymeric material is often directly caused by thermal stress, the reason of the overheating is not always the same. In the AC field, take a micro air cavity defect for example, a local air cavity defect in the insulation medium will cause the local electric field enhancement due to its permittivity difference compared to the surrounding dielectrics. When the local electric filed excess to a critical level, partial discharge activity starts to appear within the cavity to suppress the enhanced electric field by the generation the free charges thus the counter electric field. These free charges are then moved by voltage polarity shifts and consequently heating up the local defect area causing the insulation premature aging. Water tree is another example of cable premature aging caused by localized heating under AC stresses. When water/moisture immersions into the dielectric, water dipoles will follow the voltage polarity changes and act as a local heating source. With water heats-up and evaporates, small cavities can be formed within the dielectrics and followed by partial discharges activities. Figure 5 illustrate the principle of polymeric dielectric aging under multi-physical stresses and their relation to thermal aging [5, 6].

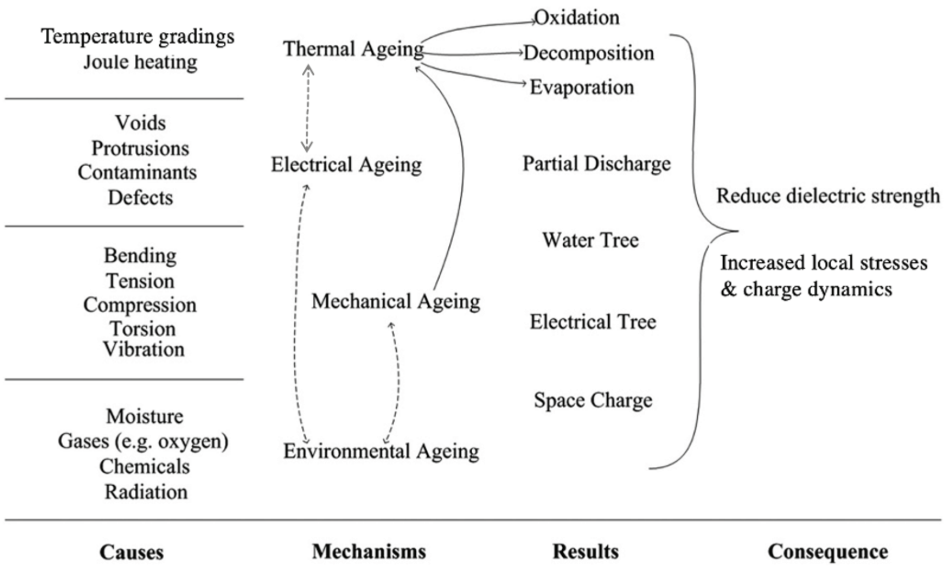


Figure 5 power cable polymeric insulation material aging correlations [6].

Nevertheless, more complex, and harsh stresses can be found in high voltage DC systems. Apart from that DC is rectified from AC via high frequency switching, after a long period of DC polarization stress followed by a sudden polarity reversal, superimposed of stresses from accumulated space charges at different levels of interfaces and external applied electric field can cause permanent damages in insulation system.

The power cable insulation system aging is a long-time battle between charge movement and insulation system. The insulation system contains many materials of different dimensions, i.e., from nano-meter polymer structure to kilometer long cable semiconductor layers, all can form space/interface for charges to generate and/or accumulate. Depending on charge mobility within the space/interface medium, the local electric field can either be enhance or reduced and dynamically balanced by partial discharge activities. This local dynamic balance can be changed with external contaminations such as water or structure changed due to thermal/mechanical stresses.

To summarize, the aging/degradation of cable insulation system is a complex process resulting from multi-physical stresses. A local dynamic stress balance can last for a long period of time with presence of measurable physical properties changes, such as partial discharge activities, loss factor changes and so on. These changes provide opportunities for maintenance engineers to measure and identify the possible defects and plan for the maintenances.

4.1 COMMON DEFECTS IN CABLE ACCESSORIES

Cable accessories are critical components, not only do they bridge different cable parts but they also handle the impedance discontinuity for electromagnetic wave propagations. As the wave impedance of different cable parts cannot be perfectly matched and ends of the cable connections need to be terminated and connected to the source and load, wave transmission and reflection may amplify the stresses on cable accessories and causes premature aging.

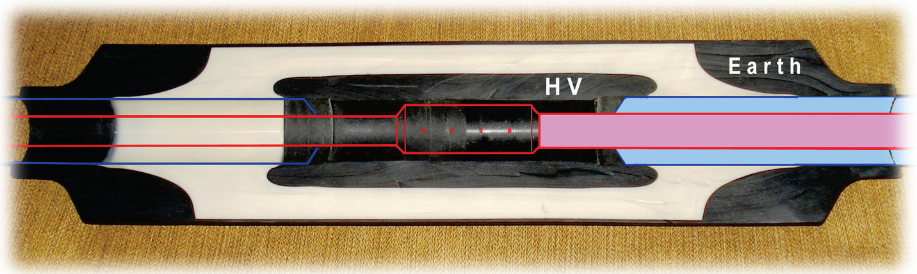


Figure 6 example of a cable joint with stress cone made of special shape and of different materials (white part).

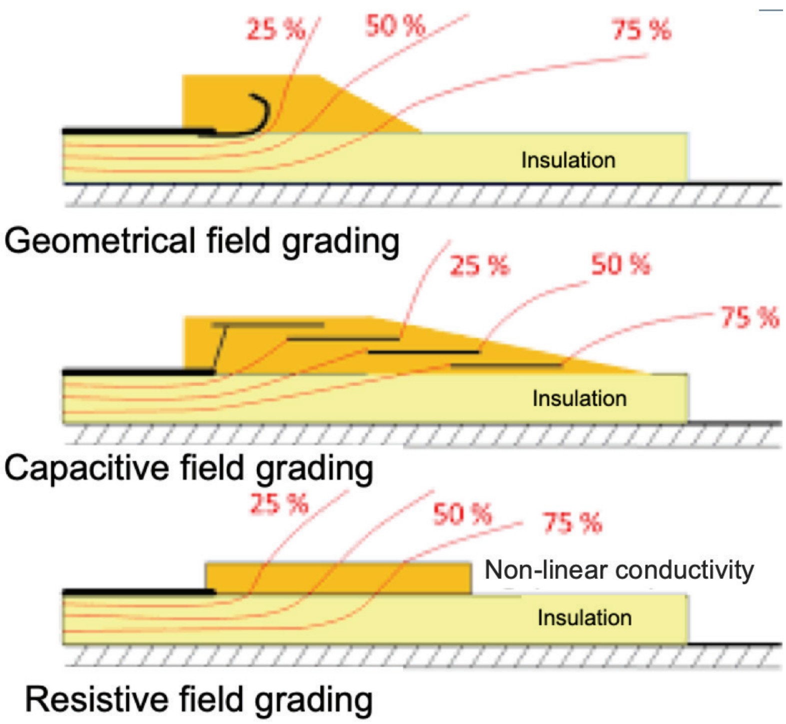


Figure 7 three common methods that can be utilized for field grading at cable accessories.

To handle these excessive stresses, stress cones are used at the cable accessories. They are often designed in special shape with of different material composites to grade the electric field at the shield termination and the cable conductor. Figure 6 shows an example of cable joints with stress cone. Three commonly used field grading methods in cable stress cones are illustrated in Figure 7, namely geometrical, capacitive, and resistive grading methods. All these solutions share one common drawback, i.e., different materials need to be laminated and form a number of interface layers. In addition, these interfaces and layers are generally made in the field with limited control of the working environment and act of technicians' work.

Though the high failure statistics at the cable accessories, as elaborated in section 3.3, can be identified as harsh working environment and limited workmanship in the field. The deeper fundamental causes are interfacial defects that allow water and contaminations to interact with multi-physical stresses. Figure 8 illustrates the radial and tangential stresses acting at cable accessory interfaces, in addition, due to surface roughness of solid materials, interfacial cavities between solid-solid cannot be avoided, as demonstrated in Figure 9, consequently electric field deviation can be found and interact at these micro cavities, Figure 10. Additionally, thermal- mechanical properties mismatch at interfaces under large temperature variation challenges the manufacturing and installation qualities. Eventually, moisture ingress via poor sealing and presents at interfaces accelerate the degradation process resulting electric tree like damages. Figure 11 shows two pictures of the cable accessories damages at interfaces due to muti-physic stresses combined with water ingression [7].

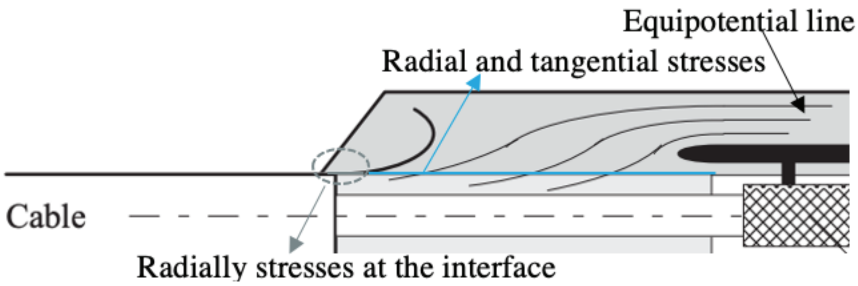


Figure 8 illustration of radial and tangential stresses at cable accessory interfaces.

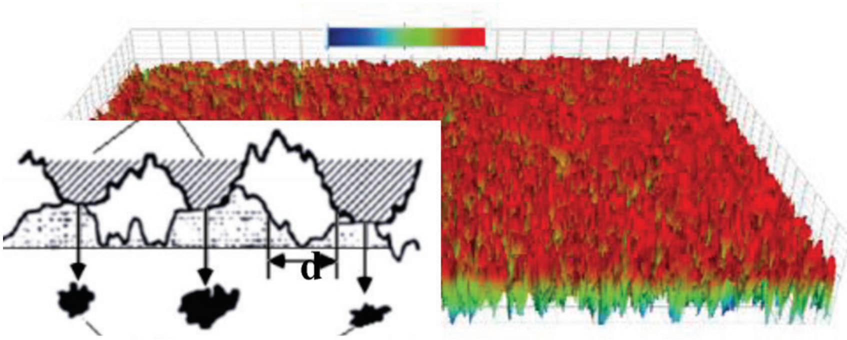


Figure 9 illustration of solid-solid interfacial cavity defects formed by solid material surface roughness (measured abraded surface roughness by P500 sandpaper)

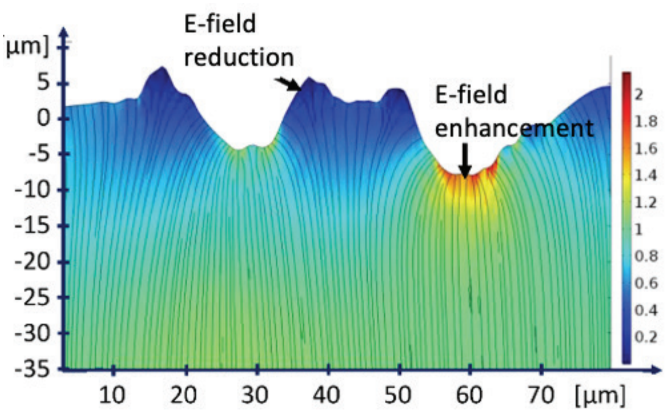


Figure 10 FEM calculated electric filed at rough surface to demonstrate electric field deviations, including both field enhancement and reduction [7].

Figure 11 Examples of failure damages appeared at MV cable accessory interfaces due to multi-physical stresses combined with water ingress.

4.2 COMMON DEFECTS IN CABLE BODY

Though cable accessories shares 70-80% of failures that relate to quality and field craftmanship, cable body is responsible for significant parts (60-70%) of cable failures in total as it is more likely subject to the third-party damages as well as manufacturing defects. Figure 12 illustrates the most common defects that found in cable body. Like the accessories, the material interfaces are the weakest parts. Defects such as cracks, contaminations, protrusions, delamination etc. are the field enhancement factors to form electric trees. Combining with water and moisture ingress, water trees are also commonly discovered the insulation body, especially at parts that are close to the accessory joints. Other defects, such as holes and cracks at the cable jacket resulting from external forces, will act as the source for moisture penetration into the insulation interface, and causes failure after a long-time water tree degradation. Figure 13 shows two typical damages commonly found at cable body after external damages and water tree degradation.

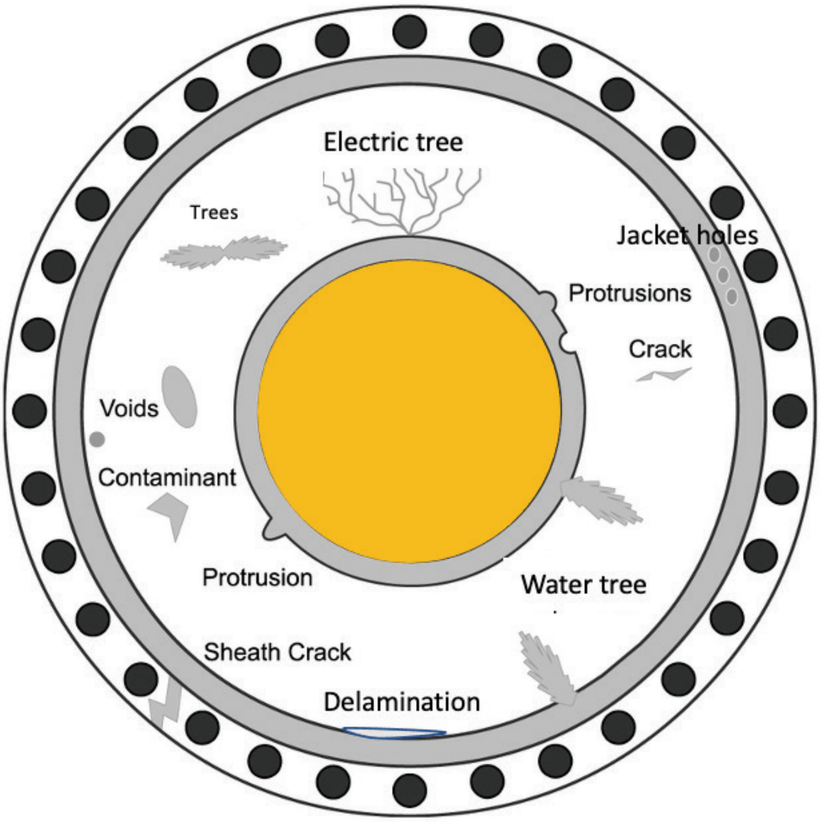


Figure 12 illustration of common defects found in cable body.

Figure 13 common damages found at cable body, top: third party damages; bottom: water damages.

5 Power cable diagnostic methods review

Generally, power cable diagnostic methods can be classified into non-electrical methods and electrical methods. The non-electrical methods are often used only in the oil-paper insulated cable systems, where gases/pressure and fluids samples can be utilized for diagnostics, whereas electrical methods are generally used in all systems. The focus of the review will be mainly on electrical methods.

5.1 NON-ELECTRICAL DIAGOSTIC METHODS

Non-electrical diagnostic methods can be simply classified as cable fluid sample related analysis and fluid pressure measurements.

5.1.1 Cable fluid tests

Cable fluid tests are effective methods to routinely evaluate health condition of the oil-paper insulated cable system. These methods including dissolved gases analysis DGA, moisture content, acidity, particle counts and so on. Electrical measurements can also apply to fluid sample for cable diagnostics by quantifying dielectric dissipation factor, dielectric strength, and DC conductivity.

These analysis methods mainly originated from power transformer diagnostics where oil-paper insulation system is developed for over 100-years history. However, the application of these diagnostic methods cannot always reference to the transformer diagnostics data, as concentration of particle indicators are often much lower in cable system.

DGA

When abnormal thermal and electrical stresses cause breakdown in the insulating fluid and paper of a cable, generating gases that dissolve into the cable fluid. DGA is one of the most efficient tests for oil-filled cable diagnostics. IEEE Std. 1406-1998 is an old guide for the use of DGA analysis of electric power cable systems.

Dissolved gases analysis DGA: same as in power transformer application, samples can be taken from cable accessories (terminations and splices) sampling ports. Low dissolved gas concentrations are observed in cables operating. On the other hand, elevated dissolved gas levels indicate electrical and/or thermal abnormalities in the cable. Acetylene (C_2H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), hydrogen (H_2), oxygen (O_2), nitrogen (N_2), carbon monoxide (CO) and carbon dioxide (CO_2), are gases of interest. DGA is generally looking for the presence of these gases, amounts and the rate at which they are produced. Table 1 shows an IEEE 1406-2004 guidelines for dissolved gas levels in SCFF cable fluids.

Hydrogen and hydrocarbons present from the breakdown of cable fluid, whereas breakdown of the paper insulation produces measurable carbon dioxide, carbon monoxide or oxygen.

C_2H_2 is another important dissolved gas, and its value should be close to zero for normal operation, as it often generated from partial discharge or arcing. Arcing produces significant amount of hydrogen and acetylene with the presence of methane and ethylene. High concentration of acetylene, hydrogen methane and ethylene may require the dissection of cable joints and terminations to investigate the source of the gases.

Decomposition of the paper insulation or high conductor temperatures from overloading or hot spots generates carbon monoxide, carbon dioxide and oxygen and combinations of these gases.

Quantities of nitrogen and oxygen may result from poor fluid quality and sampling techniques also need to be controlled.

Table 1 IEEE 1406-2004 guidelines for concentration of dissolved gas levels in SCFF cable fluid.

Dissolved Gas	Normal concentration for cable system of age (ppm):			Moderate concern (ppm)	Major concern (ppm)
	<5 yrs	5-20 yrs	>20 yrs		
N_2	50	75	100	>300	>500
O_2	25	50	70	>100	>300
CO_2	20	50	75	>150	>300
CO	10	20	50	>100	>200
H_2	50	75	100	>200	>400
CH_4	5	15	30	>50	>100
C_2H_6	10	20	40	>75	>150
C_2H_4	0	5	10	>25	>75
C_2H_2	0	0	0	>10	>25
Total Concentration of Gases	50	100	200	>400	>800

To ensure accuracy of the DGA sampling and analysis, fluid sampling is to cover both the cable system and accessories alongside the pressurizing unit. The cable accessories (terminations and splices) are typically equipped with sampling ports. DGA is recommended to be performed annually, but no longer than three years between tests.

Water Content

Karl Fischer titration method is often used in water content tests. Like the tests performed for power transformer oil-paper samples, content of water in a health cable fluid sample should be less than 20 ppm. Rather high demands on testing procedures as well as sampling and storage methods may strongly influence the accuracy of the results. Here, experienced personal are required.

Acidity test

Degree of acidity of a cable fluid can be measured by mean of neutralization value and used to indicate relative changes that appeared in insulation fluid. However, as a variety of oxidation products present in used insulation fluids contribute to acidity and these products vary largely in their corrosion properties, the test cannot be used to predict corrosiveness of the system under service conditions in cable systems.

Particle counts

In cable system, particle counts are often used for a routing test after cable jointing is installed. The conductive particles' size and number the major concern for evaluating, example of such is copper swarf in the sealing.

Automatic particle size analyser working on the light interruption principle is commonly used. Others also use optical microscope to count particles collected on the surface of a membrane filter by either the transmitted light or incident light mode.

Based on IEC 60970 "Insulating liquids – Methods for counting and sizing particles", the limit is 2-5 micron for 50 000 per 100 ml of fluid.

Fluid's dissipation factor

Dissipation factor also known as loss tangent or loss factor, is a measure of the tangent of the angle between applied voltage and resulting current differs from ninety degrees. It is often measured as function of frequency and temperatures.

Dissipation factor is an effective indicator for relative measure of the fluid degradation, however, fluid sampling, measurement procedure, used electrode system and environment control are the major interferences for accurate evaluation, similarly to the water content analysis, dissipation factor is very sensitive to the moisture content and measured frequency spectrum.

IEC60247 "Insulating liquids - Measurement of Relative Permittivity, Dielectric Dissipation Factor (tan δ) and D.C. Resistivity". Provides detailed measurement specification and conditions. Tests should normally carry out at 30°C and 90 °C, and rough acceptable level should be less than 0.01 at 90 °C.

Dielectric strength test

Dielectric strength test, also commonly known as electric breakdown test, provides indication of the presence of contaminations in the cable fluids. IEC 60156 "Insulating Liquids - Determination of the Breakdown Voltage at Power Frequency" specifies the detailed testing method and requirements. Though this method directly provides measure of the breakdown voltage level, however, statistic measure is often required for an accurate determination of the breakdown voltage, and rather high demands on personal experience as fluid sampling, used testing electrodes and voltage ramping speed all strongly influence the finally results. Nevertheless, the minimum acceptable value would be not less than 25kV across a 2.5mm testing gap.

DC Resistivity Test

DC resistivity or DC conductivity test is another method to determine the fluid quality by measuring leakage current of a fluid when it is subject to a dc voltage difference between two cylindrical electrodes. This measurement is often carried out together with dissipation factor test, as the same shielding electrode system need to be used for both tests.

For a good quality oil samples, sensitive electrometer often needed, thus shielding and noise handling are critical challenges for measuring Pico-ampere level currents under a micro-volt noise environment. In addition, due to presents of ions and the charges movements in the fluid, measurement time point is often a critical parameter to be considered, as measured leakage current can continuously decay for a very long period, in weeks. Typical, measurement time can vary from 10 minutes up to 3 hours.

IEC60247 indicates a minimum acceptable value would be 100 Gohm m at 90°C.

5.1.2 Fluid leak detection

Fluid leaks can compromise the performance of fluid-filled cables and harm the environment. Typical causes of fluid leaks are pipe/sheath lead corrosion, external damage due to excavation, poor workmanship and laying techniques, DC and stray current, mechanical stress, vibration, and compression from ground construction work. The cable fluid pressure related diagnostic including regular fluid pressure monitoring followed with oil leakage localization.

CIGRE technical 652, "Guide for the operation of self-contained fluid filled cable systems", proposed three most feasible techniques in pertaining to the leak detection of SCFF cables: freezing, hydraulic bridge technique, and PFT injection. Perfluorocarbon tracers (PFT) tracer technique is a relatively new method for finding leaks in oil-filled high voltage cables. Traditionally, injecting dyes, radioactive material, tracer gases, odorants, acoustic emission, radar, infrared, and even dogs are also applied to detect oil leaks.

Freezing method is based on the locations at which the pressure drops continuously after the cable oil is frozen at multiple spots. Safety of personal conducting the freeze and potential damage to the cable serving and the metallic sheath are concerns. It may also aggravate the state of the jacket, causing water ingress and corrosion.

Hydraulic bridge technique method is only used on single core cables and measures the flow of fluid through the cable, and by knowing the length and hydraulic resistance of the cable an estimation of the leak position can be found. The cable needs to be de-energized. Accuracy is affected by environmental conditions as well as loads above ground. Stable temperatures and pressures are required to achieve consistent results.

The reliability of the technique is largely dependent on knowledge of the cable hydraulic parameters e.g. oil viscosity, hydraulic resistance and the static head difference of the oil section where leak location is required. i.e. this method is more accurate in measuring relative changes rather than absolute numbers. A good health reference data facilitates a more accurate leakage localization.

Perfluorocarbon tracers is based on introducing a small amount perfluorocarbon tracer (PFT) liquid into the fluid of the cable. When a cable leak occurs, the fluid wets the subsurface soil allowing some evaporation of the tracer, which vents to the atmosphere close to the leak, forming a curl mapping with the highest concentration at the leakage point, Figure 14. The cable remains in service while a leak is detected. Leaks can be detected to within 1m depending on ground conditions and the local environment.

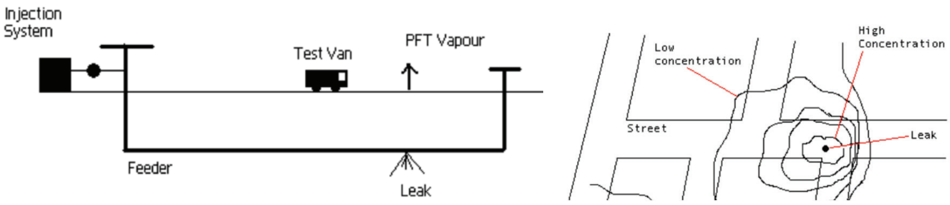


Figure 14 principle of PFT Technology and illustration of PFT mapping from a leakage point.

5.1.3 Thermal infrared imaging test

Thermal infrared image is an easy, straightforward method to identify any significant surface abnormal temperature appeared at accessible cable parts. Often defect types are limited to high contact resistance and in some cases with localized high dielectric losses.

By measuring the thermal gradients of different cable parts, such as three phase joints, inspectors can easily spot any abnormal high temperature legs. Some study suggests that this method can be used for detecting connector high resistivity and unusual heating of part of the accessory due to localized dielectric losses [8].

An infrared camera is often used in such application, meanwhile, the load of the cable and accessory must be measured and considered as the heat can be related to unbalanced load. In the case of using arc proofing or fire-retardant tapes used around the joints, the thermal monitoring is not usually accurate for such evaluation, this is due to high thermal resistivity tape layers unevenly applied to the cable surfaces.

Our review suggest that the thermal infrared image is very efficient for a quick detection of any unusual high resistance joints caused by connector oxidation and water damages. Figure 15 shows the oxidized cable connectors resulting in premature degradation at the joints. However, for abnormal surface temperature caused only by dielectric heating, sensitivity requirement on infrared camera is too high to be practical and can be easily masked by the complexed testing environment temperature variations.

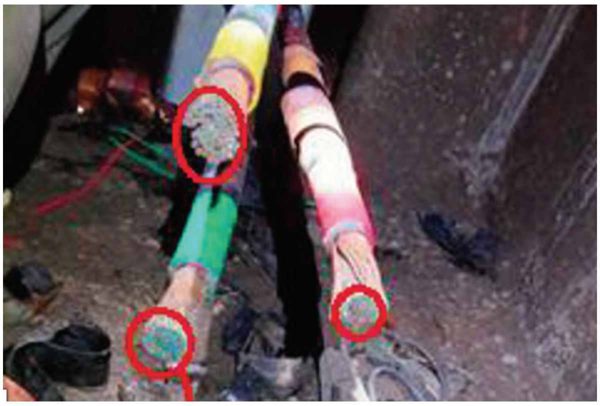


Figure 15 example of MV cable joints that been oxidized, likely due to water damages, consequently abnormal heat is generated due to high contact resistance.

5.2 ELECTRICAL DIAGOSTIC METHODS

Electrical diagnostic methods are the most utilized techniques for power cable diagnostics and maintenances. Requirement for off-line tests differentiates these techniques in possibility of continuously monitoring or routinely off-line check. Nevertheless, major techniques reviewed here and traditionally are off-line methods. With fast development of data communication and sensor technologies, more on-line monitoring methods are introduced in recent years for a more predictable and reliable power cable maintenance.

5.2.1 Voltages waveforms used in power cable diagnostics

Testing voltage shapes, shown in Figure 20, including 50/60 Hz sinusoidal, variable frequency resonance, VLF, damped AC, and even DC voltages, are the voltages been used for different on-site cable diagnostics techniques. Different advantage and disadvantages are to be considered for using different voltage shapes in cable diagnostics, following discussion will be based on different voltage stresses to elaborate technical challenges might be encountered in field measurements. It practices, most field experience exists with measurements using either VLF or variable frequency resonance systems, thanks to their low power requirements, flexibility, and compact dimensions.

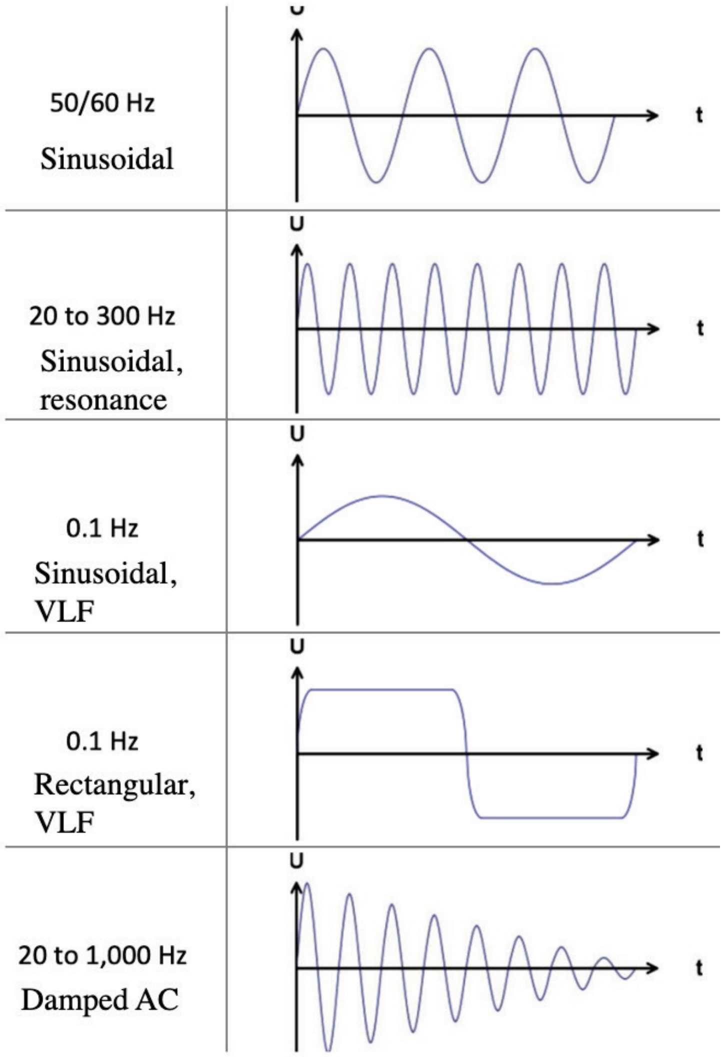
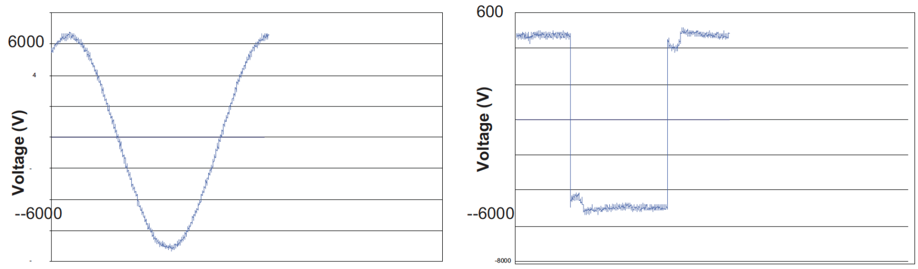


Figure 16 illustration of voltage waveforms to be used in power cable diagnostics [9].

Very low frequency (VLF) voltage

Very low frequency (VLF) voltage testing source is introduced to overcome the excessive high charging current demand that would need for field test at power frequency, as the inherent high capacitance of a long-shielded power cable. In addition, significant negative impact might appear when using high voltage DC for testing on an aged polymeric insulated power cable, as charge accumulation and its associated polarization and depolarization processes might permanently initiate defects and accompanied with electric treeing propagation under service stresses.

One may notice, there are two commonly used test voltage shapes in VLF tests, sinusoidal wave shapes and the cosine-rectangular, based on generation principle of the voltage source. Sinusoidal wave is recommended for Hi-pot and Tan-Delta testing, whereas as cosine-rectangular are more suitable for partial discharge tests, to be discussed in the later section. Figure 16 illustrate two utilized voltage shapes for the cable diagnostics. The fast voltage steps from the cosine-rectangular voltage generation are more likely to cause permeant damages to the cable under tests, such as electric tree, as well as introduce high harmonic interferences in precision determination of loss factors. On the other hand, fast voltage changes are likely to trigger partial discharges in defect that has been pre-charged, more detailed elaboration can be found in partial discharge detection parts, thus more efficient to detect small cavity detects that is often more difficult to be detected under a traditional 50Hz sinusoidal voltages.



0.1 Hz sinus waveform 0.1Hz cosine rectangular waveform

Figure 17 illustration of two commonly used VLF voltage waveforms in power cable diagnostics.

Sinusoidal series resonance voltages

The series resonant circuit, Figure 18, consists of an inductor in series with a capacitive test object and connected to an excitation transformer, a medium-voltage power source. By varying the circuit inductance or the supply frequency, the circuit can be tuned to resonance. When in resonance, a voltage considerably greater than that of the source with amplitude multiply with quality factor/resonance ratio, and of a pure sinusoidal shape will be applied to the test object. Depending on variable inductance or test frequency, two kinds of system were developed for testing: modulated power frequency series resonance and frequency conversion series resonance. The only different to the test object is difference in testing frequency. The series resonant circuit is especially useful in power cables test as in which the leakage currents on the external insulation are very small in comparison with the capacitive currents through the test object and the energy to form a disruptive discharge is very small.

The stability of the resonance conditions and of the test voltage depends on the constancy of the supply frequency and of the test circuit characteristics.

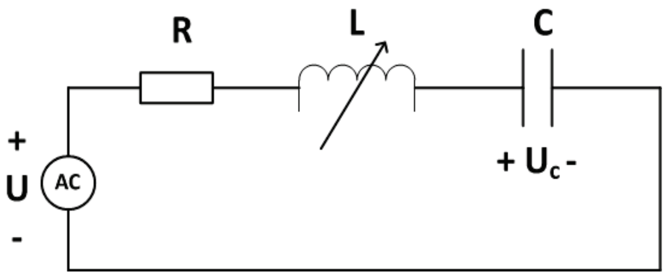


Figure 18 principal circuit of series resonance voltage source with a capacitive test object.

Modulated power frequency (50/60Hz) testing voltage is generated by adjusting the inductive reactance of the reactor. The advantages of the power frequency series resonance test are: 1, the high voltage can only be generated after the series resonant circuit condition is fulfilled, 2, In case of cable insulation failure, i.e., short circuit or breakdown of the cable, the high voltage will appear to be uniformly dropped. 3, No need of additional protection devices as short-circuit current is limited by the series reactor. The disadvantage of this test method is that the operation is rather complicated, the system quality factor is not high, which limits its application in field practice. However, to lock the test frequency to power frequency for cable testing, required inductance is often significant, which limits the field application of such test source.

Like the modulated power frequency series resonance principle, the frequency conversion series resonance is realized by adjusting the test voltage frequency within the range of 10 to 500 Hz. Rather than the fixed 50 Hz power frequency in the frequency series resonance test by regulating the heavy and large reactor.

The advantage of the variable frequency series resonance test is that with the limited instrumentation's dimension and weight, the high testing voltage with frequency range of 10 to 500 Hz can be generated which largely improves the efficiency of the field test and makes it most widely used in practices. In addition, compare to the VLF voltage sources, the operating frequency within 10 to 500 Hz, can generate sensible losses factors within short period, which is comparable with the actual losses at 50 Hz. Therefore, the results obtained by the variable frequency series resonance voltage test are more accurate, comprehensive, and reliable.

Damped AC voltage

Damped AC (DAC) voltage is mainly used in some European countries for field testing. In general, it can be applied to all types of power cable systems.

Damped AC voltages are generated by charging a capacitive test object to a pre-defined voltage level and then discharging it via an inductance. The voltage source consists of a high voltage DC source, an inductor, a capacitor, and a HV switch. When the charging voltage is reached and the switch is closed, generating on the test object a damped alternating voltage. At the charging stage, the test object is subjected to a ramping voltage at a rate depending on the test object capacitance and during the discharging stage, a damped AC voltage at a frequency dependent on the test object and the inductance, typically between 20 Hz to 500Hz.

Most applications combine the DAC voltage withstand test with PD or dielectric frequency response [10]. For voltage withstand test, IEEE P400.4 suggests that a minimum 50 shots of DAC excitation are needed. Due to shorter duration of the excitation and decaying characteristic of the voltage, test results obtained by DAC testing can be differ from those measured by continuous AC withstand voltage testing.

High voltage DC

DC testing voltages also been used in application of cable diagnostics. Thanks to its simple, lightweight, and low power demand. Earlier, it has used to test insulation conductivity on laminated cable with failures related to electrical and thermal problems. Testing voltage level is limited to below 2kV. Recent years, when testing aged polymeric dielectric insulated AC cables, large debate was raised on charge injection while performing HVDC withstand tests. Number of lab experiments have showed that HVDC voltage does cause space charge build-up in aged polymer insulation and can result in accelerated premature aging in dielectrics when an AC voltage is re-applied. Insulated Cable Engineers Association standard ICEA S-94-649 does not recommend HVDC testing on any cables more than 5 years old and indicates large amount of evidence showing that HVDC is harmful to aged extruded medium voltage cables, especially XLPE cables. Therefore, we do not recommend the use of HVDC withstand tests on aged polymeric insulated AC cables.

Though effectiveness of using HVDC voltage withstand in cable diagnostic is not clear and only limited to DC cables, alternative applications of DC voltage is to measure cable’s time domain responses, i.e., polarization and depolarization current as well as return voltage measurements, at a relatively lower voltage level, 1-2kV.

5.2.2 Voltage withstand test

Voltage withstand test is the most utilized and elementary methods in power cable test to determine its insulation system integrity and effectiveness under high and stable voltage stresses. It is a relatively simple and robust testing method to determine any significant insulation defect such as failure and short circuit of the system. Testing voltage shape, amplitude and duration are main variable factors in the tests. However, if the defect cable has tested under severe enough at the withstand testing voltage, electrical tree may initiate and grow in the insulation.

The testing voltage levels are based on the worldwide practices of from $2U_0$ to $3U_0$, where U_0 is the rated rms value of phase to ground voltage, for cables rated between 5 - 69 kV. The maintenance test level is about 75% of the acceptance test level. One can reduce the test voltage by another 20% if the voltage is applied for longer time (>1hr). Studies indicates that increasing the voltage above $3U_0$ to compensate long testing time does not linearly replicate results either on test or in service as compared to the lower voltage but longer time tests. In addition, for acceptance tests on cables rated above 35 kV, terminations need to be added to avoid flashover.

Based on measurement system used, voltage withstand tests can be classified as simple withstand and monitored withstand tests. The simple withstand is the most elementary electrical test on cable insulation, and test results pass, or fail is simply determined by withstand or breakdown, without any indication of test’s effects on the insulation system. Whereas monitored withstand tests is performed with one or more additional advanced diagnostic methods, such as dielectric response or partial discharge detection. The condition of the cable insulation is thus monitored during voltage application and used in helping insulation system health condition assessment.

The three commonly utilized voltages i.e. 1. very low frequency voltage, 2. Sinusoidal series resonance voltage, and 3. damped AC voltage, in cable voltage withstand tests applications are reviewed in following.

VLF (very low frequency) voltage withstand test

Very low frequency (VLF) voltage testing in the frequency range from 0.01 to 0.1 Hz has increasingly been used for Hi-Pot acceptance for MV extruded cables in the last 15 years. Currently, the maximum available very low frequency voltage (0.1 Hz) level for the test is about 200 kV peak. Thus, the VLF voltage testing are limited to only MV cables.

Inception of an electrical tree and growth time are largely depending on voltage amplitude and frequency, as well as the geometry of the defect. Based on lab data of needle tip initiated electrical trees in PE insulation till completely breakdown of the insulation, VLF ac voltage test levels and testing time durations have been established. However, the time to failure will vary according to the type of insulation materials, and tree growth rate is not the same for all materials and defects.

The VLF voltage withstand testing levels for installation, acceptance and maintenance are recommend in IEEE. 400.3-2013 with the cable system rating up to 69 kV and for both testing voltage shapes: sinusoidal and cosine-rectangular waveforms.

In general, the installation test voltage level is about $1.9U_0$ and acceptance test voltage level is about $2U_0$, whereas the maintenance test voltages level is about 75% of the acceptance test voltages. Testing voltage levels between sinusoidal and cosine-rectangular voltages are the same for the peak testing voltage level but differ in rms voltages, about 40% higher in cosine rectangular waveforms.

For testing with cosine-rectangular voltages, A high voltage DC source with a high-voltage inductor and a switching rectifier converts DC voltage to the VLF cosine-rectangular test signal. The system changing the polarity of the cable system being tested every 5 s and generates a 0.1 Hz bipolar pulse waveform. IEC 60060-3 specifies the qualified testing voltage waveforms should be within ±5% uncertainty in its peaks level and less than 2% drift between positive and negative peaks. The minimum requirement for the measurement system on its response time should be less than 0.5 s and the general requirement for measuring peak voltage value win an uncertainty of 5% as well as all equipment should under valid calibration.

The recommended minimum testing time for an installation acceptance withstand test on new cable is 60 min at 0.1 Hz. The recommended minimum testing time for a simple withstand test on aged cable circuits is 30 min at 0.1 Hz. If a circuit is considered as important, then the testing time can be extended to 60 min.

A test time within the range of 15 to 30 min may be possible if exitance of parallel measured parameters, such as, loss factor, partial discharges, remains stable for at least 15 min and no failure occurs. It should be noted that the recommended test time for a withstand test is 30 min.

Sinusoidal voltages withstand test

Sinusoidal alternating voltage withstand test in cable field applications were mainly carried out with frequency conversion series resonance source, where AC voltage with frequency between 10 Hz to 500 Hz (IEC 60060) is used. This is mainly due to the transportation practicality of the testing voltage source.

Based on IEEE 400.1 testing standards for field cable applications, the field-testing voltage waveform with frequencies between 20 Hz and 300 Hz are comparable to the operating voltage waveform at power frequency. It is applicable to all types of cable systems. For a more comprehensive diagnostic result, partial discharges and dielectric response measurements are often suggested to be added in parallel.

Regarding the test voltage level, the voltage shall be applied to the test object starting at a sufficiently low value to prevent any switching transient overvoltage. It should be steadily raised to permit reading of the measuring instrument, minimum required resolution for the measurement response time is <0.5s. Typically, 2 % of U_0 per second rise rate is sufficient for the applied voltage above 75 % of U_0. It shall be maintained for the specified time, typically in few minutes, and then steadily decreased, but not suddenly interrupted which may generate switching transients to cause damage and erratic results.

The test duration of a withstand test shall be 60 s. The criteria of the passed test are if no significant discharge/breakdown occurs.

Damped AC voltage withstand test

DAC voltage withstand test is to apply a pre-defined number of DAC excitations at a selected voltage level to the cable system including cable body and its accessories. Based on insulation system breakdown or withstand results to determine the success of the tests. This is considered as non-monitored withstand tests. Further, if other advanced testing methods, such as partial discharge or and tangent delta is applied in parallel, for pervading more information on tests effects on insulation conditions. This is considered as the monitored withstand test. The applied voltage level is generally higher than the rated voltage, typically is $1.7U_0$.

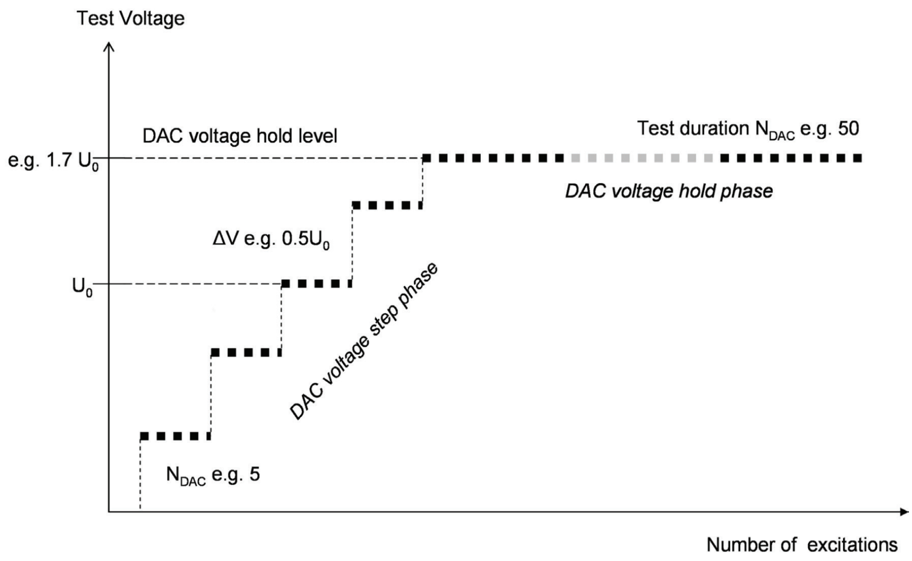


Figure 19. Illustration of a DAC voltage withstand test procedure suggested in IEEE 400.4, PD detection or tan delta test can be performed in parallel (monitored withstand test)

IEEE 400.4 suggested a DAC voltage withstand test procedure is illustrated in Figure 19. It contains two phases, step up phase and hold phase. In step up phase the delta voltage is about 0.2 to 0.5 U_0 and 5 shots per each step. Thereafter, when voltage reaches to the pre-selected peak voltage at hold phase, typically 1.7 U_0, 50 DAC excitations are applied to the cable.

The DAC frequency is determined by a given HV inductor within the power source, IEC 60060-3 specifies the test frequency for DAC voltages should be within the range of 20-1000Hz, with damping factor range up to 40%. The damping factor is defined as the voltage difference between the first and second peak of same polarity, divided by the voltage value of the first peak.

The main advantage of DAC voltage test is that test equipment is small and easy to handle, and Testing results are generally comparable to the power frequency test results. Moreover, it often combined with other advanced diagnostic techniques such as PD and dissipation factor measurement, which provides more comprehensive evaluation in cable diagnostics.

The clear drawback for using DAC voltage is that the tested cable needs to be off-line, and due to short duration of the excitation and undefined decaying characteristic of the damped AC voltage, the breakdown field strengths can be different from those measured with continuous AC. The undefined decay characteristic is due to use of fixed inductor in the power source at different cable capacitances results in variation in natural frequencies. To balance the testing frequency, an additional capacitive load is recommended in testing short cables.

5.2.3 Partial discharge tests

Partial discharge test is probability the most utilized non-destructive method to identify any potential defects in insulation system, not only been implemented as part of production and commissioning quality-control test of power cable, but also suggested to use as filed maintenance routing test for an early detection of potential insulation defects that likely leads to power cable failures in time.

Partial discharges (PD) are small electric discharges or sparks that only partially bridge the conductors. They are often occurring in insulation defects, at surface or interfaces, or floating conductive patristical/contaminations.

Partial discharge characteristics depend on the type, size, and location of the defects, insulating material, applied voltage, and environmental conditions, their amplitudes and numbers varies. The damages caused by PD activities depend on several factors and can range from negligible to causing failure within few days to years.

The fundamental of the PD is a localized phenomenon that trying to lower the local excessive electric field (E-field) stresses. The overall electric field at the local defect can be reduced by countering E-field, which is induced by PD generated free charges. Illustration of free charges and E-field superposition are shown in Figure 16. Depending on externally applied stresses (voltage shape and amplitude) and the mobility of the free charges within the different insulation medium, a neutralization and generation (PD) processes are dynamically balanced. Externally, partial discharges activate varying in time, PD numbers, and PD amplitudes can be observed. All these variations challenge the accurate detection and interpretation of partial discharges activities and thus cable diagnostics reliability.

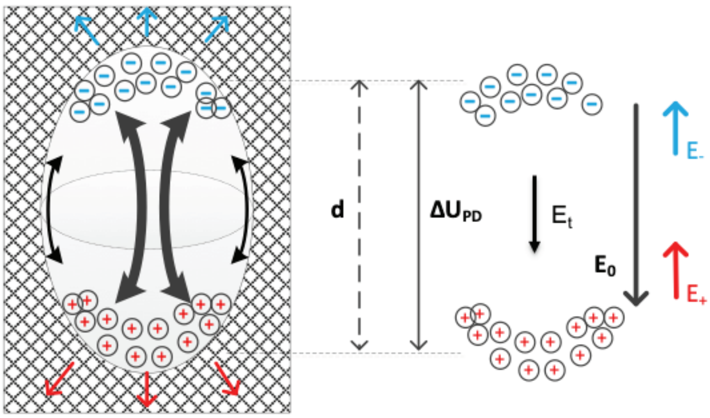


Figure 20 Illustration of charge distribution and E-field superposition in a cavity defect, E_0: externally applied E-field. E_+, E_-: charges induced fields, E_t: total E-field in the cavity.

Figure 21 shows a lab demonstrated example of PD variation in time. An air cavity within PE was stressed under a 107 Hz semi-square wave voltage, and the PD generated additional excess current (similar to the measure of tan delta tip-up), as well as PDs amplitudes were summed over a half cycle to demonstrate PD changes. As shown, for the first 10 000 seconds, PD activities gradually reduces to a stabilized charge movement: excess current. Thereafter, a more dynamic balance takes over: after every large PD followed by a slow excess current decay (neutralization). In another case, Figure 18, PD variations changes from occasionally large PDs to a non-detectable level, i.e., free charges generated by few large PDs are enough to suppress discharge activities for a long period of decay time. This phenomenon challenges the time and signal resolutions of the PD detection system as well as interoperation of the stochastic filed results. As can be seen from the measured results, Figure 18, PDs generated at number 2, 3 and 6 decays were missed by the detection system, this is likely due to dead processes time of the PD detection system.

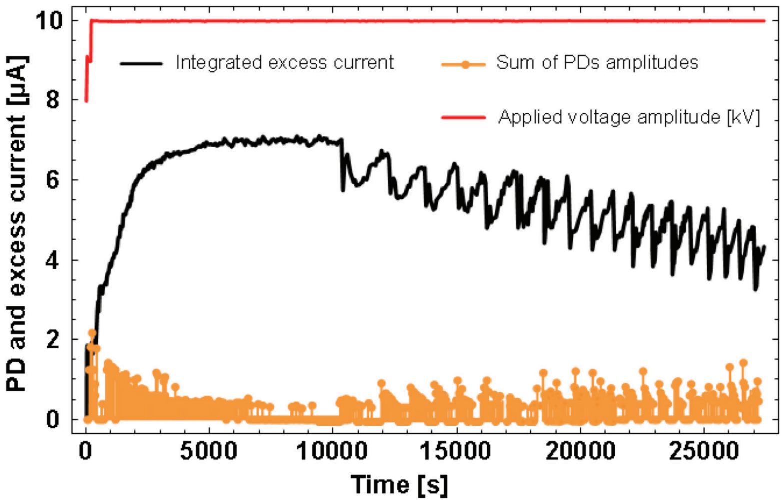


Figure 21 demonstration of Partial discharge variation in a PE cavity defect, applied voltage is a semi-square wave 107Hz, the integrated excess current can be seen as integration of loss factors (Tan delta tip up test) and sum of PDs amplitudes per half voltage cycle indicate the PD activity change in time.

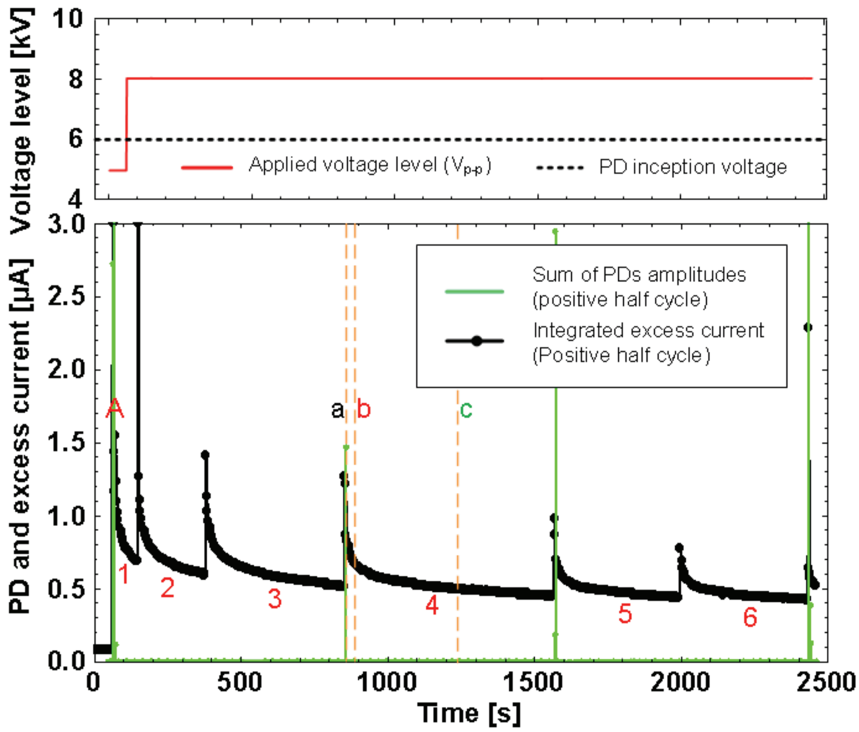


Figure 22 demonstration of partial discharge variation in a Polyamide cavity defect, the same test condition as used in Figure 17 test, but of different voltage level.

Classic PD detection relies on measuring of fast discharge current pulses via a parallel coupling capacitor to the test object. Figure 20 illustrates the principle circuit used in classic PD detection, where the fast discharges in test object C_x will induced apparent charge, q_a and coupled to the PD coupling capacitor C_k and the induced charge q_m, will be integrated and measured via a impedance Z_m. Here the PD signal strength is largely depended on capacitance of the test object and coupling capacitor as illustrated in the following equation.

$$\boldsymbol{q_m = q_a \frac{C_k}{C_k + C_x}}$$

In general, C_k is larger than C_x for a good signal strength. However, in case of field test of power cable, depending on cable length, C_x could be much larger than C_k, thus significantly limit the signal strength and measurement capability.

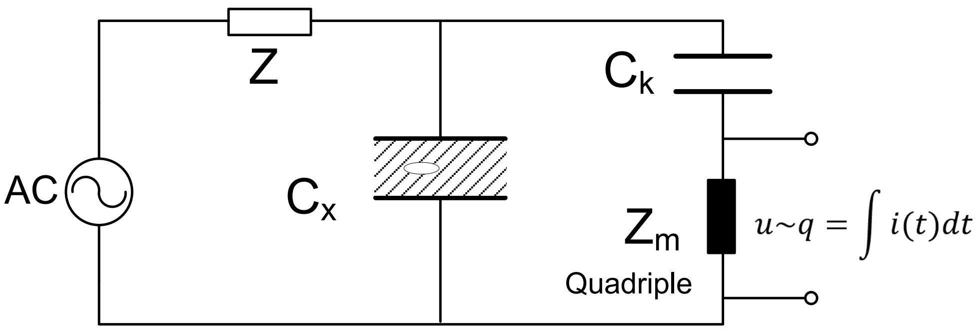


Figure 23 illustration of the classic PD detection circuit, discharges in C_x is measured via a coupling capacitor C_k.

Another challenge of on-site PD measurement is that most of the existing standards refers to the conventional IEC 60270 with assumption of a lumped capacitance test object, Figure 19. However, for cables with a length of a few km and number of joints, this is not a correct assumption. Major impact here is the signal attenuation and discharge coupling factor involved in apparent discharge interpretation. To overcome these filed challenges, so called, non-conventional PD detection techniques, including HF sensor and digital handling, were introduced to handle the complexity of filed cable system signal attenuation, dispersion, reflection, and losses of discharge signal.

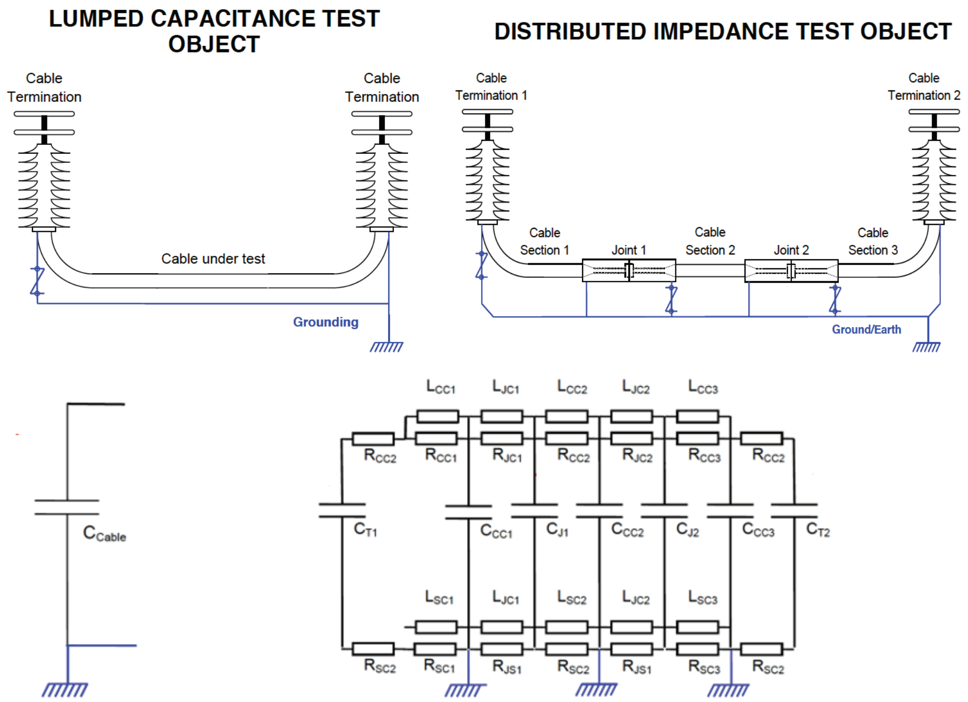


Figure 24 Comparison of lumped capacitance and distributed impedance test object used for apparent discharge interpretation in long cable PD detection, Cigre TB 728.

As a partial discharge detection is to measure of very fast charge movement, in nanoseconds, in other words, its induced very high frequency signals on power apparatus. Filtering out signals of the similar frequency but from different types of non-PD related noise sources is key. Typically, for a field measurement, the ambient noise environments vary from location to location and may also vary depending on the specific measurement environment (temperature, pressure, and humidity) is performed.

For on-line measurements, an additional issue exists: Separation of PD signals obtained from the cable under test from PD signals originating from connected power equipment (transformers, breakers etc.).

For these reasons, non-conventional on-site PD techniques were developed, which allows a wideband PD measurement with a higher frequency (1MHz or higher). To reduce the effect of attenuation for long cables with multiple joints, it is common to perform a distributed PD measurement to monitor all the accessories. In such setup, high frequency PD sensors such as HFCT, sheath sensor, differential field sensor, ultrasonic probe, or transient earth voltage (TEV) sensor were used.

Tools for improving the signal to noise ratio exist and are well known. They include front-end analogy noise filtering, gating (rejection) of ambient noise pulses. With fast development of digital technology in last decades, PD measuring instruments have become more sophisticated with the application of digital filter for reducing noises and improved high-frequency electronics, many utilities and testing service companies have added PD digital monitoring ‘on-the-fly’.

The onsite PD test is more popular for HV cables. However, some of the utilities have been doing PD testing for newly installed MV cables or service aged MV cables. IEEE 400.3-2006, which provides a guide for onsite PD testing of shielded power cables, is under revision and requirements of PD extinction voltage (PDEV) for different cable voltage class and cable accessories are expected to add. From PD memory effect perspective, PDEV is relatively more reliable and repeatable measure than PD inception voltage (PDIV), as cable with defects are likely to be dynamically charged after a certain period of voltage stress.

Regarding the test setup circuit, Cigre TB 728 provides clear illustration on different measurement circuit used in filed testing and elaborated more in following:

Single end PD measurement circuit, also known as classic PD measurement circuit, is illustrated in Figure 21. This test setup is often used for a short cable system, up to 2km, without any joint, where a lumped capacitance model can be used for coupling of the discharges. The results are reported in apparent charges in pC. PD signal attenuation along the cable is the major limitation for the sensitivity of such setup in the filed applications.

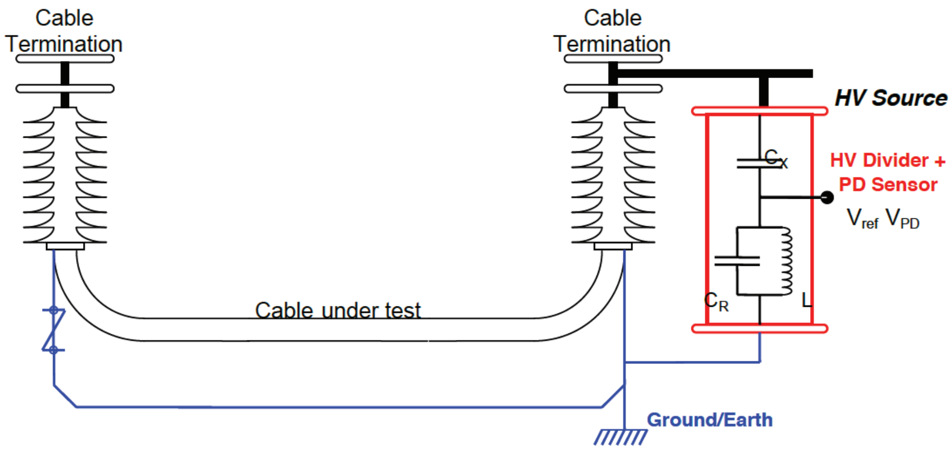


Figure 25 illustration of a single ended PD field measurement setup, Cigre TB 728

Double Ended Terminal PD Measurement: simply understanding is the system doubles the PD coupling circuit to the other end of the cable termination, Figure 22, to address the sensitivity of the measurement with respect to attenuation and loss of charges for induced propagating of PD pulses.

This measurement setup is typically used for cable systems with up to two joints. Typical cable lengths are less 2km measuring from each side of the PD sensor. The results are reported in apparent charges in pC. PD signal attenuation along the cable is also the major limitation for the sensitivity of the setup.

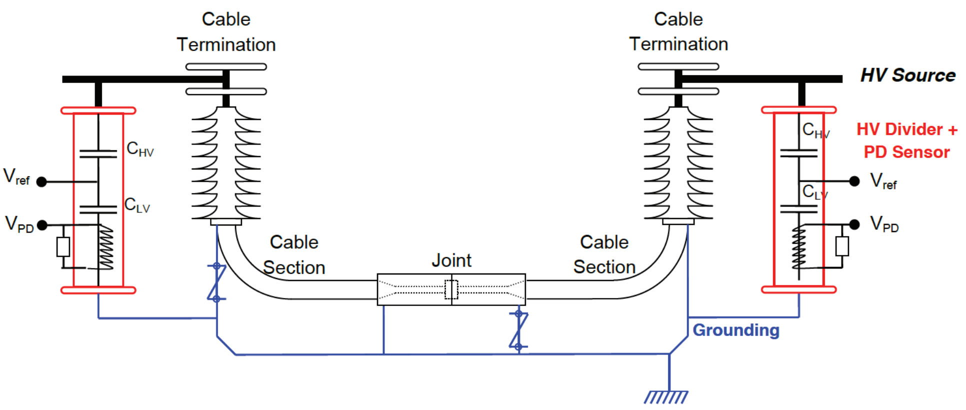


Figure 26 Illustration of a double ended PD field measurement setup, Cigre TB 728

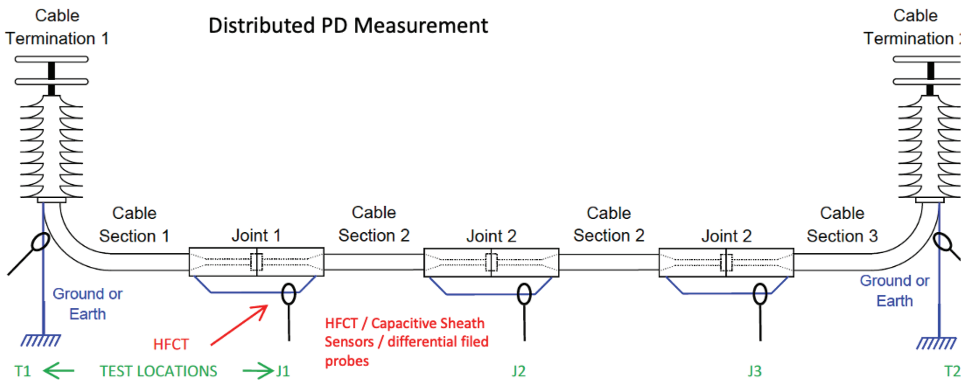


Figure 27 Distributed field PD measurement, Cigre TB 728

Distributed PD measurement, also known as periodic distributed measurement, is developed to measure PDs from long power cable via its accessible cable accessories, it is often measured during or right after AC withstand voltage testing. As illustrated in Figure 23, PD sensors (e.g., HFCTs, or Capacitive Sheath Sensors or Differential Field Probes) were used in all accessible cable accessories. Configuration of the bonding and/or grounding configuration of the cable requires special attestation during of sensor installation to ensure optimal PD signal coupling. Depending on used sensors, PD is measured as either in apparent charge or in mV voltage pulses. One should note that apparent charge measured on-site does not correlated the apparent charges known from a lumped test object in lab. In addition, PD activities are not always active when personals are present at the defect accessory, due to charge memory effect that elaborated in the earlier part.

Continuous Distributed PD Measurements, also known as synchronized PD Measurements, setup is shown in Figure 24. It is very similar to the distributed PD measurement setup, but all the installed sensors were communicated via either fiber optical cables or wireless communication system. This measurement system can provide continues PD monitoring with optimal coverage of the cable system, and no need of personal access to the accessories' manhole. The measured PD results is similar to the distributed field PD measurement system.

Limitation of the synchronized PD Measurement system is that all the sensors and communications need to be permanently installed at every cable accessory, often the communication devices has much less lifespan than the cable system, reliability and maintenance of the measurement devices is another cost and challenge for power grid companies.

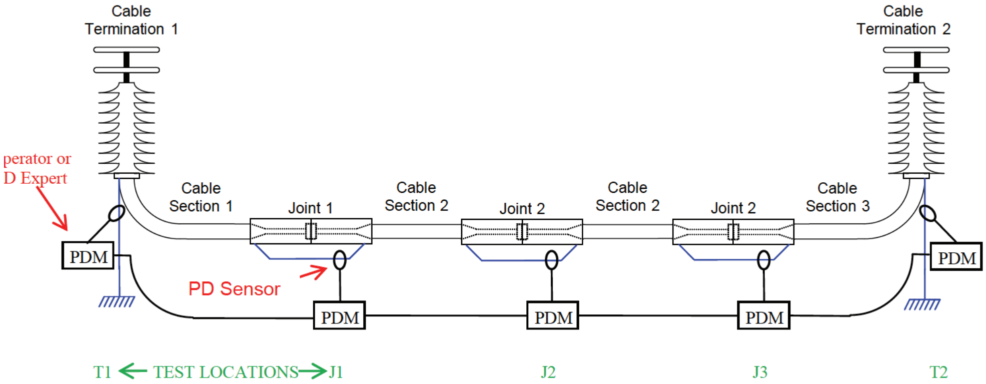


Figure 28 continues distributed PD measurement system, Cigre TB 728

Consideration of PD detection and monitoring function should be given in cable design and construction to building in PD sensors for future uses, both in fault investigations and for on-line monitoring.

Integrated HFCT PD sensors at cable terminations should be considered in new cable installation for providing a convenient means of monitoring, as well as differentiate the PD sources that possibly appear within the connected substation equipment, such as transformers, switchgear, surge arresters.

Experienced engineer on PD detection and interoperation is need at utility for the commissioning of new cables and diagnostics on cables that have been in service.

In the absence of standards for PD detection procedures in the field, it is important to follow a consistent and repeatable test procedure and the validation in all PD testing.

Monitoring of PD during commissioning tests should be performed. Absence of PD during voltage withstand test, measurement setups and procedures as well as background noise conditions need to be documented for later comparison.

Partial discharge testing voltage shape, amplitude and duration are important factors to be considered in the field test. As elaborated earlier, charge memory effect is likely to mask the PD activates both in its discharge amplitude and numbers for diagnostic. The ways to trigger large enough PDs for detecting the potential defect are either to increase the testing voltage amplitude or to keep the testing voltage duration long enough for allowing space charges to be dissipated/naturalized. Both parameters need to be balanced for not causing any damages to the insulation system at high stresses but be able to generate large enough PDs at defects for detection.

Power Frequency or Near Power Frequency PD

Alternating voltage at system frequency: This is the waveform generally used for factory and field testing of short cable systems. Due to the substantial capacitance of typical cable circuits, resonant test systems are generally applied (Variable Inductance Resonance Test Systems). For a given cable system (fixed capacitance), an inductor is tuned such the capacitive and inductive test currents cancel each out at 50/60Hz. There is full control of the applied voltage with a pure sine waveform, but the frequency is locked to system frequency.

On-line PD monitoring is a special case of system energized AC voltage PD test at the system frequency.

Alternating voltage with near power frequencies. For testing installed circuits at alternating voltage, a transportable resonant system is often used. The frequency span is specified by IEC standards and range from 20 Hz to 300 Hz, and when testing very long lengths of cables frequencies down to 10 Hz have been used. Research has shown that variation in test voltage ranges less than 8% from 20 Hz to 300 Hz.

An advantage for PD testing at near power frequencies is that any possible PD noise from adjacent HV components can be filtered by using phase resolved PD recognition technique.

Resonant voltage generation involves the combination of power electronic switches with a fixed-inductance resonant circuit. Both the frequency and the amplitude of the low voltage waveform injected into the resonant circuit can be adjusted. Main advantage of this voltage source is the reduced cost and size. This is now the dominant method of testing circuits in the field.

Regarding the testing AC voltage levels at power frequency or near power frequencies, to avoid any potential damages to the insulation system, IEC 62067 recommends for the electric stress in the cable or accessory should not exceeds a threshold limit of 27 kV/mm. With this background, Cigre TB 728-2018, the latest international guide for the onsite withstand & partial discharge assessment of HV cable systems, recommended testing voltage level, duration and PD acceptance level are listed in Table 2.

Table 2 recommend the testing voltage level, duration, and PD acceptance level for power cable maintenances

<table>
<tr><th rowspan="2">Voltage Class [kV]</th><th rowspan="2">Frequency Range [Hz]</th><th rowspan="2">Duration [min]</th><th colspan="2">5 Years* to 15 Years</th><th colspan="2">> 15 Years</th></tr>
<tr><th>Test Level [U₀]</th><th>PD Pass/Fail Criterion</th><th>Test Level [U₀]</th><th>PD Pass/Fail Criterion</th></tr>
<tr><td>66-72</td><td rowspan="8">10-300</td><td rowspan="8">60</td><td rowspan="2">1.5</td><td rowspan="8">No Detectable PD</td><td rowspan="8">1.1</td><td rowspan="8">No Detectable PD</td></tr>
<tr><td>110/115</td></tr>
<tr><td>132/138</td><td rowspan="6">1.4</td></tr>
<tr><td>150/160</td></tr>
<tr><td>220/230</td></tr>
<tr><td>275/285</td></tr>
<tr><td>345/400</td></tr>
<tr><td>500</td></tr>
</table>

Though the recommend acceptance criteria for on-site test are that there should be no detectable PD for giving test voltage levels, this is generally be limited by external noise on-site. Meanwhile, the interpretation of PD data still needs to be improved through the sharing and discussion of the collected PD data.

A new guideline for MV and HV cable onsite withstand and PD testing with power frequency or near power frequency resonance circuit is under development by IEEE 400 working group: "Constant Voltage AC Testing of Cable Systems (Resonant Testing)" and it is expected to be published in 2022.

VLF PD Partial discharge (PD)

To generate VLF test voltage, energy is injected into, and extracted from, the load capacitance cyclically by modulating the output of a direct voltage source. as the VLF voltage polarity shift is very different from the service frequency, so the PD phenomena which are the target of the measurement are different. As illustrated in Figure 15, two commonly utilized VLF voltage test waveforms have large difference in polarity shift time and can trigger PDs in different manners with involvement of space charges at the defects. Thus, measured VLF PD results may not be comparable to that at power frequency.

Though, recent study conducted by CIGRE, WG D1.48 found that the risk of space charge accumulation is very low, and the electric field distribution of VLF is like that at power frequency, this study mainly refereeing to the space charges that accumulated at solid dielectrics. The free charges that generated by PD at defects were not considered, and it is likely to be accumulated at voids filled with gas medium. As illustrated in Figure 16, these space charges have much shorter "lifetime" and higher mobility compared to that in solid dielectrics, and dynamically influence the PD activity.

PD test under VLF voltage also been reported in monitoring aging and degradation of paper-insulated cables. In these applications, time resolutions demand for such measuring system is relatively low, not be greater than 0.5s, as specified in IEC 60060-3. With such time resolution, detection of each individual PD pulses that might appeared at fast voltage change slopes, such as 0.1Hz cosine rectangular waveform slopes, is impossible. Such PD pulses might be able to be integrated and measured as Tangent delta tip-up test principle. However, long integration time and switching voltage interferences will minimize its application in practice.

PD test under VLF voltages can be considered as a supplement test during VLF withstand voltage test to provide more information regarding insulation defects. However, repeatability and reliability might be interference with accumulated charges at defects, i.e., the pre-conditioning of the cable system and measurement sequences might affect largely when taking PDIV readings. Here, PDEV might be a better alternative for a repeatable reading.

VLF voltage PD tests are more valuable if historical VLF voltage PD test data measured from the same procedures is available. Here relative changes are more valuable than the absolute numbers, any significant deviations in history can be considered as an early warning for a further study and scheduled maintenance.

Some additional major challenges for VLF voltage PD tests are external noises, these noises include PDs appeared at external cable surfaces, joints, accessories, corona discharges, as well as nearby switch components. Filtering out these noises not only requires high-resolution measurement systems for phase resolved PD results, but also, expertise for pattern recognition. In addition, aged/ corroded cable accessories, semiconducting layers, taped shields will all contribution to attenuation of PD signals and thus compromise the sensitivity of the system and accuracy of the results.

With VLF sinusoidal voltage waveforms, as change of the voltage polarity is very slow, charges that accumulated at the defects has enough time to move to the other side of the defect for suppressing the PD activates, the charges that even been loosely trapped at the cavity surfaces can be moved, resulting a lower level of PD activities.

However, when VLF cosine rectangular waveform with a much faster polarity shift is used. At the polarity reversal, those loose surface trapped charges are more difficult to be moved, but rather neutralized with space charges that are accumulated in the gas medium. Consequently, significant reduction of the space charges within the defect and a higher level of PD activities, compared to the tests under sinusoidal voltages.

Based on filed experiences, Cigre TB 728 suggests the voltage levels for VLF PD tests, Table 3. Please note that the suggest PD testing voltage level is lower than that used for voltage withstand tests, often 2-3 U0. Common practice is that voltage withstand tests is performed in parallel with the PD tests. For cables with voltage class higher than 220 V, there are not sufficient experiences on VLF voltage PD tests, thus, not specified in the table.

Table 3 recommend the testing voltage level and duration for power cable commissioning PD test with VLF voltage, acceptance criteria been no detectable PD.

Voltage Class [kV]	Test Level [U_0]	Frequency Range [Hz]	Duration [min]
66-72	≥1.9	0.05 – 0.1	Appropriate Minimum Time is Unknown ≥ 60* min for 0.1 Hz It is possible that this time might need to be increased if frequencies approach 0.05 Hz
110/115	≥ 1.9		
132/138	≥ 1.7		
150/160	≥ 1.7		

* The recommended minimum testing time for commissioning test on new cable is 60 min, the same as the VLF voltage withstand tests, testing time might need to increase for allowing enough voltage flanks to be accounted at the reduced test frequencies.

The rate of electric treeing at VLF voltage is lower than power frequency primarily due to the lower number of partial discharges per time unit and reduced voltage drop across voids and electrical tree channels. On the other hand, using cosine rectangular VLF, it is possible to perform PD testing during the period of polarity reversal. The PD parameters, such as partial discharge inception voltage (PDIV) and PD magnitudes measured during the period of polarity reversal, are expected to be comparable to that at power frequency.

Damped AC PD

The Damped AC (DAC) test set uses a high voltage DC source to charge up the cable circuit under test to a specified voltage and excites a damped oscillation at the natural resonant frequency (10 Hz to 500 Hz) of the often-fixed inductance of the test instrument and the capacitance of the cable under test. The damped oscillation usually has a duration of hundreds of milli-seconds, providing an alternating voltage at which partial discharge measurements can be made. The damped nature of the voltage waveform making specification of test duration and voltage exposure challenging. Though, the appropriate number of shots of damped AC required to initiate detectable PD in solid dielectric defects is unknown. IEEE and Cigre working groups suggest the number of shots at each voltage level is minimum 50, and the test levels for new cable systems (peak voltage to ground) is suggested in Table 4.

Table 4 recommend the testing voltage level and duration for power cable commissioning PD test with damped AC voltage, acceptance criteria been no detectable PD. By Cigre TB 728.

Voltage Class [kV]	Test Level $[U_0]$	Frequency Range [Hz]	Duration [min]
66-72	≥1.9	10-500	Appropriate Minimum Number of Shots is Unknown ≥ 50*
110/115	≥ 1.9		
132/138	≥ 1.7		
150/160	≥ 1.7		

Damped AC withstand and PD test is not very popular all over the world other than Europe, thus limited data available for comparing the PD characteristics (magnitudes, inception, extinction, etc.) between the power frequency and DAC tests.

The appropriate initial voltage test level to initiate PD in life limiting defects within solid dielectric cable systems are largely unknown. Risk of initiating electric trees during testing and the electrical tree initiation and growth dynamics are largely unknown for repetitive applications of damped oscillating waveforms.

An advantage of using the damped AC test is that both the PD inception (PDIV) and extinction voltages (PDEV) can be measured during any shot if PD appears.

The non-constant nature of the applied test voltage provides the possibility for previously PD generated free charges to be dissipated or naturalized more easily. Thereby likely to generate more and larger PDs for detection.

5.2.4 Frequency domain tests

Frequency domain spectroscopy (FDS) has been used for more than 30 years for diagnostics of power cables, specially PILC cables. For oil-filled cables, there is a direct relation between the moisture content in paper insulation and FDS curve behavior.

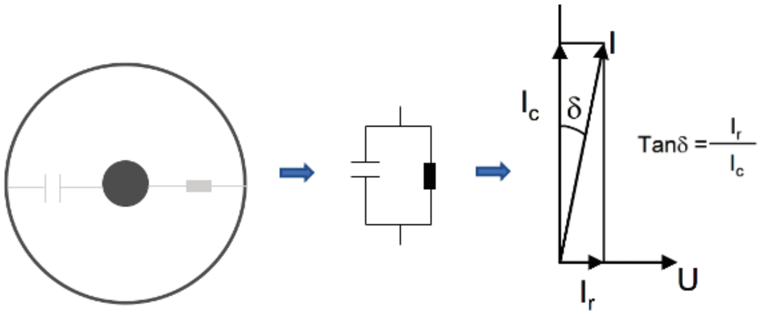


Figure 29 principle of loss factor (tan Delta) calculated form a simple circuit model, losses is represented by a resistor.

Figure 29 shows the principle of frequency domain spectroscopy measurement, the change of a phase shift between the complex voltage and current other than 90-degree angles is measured as tan delta, or loss factor. Which is used to determine health condition of the cable. Figure 29 illustrates a muster curve of tan delta measured from oil-paper samples, it is indicating how moisture, oil conductivity and temperature will influence the measured FDS data. With these lab experimental databases, measured field data can thus be compared and use as diagnostic indicator for oil-paper cable health evaluation.

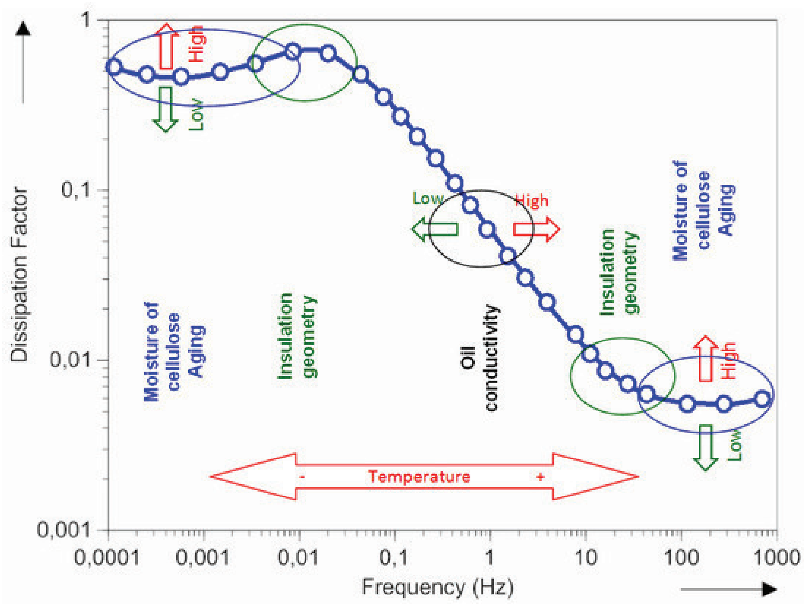


Figure 30 illustration of different properties influence on the master curve of tangent delta as function of frequency, abstracted from the lab measured oil-paper samples [11].

The preferred method for measuring the moisture in cellulose is FDS. FDS test technique has also been applied to polymeric cables. Unlike oil-filled equipment, loss factors found in solid polymeric insulation system are often ten times lower or more. To reach measurable losses level, high voltage variable frequency source with high reactive power capacity is needed to generate output voltage equal or higher than the rated voltage in a wide frequency range (0.001 Hz to 1 kHz). This requires a huge and expensive power supply, which makes the field application nearly impossible to test several kilometers cable system at the power frequency. Moreover, loss factor generally increases as frequency decreases, which easy the measurement sensitivity requirement. The change of the loss factor as functional of the frequency is result of rather complex material responses and environmental parameters, including temperature, moisture, aging processes, interface properties, discharge activates, space charge dynamics and so on. Therefore, correlation between the loss factor at given frequencies and different cable dielectric aging statutes remains unclear. Nevertheless, some studies show promising results utilizing FDS to indicate the extent of the water treeing effect as well as thermal aging of XLPE cables and moisture ingress in oil-filled cables, at test voltage levels equal to or lower than the rated voltage. IEEE guide C57.161-2018 for power transformers diagnostics is a good reference for using DFS in power cable diagnostics of short cables or accessories, so far, there is no standard guide for FDS testing of field cables.

Power frequency Tan δ measurement

The tan δ can be measured at power frequency with voltage level of U_0, the cable shall be heated by the rated current flow until the conductor reaches a stable operational temperature, The measured absolute value shall not exceed the value given in Table 5, for the newly installed cable system of different insulation dielectrics. This measurement can be performed both on-line and off-line. With historical data measured at the same temperature, these results can be used for cable dielectric monitoring and provides value information on cable insulation aging development. However, as the applied voltage level is often limited to the rated/operation voltage level, thus not possible to perform tan δ tip-up tests for checking linearity of dielectric response. The alternative solution is to perform *tan δ* measurements at VLF voltages of different amplitudes, where linearity of the *tan δ* as function of test voltage level can be evaluated and used for insulation aging diagnostics.

Table 5 - maximum tan *δ* level for newly installed cables of different main insulation dielectric, based on IEC and IEEE recommendations

main insualtion dielectrics		PE	HDPE	EPR/HEPR	XLPE
Maximum tan delta	10^{-4}	10	10	50	10*

* Special XLPE cables with additives, may increases the reference level to 50×10^{-4}.

Very Low Frequency tan δ tests

Very Low Frequency *tan δ* tests are the most applied methods in the field for service aged cables diagnostics, likely due to low power demand on voltage source and higher measurable loss factor level at very low frequency range (0.1Hz-1Hz) [12].

At VLF responses, Tangent delta is mainly determined by dipole moments (water content), trapped charges amount and electrical conduction of insulation system. With increasing of tangent delta and its non-linearity as function of voltage stresses, degradations of the cable insulation (water-trees), corroding metallic shields, insulation moisture, and degraded accessories can be correlated. Cable systems can be tested in preventive maintenance programs and returned to service after testing. However, absolute loss factor value varies largely among different dielectric systems. In general, the relative test results and comparing with the historical data, permit to distinguish among new, defective, and highly degraded cable systems. Results can be used to make decisions on cable/accessory replacement, and cable rejuvenation or repair.

One should notice, tangent delta measurement only gives the average value of the dielectric loss for the whole measured cable system. To overcome this deviation, the loss factor results can be compared as function of physical characteristics, such as cable length and number of joints in the circuit, and analysis the data in log-log scale for a better interpretation.

In addition, data from VLF might not be comparable with the power frequency results, especially for the cables with defects of large delamination layers filled with gas medium, as accumulate space charge movement will not be reflected in VLF test results.

In addition, absolute loss factor value of polymeric dielectrics is often much lower compared to oil-paper system, results are thus more sensitive to following interferences and need to be handled accordingly. Therefore, it is good field diagnostics practice to ensure that the cable terminations are clean and in a good condition prior to the test.

Temperature variations: loss factor is sensitive to temperature in cable. As such testing requires cable to be taken out of service, temperature variations are likely to be appear right after a loaded cable, and very difficult to control. To minimize such interferences, multiple measurements under different temperatures can be a good approach for later interoperation of the loss factor at a desired reference temperature.

Connected accessories and cable circuit: cables are likely to be connected to different accessories, such as cable splices, terminations, as well as system circuits: like circuit breaker and switches, might not be able to remove, additional guard circuit or short circuit of such components will largely remove the losses, otherwise to be averaged into the results.

Contact impedance is another error source that might be largely forgotten, as copper conductor are likely to be oxidized and form contact resistances and loose connections to the test leads.

IEC 60060-3 suggests that the measurement of VLF-TD requires the peak level of the test voltage should within ±5%, and with symmetrical polarity. The response time of the measuring system should be shorter than 0.5 s.

IEEE Std. 400-2.2013, provides recommended test voltages, test times, and withstand hold times for different types of cables for VLF tan δ tests. In addition, different used calculation methods and testing procedures, including tangent delta (VLF-TD), differential tangent delta (VLF-DTD), and Tangent delta stability (VLF-TDTS) measurements have been addressed to provide indication factors for cable diagnostics. In the standard, description of VLF-TDTS is not very clear and mixed at different testing voltage levels. Here we will try to discuss in more detail as following:

The tangent delta TD: VLF-TD is the single tan δ value that been measured at given a voltage stress. It is often measured at three different voltage levels 0.5 U_0, U_0, and 1.5 U_0 and following parameter can be calculated accordingly.

Differential tangent delta: VLF-DTD = TD(@1.5 U_0) - TD(@U_0). Can be seen as tip-up test in cable diagnostic.

Tangent delta stability, VLF-TDTS is a measure of stability of loss factors under the same test conditions over time. It is obtained by number of VLF-TD measurements (minimum 6 single measurements at interval of 10s in between two 0.1 Hz measurements) over a period of few minutes.

$$VLFTDTS = \sqrt{\frac{\sum(TD - \overline{TD})^2}{n-1}}$$

The specific tests voltage for VLF-TDTS is not clearly specified in the standard, however, for practical reasons, measurements at voltages of 0.5U_0, U_0, and 1.5U_0 are recommended for a more comprehensive evaluation. For testing at 1.5U_0, with any defect partial discharge sources, VLF-TDTS is likely to increase. This is due to stochastic nature of PD activities resulting from space charge dynamics combined with external voltage variations.

In general, Tangent delta measures an overall dielectric loss of the cable system. Cable's loss factor is mainly influenced by the condition (age, contamination, and moisture ingress) of the various cable components (body, shield, accessories) that within the cable system and even the other grids components that connected to the cable. Therefore, any single region of high loss such as a region of severe water treeing, degraded accessory, area of high moisture or different cable insulation can cause the measured value to rise even though the bulk loss of most of the system will be lower. The measured value will be less than the actual loss of the high loss region. A comparison of results between different phases of the same segment or sequential section will help identify. In this case, if any abnormal value is detected following actions can be taken in practice.

- If possible, divide cable system into sub-parts, inspect and replace any suspect accessories, redo the measurements
- Compare the results from different phases/cables
- Carry out additional test, such as partial discharge, withstand voltage tests to localize potential defects, replace/repair, then redo the tests
- If possible, add the guarding circuit at the termination.

After clearing out any external uncertainties, measured parameters can be used to determine three maintenance actions: no action needed, further study needed, and action required. Table 6 gives the assessment criteria for shield cable systems of different dielectric system: PILC, EPR, and PE based cables.

Table 6 shield cables assessment criteria based on VLF tan δ test, summarized from IEEE 400.2

Cable assessment criteria for VLF - tan δ test					
Condition	VLF-TD tan δ at $U0$; (10^-3)		VLF-TDTS tan δ stability at $U0$; (10^-3)		VLF-DTD (tan δ at 1.5$U0$ - tan δ at 0.5$U0$); (10^-3)
	PILC				
No action needed	< 90	&	< 0,1	&	-35 to 10
Further investigation	90 to 200	or	0,1 to 0,4	or	-50 to -34 or 10 to 100
Action needed	> 200	or	> 0,4	or	<-50 or > 100
	EPR				
No action needed	< 40	&	<0,35	&	< 40
Further investigation	40 to 125	or	0,35 to 1,5	or	40 to 125
Action needed	> 125	or	> 1,5	or	>125
	PE				
No action needed	< 4	&	<0,05	&	< 5
Further investigation	4 to 50	or	0,05 to 0,5	or	5 to 80
Action needed	>50	or	> 0,5	or	> 80

As tangent delta measures average value of the dielectric losses of the system, the length of the cable will influence the resolution of the diagnostic. As a high losses local defect can be measured as low losses for testing on a long cable where the reset of the system has low losses. Practical solution is to compare the data with cable length and number of accessories and plot the data in log-log for tangent delta as function of cable length. Based on the slope of the plot Table 7 provides interpretation of possible causes.

Table 7 slopes interpretation of the tangent delta vs. cable length plot. IEEE 400.2.

Slope of tan δ and cable length	Possible causes
Flat (indepedent from length)	uniform losses for the whole system
Radom, up and down	no clear pattern, possible due to interface polarizaiton at shield and lossy accessories
Positive slop	Corrosion of the metallic shield or poor interfaces between the shield and the insulation. Isolated lossy accessories.
Negative slop	local high loss parts such as lossy accessories or water tree regions within a long and low loss cable

Broadband Impedance Spectroscopy

Cable's broadband impedance spectroscopy (BIS), also known as line resonance analysis (LIRA) is essentially based on frequency domain reflectometry. Often low voltage (3V to 5V) signals are injected to a cable system over a range of frequencies up to hundreds of MHz. The complex input impedance of the cable is then measured by both input and reflected signals in amplitude and phase at different resonance frequencies. The similarity for this test is the power transformers sweep frequency response analysis (SFRA) or dielectric frequency domain spectroscopy

(FDS) test, but of different frequency ranges. Where SFRA and FDS often measured between 0.1mHz up to 1kHz. Theoretically, BIS technique can be applied to all LV, MV, and HV cables. This method is relatively new and needs additional work to verify its associated claims e.g., in terms of the ability to detect high ohmic defects such as insulation material oxidation, moisture ingress, and the influence of external noise, especially for long cables with low voltage test signals and its attenuation issues. In addition, a common technical barrier is lacking experience personal to interoperate the measured results and practical handing of on-site interferences.

Based on the manufacturer's claim and its working principle, BIS has greater advantages over TDR, including higher signal strength and less influenced by noise, therefore more sensitive and accurate, greater possibility to focus on blind zone spots at the near end and measure on long cables, and global aging assessment. Figure 31 illustrates the signal strength different between BIS and TDR measurements. In BIS, test signal is injected either by frequency sweep or a repeated chirp signal, the source of signal strength is kept at the same level over the spectrum, whereas in TDR test, only one or few signal pulses of the same frequency content been used, thus the signal strength over the spectrum is depending on its harmonic's strength. Figure 32 illustrates the difference between BIS and TRD techniques in detection and localization cable defect. The same detect cable were measured by both techniques, where BIS provides a much clear signal indication in detection defect that related to impedance changes, however, due to aliasing effect in data sampling process, high order of harmonic signals are aliased with low frequency spectrum resulting large shielded area as illustrated in BIS results, Figure 32, consequently, both detected distance window and shielded spectrum reduces the time resolution and measurement range for using BIS techniques.

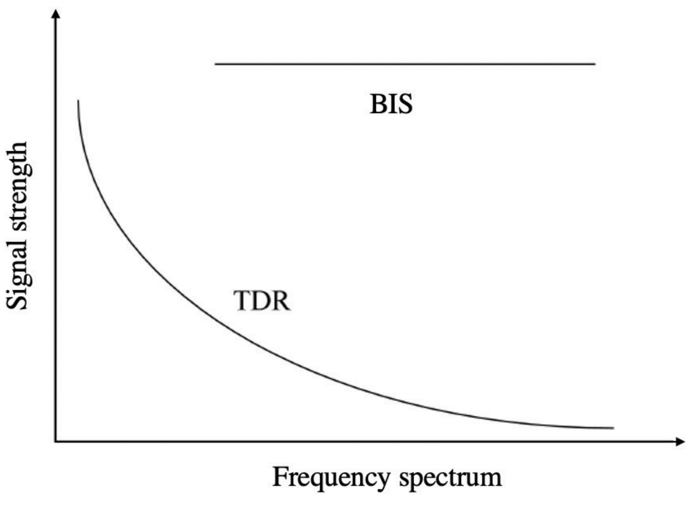


Figure 31 illustration of signal strength comparison between BIS and TDR measurements.

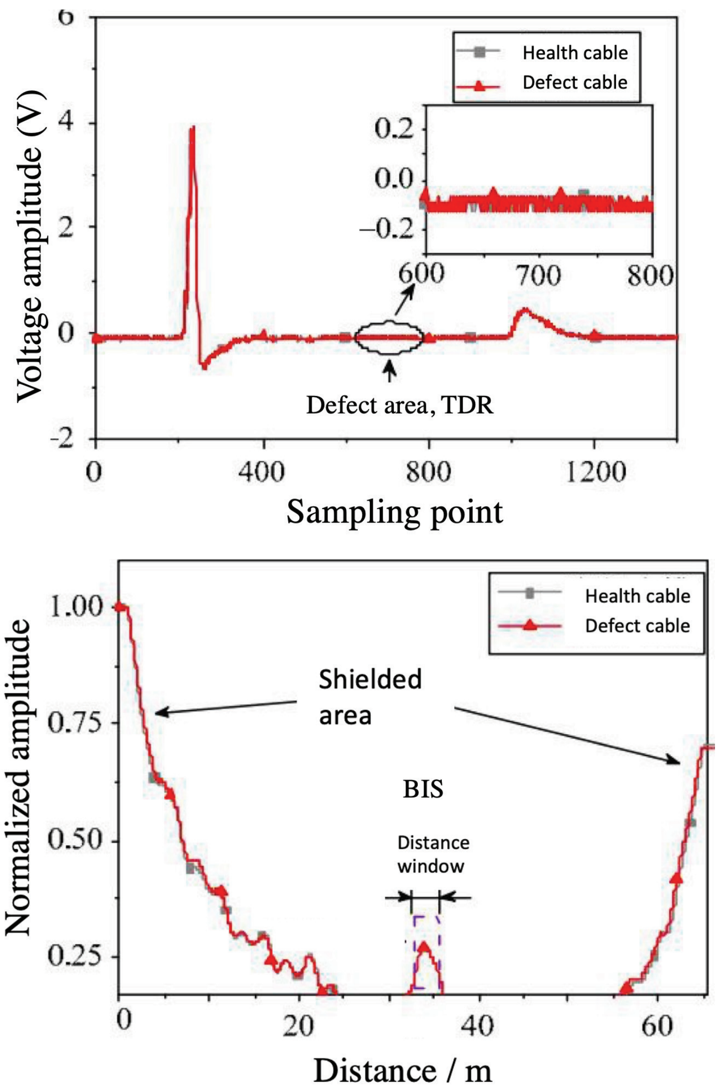


Figure 32 comparison of cable defect detection and localization by using TDR and BIS measurements[13].

Though, BIS still has some technical difficulties in the complicated field application, number of signal processing techniques has been implemented to facilities and improve the signal resolutions for minor defect detections as well as more precision defect localization. These techniques including fast Fourier transform of input impedance phase spectrum for detecting small defects with low impedance changes, averaging of multiple impulse response as function of time to provides more precision localization of impedance discontinuity comparing to TDR.

5.2.5 Time-domain tests

Like frequency domain spectroscopy, number of time-domain spectroscopy (TDS) based diagnostic methods have been developed more than 3 decades ago and becomes more popular in applications of polymeric insulated cable diagnostics [14]. This is likely due to very low losses in polymeric dielectrics and a higher relative sensitive of the TDS methods in measuring DC responses.

The basic principle of time domain measurements realis on measurement of total current flow within the insulation system after been exposed to a DC stress. Figure 33 illustrates that this total current can be simply classified into three main parts: capacitive current, conductive current and absorption current.

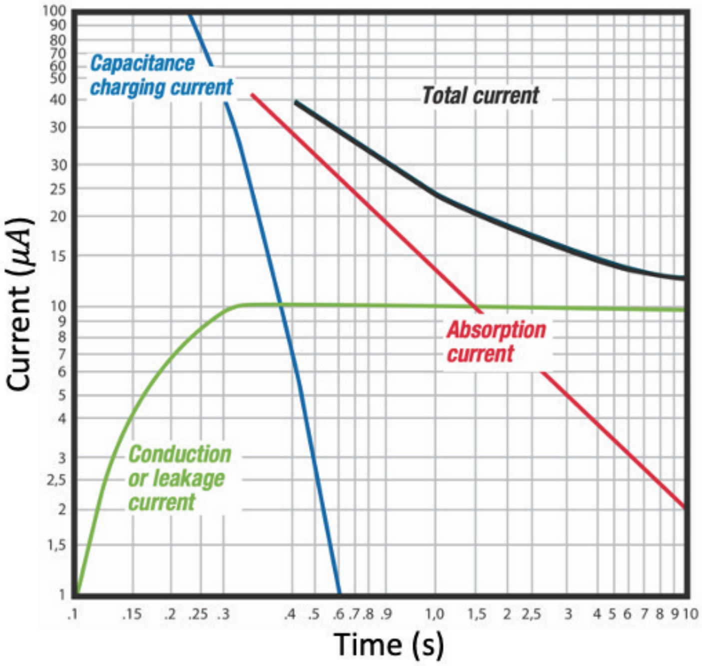


Figure 33. illustration of three main current contributions within the insulation system after been exposed to a DC stress [15].

Capacitive current is the charging currents that charges the capacitance of the insulation system under the test, often it measures the charges at two interface layers separated by the dielectrics. This is a transient current which starts at relatively high level then exponentially decay to a negligible level.

Conductive current is also known as leakage current. It is a measure of insulation capability and stable over time at a given condition. This current includes the bulk and surface leakage currents as well as any partial discharge induced current flow. The stable time is largely depending on material properties and space charge dynamics.

Absorption current: the current that responsible for the charge redistribution within the dielectrics structure as well as reorient dielectrics molecules under the external applied field. The motion of the charges or charge carriers causes a change in the image charge on external electrodes to be measured. This current decays slower than the capacitance current, often requiring several minutes or even longer period to reach to a negligible level.

Polarization Depolarization Current (PDC)

By applying a relatively low DC voltage, typical range of 1 to 5kV, for a period of 5 to 30 minutes to charge the cable under test and discharge it in the same amount of time through a resistor, both polarization and depolarization currents are then recorded and analyzed in the time domain to evaluate the overall degradation of cable systems in the field. Figure 34 shows the principle of PDC measurement in applied voltage and measured current. PDC measurement identifies conduction and polarization effects in the insulation.

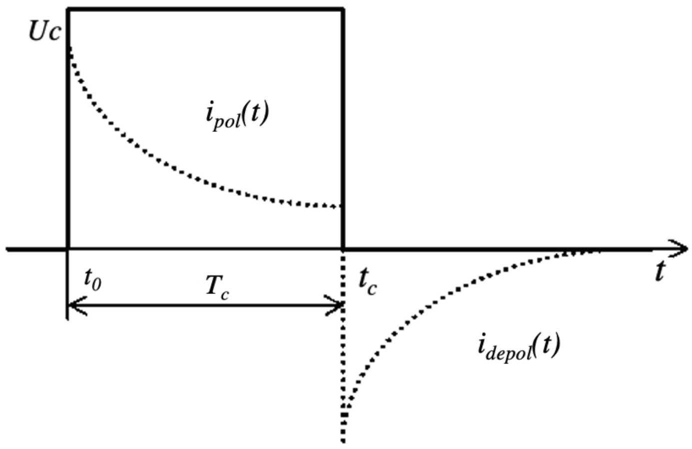


Figure 34 principle of polarization depolarization current measurement.

The measured total charge current consists of the capacitive current, which decays relatively faster after the voltage reaches the steady state; the absorption current, which decreases more slowly with time; and the conductive/leakage current, which is due to the resistance of the insulation system often takes much longer time to stabilize.

The discharge current consists of capacitive current decay, which quickly decreases in time. The depolarization current results from the relaxation of the polarization process after removing voltage stress. This process is strongly influenced by the degradation of the insulation. Polarization and depolarization currents can thus be used to evaluate insulation degradation.

Absorption current is one important current contribution that PDC measurement is looking for, as an increase in the absorption current are often resulting from various defects including interfacial polarization and the presence of by-products from PD, oxidation, and thermal degradations [16].

On the other hand, the formation of voids in extruded cables can cause a reduction in the measurable absorption current due to induced space charge dynamics. Since the current measurement is in the range of nano-amp or pico-amp, reproducibility and noise suppression are critical issues for field measurement. The interpretation of the results could be complicated. This technique is sensitive to water tree degradations; however, more onsite testing and validation is needed to accept this technique for practical diagnostics.

PDC has been used in diagnostic and evaluate water tree and thermal degradation in polymeric cables.

During the commissioning, it is possible to measure the resistance of both the main conductor and the metallic shield (including the splice). However, it is a challenge to measure the metallic shield of a service aged cable unless one side of the grounded shield crimp is open or disconnected from the ground.

Different data analysis methods are available for cable diagnostics: apparent insulation conductivity, polarization index, polarization current and depolarization current, or a combination of polarization and depolarization currents.

The following different analyses have been used to interpret the results of such tests to assess the cable system degradation:

- Normalized dielectric discharge (DD): polarization current measured at 1-minute voltage stress, divided by the total capacitance of the measured cable as well as applied testing voltage, the dielectric discharge is normalized from the cable's geometry factor as well as voltage stress, which facilitates relative comparison among cables of different dimensions.

$$DD = \frac{I_{pol,1min}}{U\ C_0}$$

DD	Condition
>7	bad
4 to 7	poor
2 to 4	moderate
<2	good

- Polarization index (PI): it is the ratio of insulation resistance measured at 10 minutes divided by the value measured at 1 minute. Other time ratios can be used. The index should be higher or close to unity. An index of less than one would indicate an abnormal condition.

$$PI = \frac{R_{10min}}{R_{1min}} = \frac{I_{1min}}{I_{10min}}$$

PI	Insualtion Condition
<2	aged
2 to 4	good
>4	excellent

- Dielectric absorption ratio (DAR): is the ratio of the measured insulation resistance at 1 minute divided by that measured at 30 seconds. This ratio is often used when the measured leakage current stabilizes within 1 minute. As if this happens, the 10 minutes polarization index (PI) becomes close to 1 and useless.

$$DAR = \frac{R_{60s}}{R_{30s}} = \frac{I_{30s}}{I_{60s}}$$

DAR	Insualtion Condition
<1.25	insufficient
<1.6	moderate
>1.6	good

- Non-linearity factor NLF: Comparing the non-linearity of two depolarization currents measured after two voltages (U0 and 2U0) stressed for a certain period (100s for example). For a linear cable, this factor should be close to two. And aged cables have ratios of currents greater than two.

$$NLF = \frac{I_{dp\ 100s\ 2U_0}}{I_{dp\ 100s\ U_0}}$$

Comparing the total polarization current per unit length of new and aged cables. This method demonstrates a good indication of paper-oil insulated cables aging [17].

- Apparent insulation conductivity σ_{app}: is calculated from difference of polarization and depolarization currents that measured after the same period (Typically 10 minutes). With consideration of geometry factor by dividing the cable capacitance, the obtained apparent insulation conductivity can be used for across comparison among cables of different dimensions [18].

$$\sigma_{\mathrm{app}} = \frac{\varepsilon_0(\mathrm{ave}(i_{\mathrm{p}}) - \mathrm{ave}(i'_{\mathrm{dp}}))}{U_0 C_0}$$

- Degree of nonlinearity factor (DONL) [19]: is used to estimate the cable insulation's nonlinearity factor from a short-time PDC measurement. It is the ratio between the measured depolarization current after 20 s at 5kV and 1 kV respectively:

$$\mathrm{DONL}_{I_{\mathrm{dp}}} = \frac{I_{\mathrm{dp}}(u,\ t)\big|_{u=5\,\mathrm{kV},\ t=20s}}{5 \cdot I_{\mathrm{dp}}(u,\ t)\big|_{u=1\,\mathrm{kV},\ t=20s}}$$

DONL is often combined with apparent insulation conductivity to evaluate cable insulation conditions in general, evaluation criteria shown in following table.

σ_{app} & DONL	Cable insulation condition
$\sigma_{app} < 10\times10^{-16}$, DONL = 1	cable in good condition
$100\times10^{-16} < \sigma_{app} < 1000\times10^{-16}$, DONL =1	widespread degradation in the cable insulation
$\sigma_{app} < 10\times10^{-16}$, DONL > 1.2	cable have good insulation but poor joints insulation
$\sigma_{app} > 10\times10^{-16}$, DONL > 1.2	cable in bad insulation conditions

Moreover, if water tree is suspected to be the major issue in the cable under the test, Apparent insulation conductivity σ_{app} and degree of nonlinearity factor DONL can further be used for evaluating water tree degradation. Following 4 different assessment criteria can be used as reference for water tree degradation in the polymeric insulated cables [20].

σ_{app} & DONL	Insulation water tree condition
$\sigma_{app} < 10\times10^{-16}$ and DONL < 1.2	good, no water tree
$\sigma_{app} > 10\times10^{-16}$ and 1.2 < DONL < 2	likely have water tree problem
$\sigma_{app} < 10\times10^{-16}$ and 1.2 < DONL < 2	high water tree density but not bridges the insulation
DONL > 5 at 5kV test	cable poorly installed or having degraded joints

– Isothermal Relaxation Current analysis, ICR analysis is achieved by separating three relaxation charges from the depolarization current integration over time [21]. As illustrated in Figure 35, relaxation charges are identified with an assumed model that considers three exponential currents of different time constant and contributed from: 1. cable main insulation, Q_1, 2. current coming from the semi-conductive layer Q_2, and 3. current associated with insulation defects Q_3.

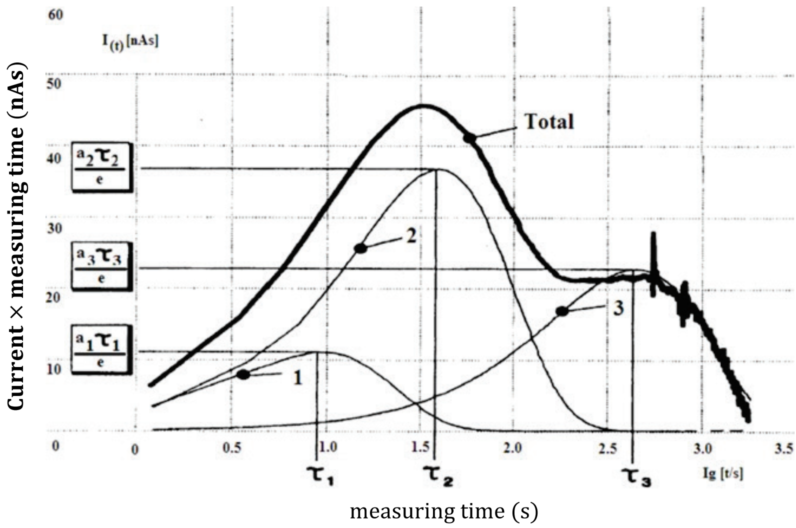


Figure 35 separation of current contributions of polarization current by interoperation approximation, 1. Cable main insulation contribution Q_1, 2. Semiconductive layer contribution Q_2 and 3. Insulation defects contributions Q_3.

The aging factor IRC-A is then calculated by the peak value of two identified relaxation charges contributions from insulation defects and semiconductive layers. Aging factor IRC-A has a strong correlation to aging classes, Table 8 provides an example of different power cable aging classes in relation to the IRC-A aging factors.

$$ICRA = \frac{Q_3}{Q_2}$$

Table 8 power cable aging classes in relation to the IRC aging factor.

IRCA	Cable insulation condition
IRCA< 1.75	Good
$1.75 < IRCA < 1.90$	Moderate
$1.90 < IRCA < 2.10$	Aged
$IRCA > 2.10$	Critical

Diagnostic criteria of PDC measurement could indicate the quality level of the cables by as "healthy," "aged" or "severely aged" based on the magnitude of these factors. These PDC measurement-based factors largely depend on the materials aging statutes as well as on the statistical nature of the local defects in a cable, therefore, is difficult to build a definite and clear correlation between failure voltage and these factors, apart from giving tendencies of cable insulation health condition.

Though, number of indicators can be obtained from PDC measurements of different procedure and voltage levels. Fundamental of PDC based diagnostic principles remains same. It is either based on absolute or relative value of the insulation conductivity over time or depending on its voltage depend non-linearity conductivity. In general, PDC measurements can provide relative evaluation of the overall cable insulation system, but specific insulation detects, and their localization remain to be solved with combined other diagnostic methods. Following summarized advantages and disadvantages for PDC based methods in cable diagnostic applications.

PDC advantages:

It is a relevant indicator for the overall condition assessment

It is generally sensitive to low impedance defects

- such as contaminated terminations, some improperly installed accessories, and overheating.
- It is a sensitive method for diagnosing water tree degradation in PE cable.

It is more effective with relative comparisons:

- Cross-comparison among different phases and backup cables of the similar configurations.
- Periodically comparison with historical testing data provides more details in degradation trend and sudden detection of non-linear behavior indicates a high risk of failure.

Diagnostics can be made at low voltages (<U_0).

- Measuring of non-linear insulation conductivity can be made at lower voltage levels.

PDC disadvantages:

- Low measurable currents signals are largely affected by the high noise testing environment.
- Assessment criteria and calculation methods are not standardized.
- Cables need to be energized and stabilized prior to measurement for a repeatable and comparable results.
- Cable needs to be properly discharged after each test to avoid potential charge accumulation caused degradation risk.

Recovery Voltage Measurement (RVM)

The RVM test was originated for power transformer testing in the 1990s and gained some popularity around the 2000s for oil-paper insulated cables but experienced a decline in the 2010s. Limited experiments show that the RVM can be used for oil-filled single insulation system cables, but not in application of XLPE cables nor hybrid insulation systems.

RVM is a method where the cable circuit is charged using a DC voltage for a given time. This concept is based on applying DC voltage until a short circuit condition is produced and measuring the open-circuit voltage. The circuit is usually charged for 15 minutes, with voltages ranging from 1 to 2 kV. The charged circuit then discharges through a ground resistor within a short period of time (5 seconds). The open-circuit voltage is recorded versus time during the test.

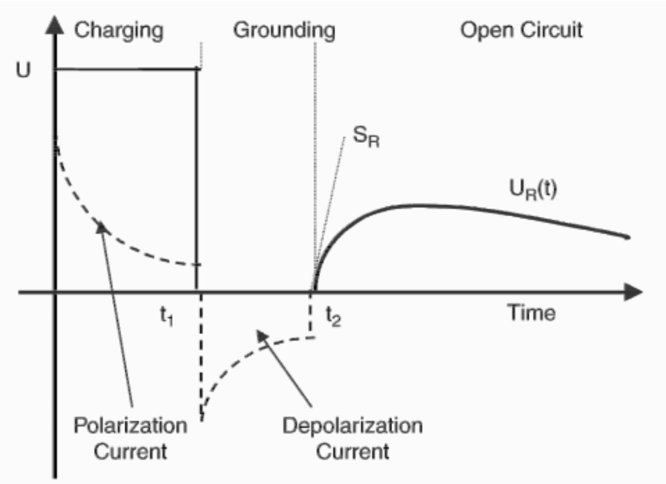


Figure 36 principle of recovery voltage measurement

To simplify the interoperation of the cable aging statutes, Georgia tech research corporation introduced a diagnostic factor D, Equation 2, which is the ratio of the peak recovery voltages measured at $2U_0$ over U_0. Interpretation of the obtained diagnostic factor D is based on voltage dependent non-linearity of the insulation system. Unaged cables would have D close to 2. However, this kind of single value evaluation on degree of non-linearity may resulting a false evaluation. This can be avoided by testing more voltage levels to determine its non-linearity.

$$D = \frac{\text{Recovery Voltage}_{\text{Max}}(2U_0)}{\text{Recovery Voltage}_{\text{Max}}(U_0)}$$

Equation 1

Table 9 interpretation of diagnostic factor D measured by RVM.

Diagnostic Factor D	Evaluation	Action
2.0 – 2.5	Insulation in good condition	No action
2.5 – 3.0	Insulation in fair condition	Other tests are recommended to identify isolated weak areas
> 3.0	Severely damaged	Replace cable

This technique cannot be applied to the polymeric cables, as the insulation resistance is too high to generate high recovery voltages for instrument to handle and may introduce trapped charge and accelerate the cable aging over a suggested period of 15 minutes DC charging.

Time Domain Reflectometry (TDR):

TDR relies on measuring impedance discontinuities in the cable impedance caused by splice, faults such as open or short, and deteriorated metallic shielding. As different cables have different impedance characterizations, so far, there are no unified assessment criteria for TDR testing and applications of the TDR are mainly limited in of significant defect/failures identification and localization. Another difficulty in TDR test is that there should be a balance between the injected pulse "amplitude resolution" and measurement "time resolution". Though, TDR seems a straightforward test method in principle, proper interpretation and noise handling of the TDR test data requires the experienced personal.

TDR has been developed to assess the presence and relative severity of neutral corrosion, as cable shield corrosion, splice shield crimp corrosion, or splice thermal defects can change the impedance of the cable thus the TDR waveform reflection. Figure 35 shows the 6 different common TDR signals that corresponding to different ideal cable impedance discontinuity for a theoretical impropriation of the different detect classification in cable diagnostics. The practical application is often limited to long cables with few joints.

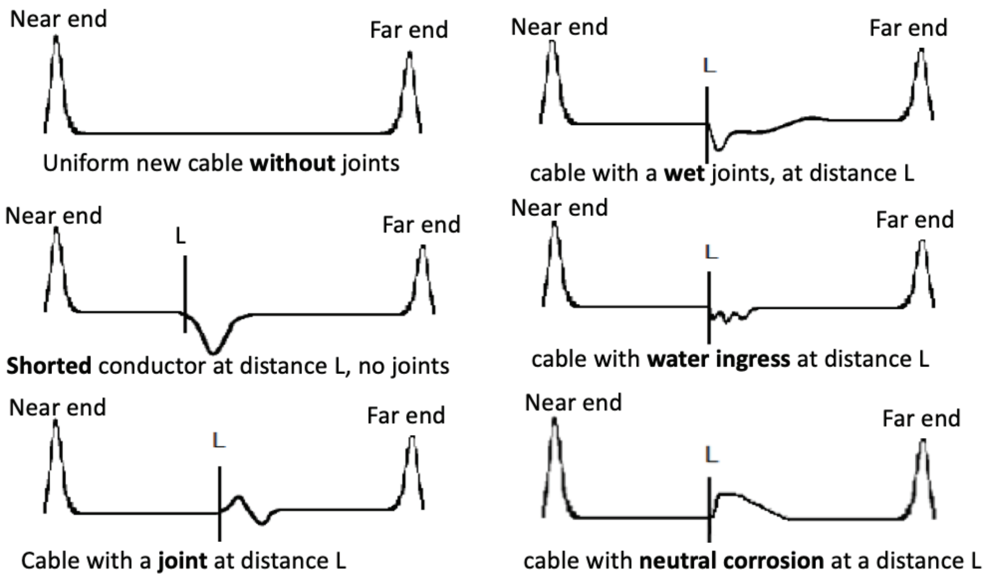


Figure 37 illustration of TDR signals correlated to different cable impedance discontinuity, IEEE Std. 1617-2007.

The most common application of TDR tests been utilized in assessment of cable's neutral corrosions. Studies show that a cable may have up to 25% of its neutral conductor damage before any recognizable signals appears on the TDR.

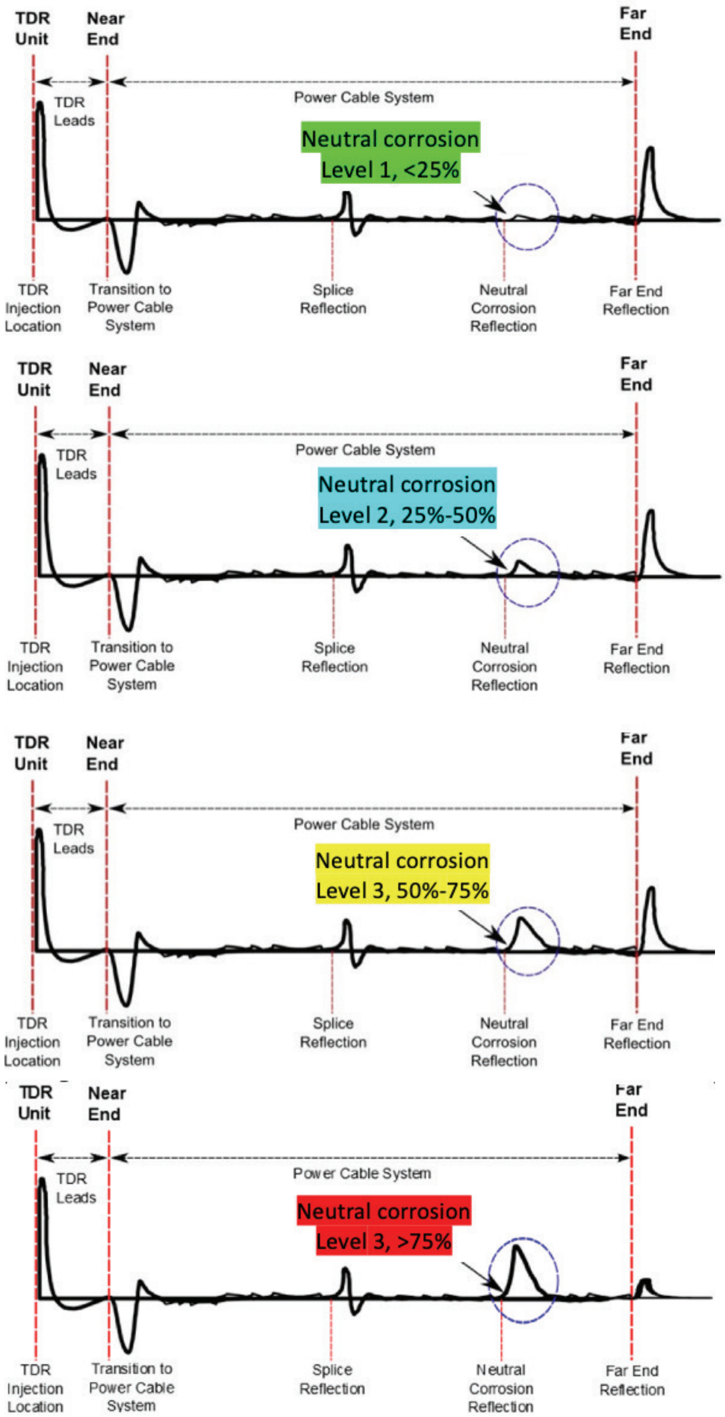


Figure 38 illustration of 4 different level of neutral wire corrosion measured by TDR, splice reflection is used as the reference level, IEEE Std. 1617-2007.

IEEE Std. 1617-2007 gives a technical guide for condition assessment of the metallic shield and provides a four-level rough neutral corrosion condition assessment based on the TDR pulse compared with the cable splice reflection, Figure 38. Applicability is very limited due to the impetration of the reflected TDR waveforms are uncertain and different in every cable system.

This method is relatively simple and can locate neutral corrosion as long as the several neutral wires are lost more than 25%. Typically, TDR is performed when cable is de-energized. Recent developments allow TDR to be performed on-line. Broken neutral wire will not create a reflection, which can be simply detect by TDR. The pulse must encounter several degradations superimposed for the reflections to combine and interfered among them.

NEETRAC also suggest that TDR is a reliable practical method for metallic shield assessment. CIGRE WG B1.55, recommends adding extra commissioning tests of TDR, OTDR, and sheath insulation resistance for submarine MV cables.

5.2.6 Metallic shield tests

Statistically, metallic shield integrity is one of the major causes of MV cables failure. This is likely due to combined degradations from internal thermal grading effect and external water ingressions. The grids and testing companies usually intent to more focus on main insulation diagnostic by PD or VLF-Tan Delta tests and underestimate the damages on metallic shielding. At the same time, it is essential to ensure concentric neutral integrity, especially for old and long cables. Jacket integrity test, DC resistance of the shield, and TDR for corrosion investigation are the most important and effective tests to assess the metallic shield integrity.

6 Practice in power cable system diagnostics and its remaining life evaluation

6.1 PRACTICAL REMARKS ON DIAGNOSTIC TECHNIQUES

In all, the practical remarks for electrical diagnostic techniques are suggested based on different method categories as listed below.

Remarks on voltage withstand, hi-pot tests:

- Not recommend for aged cable diagnostics, only for newly installed cables.
- For new DC cables, uses DC voltage source tests and control the ramping speed.
- For new AC cables, uses VLF voltages (0.1Hz) $3U_0$ for 1 hour and monitoring PD in parallel.

Remarks on partial discharge tests:

- PD tests is to confirm the existence of defect and its location.
- PDs are stochastic and unstable and have charge memory effect, cannot trust PDIV only.
- PRPDA has limit effect in few defects' identification.
- Practical to use VLF voltages (0.1Hz) or DAC up to 2 U_0 for aged cable PD tests.
- PD on-line monitoring of accessories with HFCT is a meaningful approach.

Remarks on dielectric response tests:

- FDS is a useful tool for overall insulation evaluation, but in practice, only limited in low frequency sweep (<1 Hz) in cable application;
- VLF tan δ Tip-up test up to 2U0 is an effective method for insulation defects/aging overall evaluation. But with risk of insulation degradation during test.
- PDC (RVM) is an effective method for aging evaluation at low DC voltages (1-3kV), low risk of degradation during tests
- Common challenges from noise handling and differentiate between overall aging and local defect.

Remarks on defects/faults localization:

- TDR is a simple method for fault/large defects localization.
- BIS is more effective method for defects localization but with much higher technical demands.
- Other methods: high demands on operator experiences, detection principle remains the same, all may subject to high noise interferences.

6.2 OIL-PAPER INSULATED CABLE SYSTEMS

There are numerous MV oil-filled cable circuits with an average age of 50 years or older in Sweden. These cables are generally reliable and have a long life. The main mechanisms of aging and failure of oil-impregnated cables are leak and corrosion, thermal aging, paper thermomechanical deterioration, metallic sheaths thermomechanical deterioration, and paper electrical aging. One of the challenges is to maintain the integrity of the oil-filled cables such as the pipe for High-Pressure Fluid Filled (HPFF) and the sheath for Self-Contained Fluid Filled (SCFF) cables against corrosion.

IEEE Std. 1425-2001, "Guide for the evaluation of remaining life of impregnated paper-insulated transmission cable systems", is a decent document for diagnostics and condition assessment of oil-filled cables. Furthermore, CEATI developed a guide for "Transmission Underground Cable Reference Manual Maintenance" in 2014. This guide provides detailed procedures for both LPFF and HPFF cable oil leak tests such as PFT. It also covers maintenance testing such as anti-corrosion sheath tests, measurement of sheath bonding currents, cross-bonding check, partial discharge (PD) diagnostic test during the 1-hour AC withstand test, resistance measurement of the conductor, capacitance and dissipation factor, TDR, positive and zero-sequence impedance measurements, Dissolved Gas Analysis (DGA), jacket withstand and insulation resistance, and dielectric insulation resistance measurements.

6.3 EXTRUDED POLYMERIC DIELECTRIC CABLES SYSTEMS

In Sweden, XLPE cable installation peaked after 1980 which has resulted in the average age of nearly 40 years for the MV XLPE cables. Like other MV & HV assets, underground cables and cable accessories are subject to electrical, thermal, mechanical, and environmental stresses during their lifetime and cause degradation of the cable system that can lead to failure. The main mechanisms of aging and failure modes of the polymeric cables are water ingress, water/electrical tree, partial discharge, overheating, thermomechanical stress, and intrinsic breakdown.

Accessories, including splice and termination, have a major role in the cable system failure for both MV and HV cables. The CIGRE TB 560 presents a review of the experience of failures in terminations and joints (rated at 60 kV and above), including failure modes, consequences, and corrective actions. Accessory failure was caused by major factors: moisture ingress, manufacturing defects, and poor installations.

Some of the power utilities and industrial cable owners run the MV cable systems to failure, apart from Factory Acceptance Tests (FAT) and site acceptance tests (SAT) have become very popular for both MV and HV cables in the past 20 years, without any testing or maintenance plan after the commissioning. Replacement of cables based on failure or purely on age-based have disadvantages such as lowering the power system reliability and increasing the cost of repair or premature replacement.

as reviewed in the report, there are various advanced cable test techniques available for the diagnostics of MV and HV cables. The most popular test based on industry practice is withstand Hi-Pot & PD for FAT and SAT tests and VLF Tan-Delta for maintenance test. The interpretation of advanced cable test diagnostics is a crucial component that determines the relative success of the testing and maintenance program. It is a common practice to engage a third party with field experience to perform advanced diagnostics and subsequent interpretation. Following are number of challenges and open issues specific to be addressed in the industry:

- On-site PD testing, including criteria of PDEV for different power cables, PD sensitivity, background noise, measurement frequency, proper calibration, signal attenuation, and PRPDA interpretation.
- Lack of field data and test equipment for VLF Hi-Pot and PD and VLF Tan-Delta testing.
- Lack of available guidelines for FDS, RVM, and PDC.
- Lack of experience and guidelines in defect localization tests, such as BIS.

Thus, diagnostics of underground cable is still in high demand and requires innovative ideas to improve the existing techniques, bring new ideas, and help the industry for a better condition assessment.

Research organizations and industry will have to cooperate more efficiently to improve the existing diagnostic techniques and offer new technologies toward a better practice and extending the lifetime of the aged cable systems, based on availability and economic aspects following are recommend cable dianostics steps and techniques for MV cable utilities:

1. Start with PDC/megger tests (1-2kV) for both conductors to shields and shields to ground, measuring from high potential side and comparing different phases. (GΩ vs. MΩ), comparing 3 phases/backup cable results, if not sure, go to step 2.
2. VLF Tan Delta tip-up test (0.1Hz sinusoidal) at three voltage levels 0.5, 1 and 1.5U_0, Check any potential defects and or overall degradations by its non-linearity.
3. Perform BIS test for defects localization, if results show at accessible accessories, consider localized PD tests with HFCT and DAC voltage up to 2U_0 to confirm and replace; if results show overall degradation, consider rejuvenation and VLF Tan Delta tip-up test again.

7 List of references

Following listed standards and literature are used as main references for the review.

7.1 IEC STANDARDS

IEC 60055-1:1997+AMD1:2005 CSV Paper-insulated metal-sheathed cables for rated voltages up to 18/30 kV (with copper or aluminium conductors and excluding gas-pressure and oil-filled cables) - Part 1: Tests on cables and their accessories.

IEC 60141-1:1993 Tests on oil-filled and gas-pressure cables and their accessories - Part 1: Oil-filled, paper, or polypropylene paper laminate insulated, metal-sheathed cables and accessories for alternating voltages up to and including 500 kV.

IEC 60183:2015 Guidance for the selection of high-voltage A.C. cable systems

IEC 60230:2018 Impulse tests on cables and their accessories

IEC 60502-2:2014 Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) - Part 2: Cables for rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)

IEC 60502-4:2010 Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) - Part 4: Test requirements on accessories for cables with rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)

IEC 60840:2020 RLV Power cables with extruded insulation and their accessories for rated voltages above 30 kV (Um= 36 kV) up to 150 kV (Um = 170 kV) - Test methods and requirements

IEC 61442:2005 Test methods for accessories for power cables with rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)

IEC TR 61901:2016 Tests recommended on cables with a longitudinally applied metal foil for rated voltages above 30 kV (Um = 36 kV) up to and including 500 kV (Um = 550 kV)

IEC 62067:2011 RLV Power cables with extruded insulation and their accessories for rated voltages above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) - Test methods and requirements

IEC 62895:2017 High voltage direct current (HVDC) power transmission - Cables with extruded insulation and their accessories for rated voltages up to 320 kV for land applications - Test methods and requirements

IEC 63026:2019 Submarine power cables with extruded insulation and their accessories for rated voltages from 6 kV (Um = 7,2 kV) up to 60 kV (Um = 72,5 kV) - Test methods and requirements

7.2 CIGRE TECHNICAL BROCHURES

TB 182, WG. 21.16 Partial discharge detection in installed HV extruded cable systems, April 2001.

TB 279, WG. B1.04 Maintenance for HV cables and accessories, Aug. 2005.

TB 303, WG B1. 06 Revision of qualification procedures for HV and EHV AC extruded underground cable systems, Aug. 2006

TB 338, WG B1.07 Statistics of AC underground cables in power networks, Dec. 2007

TB 379, WG B1.10 Update of service experience of HV underground and submarine cable systems, April 2009.

TB 415, WG B1.24 Test procedures for HV transition joints for rated voltages 30kV up to 500kV, June 2010.

TB 493, WG D1/B1.20 non-destructive water-tree detection in XLPE cable insulation, April 2012.

Nr 560, WG B1.29 Guidelines for Maintaining the Integrity of XLPE Cable Accessories, Dec. 2013.

TB 652, WG B1.37 Guide for the operation of self-contained fluid filled cable systems, March 2016.

TB722, WG B1.55 recommendations for additional testing for submarine cables from 6kV (um=7.2 kV) up to 60 kV (um = 72.5 kV), April 2018.

TB 728, WG B1.28 on-site partial discharge assessment of HV and EHV cable systems, May 2018

TB 758, WG B1.46 Test regimes for HV and EHV cable connectors, Feb. 2019

TB 773, WG B1.52 Fault location on land and submarine links (AC & DC), Sep. 2019.

7.3 IEEE STANDARDS

IEEE ICC provides a family of guides for field testing and evaluation of shielded cables.

IEEE Std 400™-2012 IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above

IEEE Std 400.1-2018 IEEE Guide for Field Testing of Laminated Dielectric, Shielded AC Power Cable Systems Rated 5 kV to 500 kV Using High Voltage Direct Current (HVDC)

IEEE Std 400.2-2013 IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz)

IEEE Std 400.3-2006 IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment

IEEE Std 400.4-2015 IEEE Guide for Field Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current (DAC) Voltage

IEEE Std C57.161™-2018 IEEE Guide for Dielectric Frequency Response Test

IEEE P400.5 D17 Draft Guide for Field Testing of DC Shielded Power Cable Systems Rated 5 kV and Above with High Direct Current Test Voltages

IEEE Std 1406-1998 IEEE Trial-Use Guide to the Use of Gas-In-Fluid Analysis for Electric Power Cable Systems

IEEE Std 1425™-2001 IEEE Guide for the Evaluation of the Remaining Life of Impregnated Paper-Insulated Transmission Cable Systems

IEEE Std 1234-2019 - IEEE Guide for Fault-Locating Techniques on Shielded Power Cable Systems

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POWER CABLE DIAGNOSTIC REVIEW

In this project, different methods for power cable diagnostics have been reviewed, with the intention to identify pros and cons for the respective methods. By studying standards for a number of methods, it is evaluated how the methods should be carried out and for what applications they are useful.

The purpose of the review is to support the maintenance organizations of grid owners and to give pointers on how to improve on their maintenance strategies. By giving a comprehensible summary of different methods and providing an overview of them, this report should be useful to any grid owner.

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