

Guide for Non-Destructive Diagnosis of Distribution Cable Systems

Technical Report

Guide for Non-Destructive Diagnosis of Distribution Cable Systems

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PRODUCT DESCRIPTION

This guide provides information needed to implement an evaluation plan for underground distribution cable systems using non-destructive diagnostics. Many diagnostic methods are available, but not all are suitable for all types of cable, and results are open to interpretation. This report compiles all commercially available techniques into one manual, reviewing advantages and disadvantages for each type of test on every type of cable in service today.

Results & Findings

This guide will

- Summarize aging, degradation, and failure mechanisms of paper-insulated lead-covered (PILC) and extruded cable systems
- Describe the principles of various diagnostic tests available
- Summarize different commercial tests currently in use
- Review the present status of data interpretation
- Summarize criteria used for condition assessment

Challenges & Objective(s)

Underground distribution cables are the backbone of the utility business. However, being underground and expected to last for decades, they do not get much attention until they fail. Knowing the condition of the underground distribution system is critical to effective planning and replacement. Many techniques exist to determine the condition of underground cables, but not all have the same effectiveness on all types of cables and system designs.

This report helps sort out the confusion faced by planners and engineers responsible for developing inspection and replacement plans for underground distribution cables.

Applications, Values & Use

This guide can be used as the basis for developing an inspection and condition assessment component of a utility cable replacement strategy. A cable replacement strategy is an important part of a utility's overall asset management strategy.

EPRI Perspective

Managing distribution assets remains an ongoing concern for many utilities. Managing underground cables still remains a challenge since techniques and methods that can provide utilities with a better understanding of the health of insulated cables are still being developed. This project is the latest in a series to better understand the capabilities and limitations of cable diagnostic tools as applied to underground cables.

As diagnostic technology advances, EPRI will build on its extensive industrywide database of cable failures and condition assessment of PILC and extruded cables.

Approach

This guide reviews various non-destructive diagnostic techniques available to evaluate underground distribution cables. Tests are categorized into those that measure global properties, such as dissipation factor, and those that provide information on local defects, such as partial discharge.

The principles of each test are reviewed, and various specific tests are summarized and reviewed with regard to the present status of data interpretation.

Keywords

Non-destructive diagnostics

Cable aging and degradation

Global diagnostic techniques

Local diagnostic techniques

Dissipation factor

Isothermal relaxation current (IRC)

Return voltage method (RVM)

Dielectric spectroscopy (DS)

Oscillating wave test system (OWTS)

0.1 Hz dissipation factor (DF)

Partial discharge (PD)

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1

INTRODUCTION

Electrical utilities have a large investment in their distribution cable systems. Older underground medium voltage cable circuits are reaching the end of their useful lives and some vintages of cables have been prone to higher failure rates than others. These factors along with the high cost of cable circuit replacement, the high reliability needed to avoid lost revenues, and customer dissatisfaction in the event of premature failures make it essential that utilities know the condition of their cable circuits to determine if repair, refurbishment or replacement is required. Many utilities are already undertaking cable replacement programs and need an effective assessment of their cable circuits to prioritize the cables to be replaced.

There are several different diagnostic technologies being offered to utilities, over and above DC Hipot testing, which was developed for paper-insulated lead covered (PILC) cables several decades ago and has been found to be very effective for this type of cable. However, DC Hipot testing has not been found to be an effective test for extruded cable systems - high molecular weight polyethylene (HMWPE), cross-linked polyethylene (XLPE), and tree retardant XLPE (TRXLPE) - due to their different aging, degradation and failure mechanisms; hence the development of alternative diagnostic tests. There is little information on the effects of DC Hipot testing of other extruded cable systems - ethylene propylene rubber (EPR) and ethylene propylene diene modified rubber (EPDM, but often also referred to as EPR).

This guide reviews the different diagnostic tests that are available and gives an explanation of their effectiveness based on the aging, degradation, and failure mechanisms for PILC and extruded cable systems. It will be shown that some diagnostic techniques are more sensitive to specific types of aging and degradation than others. The limitations of the different techniques will also be discussed. Thus the guide will be useful for utilities that are conducting diagnostic testing or are interested in setting up a diagnostic test program.

The guide will:

- give a summary of the aging, degradation, and failure mechanisms of PILC and extruded cable systems
- describe briefly the principles of the different diagnostic techniques available
- summarize the different commercial diagnostic tests presently in use
- review the present status of data interpretation
- summarize the criteria used for condition assessment

2

DIAGNOSTIC TESTING

For this guide a **diagnostic test** is a test made during the operating life of a cable system that is intended to evaluate and locate aging or degradation that may cause cable and accessory failure. This definition is similar to that given in CIGRE [1]. Although there has been considerable effort to develop tests to assess the condition of the insulation of cable circuits, it is also very important to carry out a visual inspection of the visible components, and to test the integrity of the conductor and neutral (shield). The testing of the conductor and neutral shield are not covered in this report.

Diagnostic tests may be potentially destructive (e.g., a withstand or Hipot test) or non-destructive (e.g., a power or dissipation factor test). A withstand test, in which a constant voltage of up to $3U_0$ is applied for a specified time, ensures that the circuit under test has a breakdown voltage greater than the test voltage. It is a Pass/Fail test to weed out weak cables and accessories that have a high risk of failure in less than a year. Some utilities perform this type of test to reduce the risk of unexpected failures during the high load season.

Non-destructive tests, the focus of this guide, are performed at lower voltages so that the risk of causing a failure is reduced, either during or immediately after the test. Non-destructive tests measure properties, other than the breakdown strength, that are related to the aging or degradation of cable circuits. Different non-destructive tests are sensitive to the different mechanisms of aging and degradation, so that there is no single test that can give a complete diagnosis of any cable circuit. Thus the aging and degradation mechanisms should be known for the different cable and accessory types in order to develop useful diagnostic tests, and also to interpret the data from such tests.

Non-destructive tests fall into two categories:

- Tests that measure the general or global condition, e.g., dissipation factor. These type of tests give an average condition and are not usually sensitive to local variations that may often occur along a length of cable or in an accessory
- Tests that are sensitive to the weakest spots (defects), e.g., partial discharges. It should be noted that defects can exist in cable systems that may not be a source of partial discharges. For example, a contaminant in extruded insulation that is in good contact with the insulation will not be a source of partial discharges unless the contact between the contaminant and the insulation is broken creating a gas-filled void or a very high test voltage is applied.

Each of these categories can be further divided into on-line and off-line tests.

The advantages and disadvantages of withstand and non-destructive tests are listed in Table 2-1.

Table 2-1
Advantages and Disadvantages of Withstand and Non-Destructive Tests

Advantages of Withstand Tests
• Test equipment is basically a high voltage supply (DC, power or very low frequency). • DC and VLF equipment is compact and portable. • Standards available for most cable types (IEEE Std 400, (some parts under preparation)). • Tests are relatively simple to perform. • Tests are less costly than non-destructive tests. • Test results are easy to interpret (Pass/fail criterion)
Disadvantages of Withstand Tests
• Only gives pass/fail criterion • Not easy to assess trends in condition of cable. The sensitivity to detect defects depends on the type of withstand voltage applied • Risk of inducing damage to cable during test that might cause failure a short time after being put back into service (test values recommended in the standards have been chosen, based on experience, to make this risk small). • Outage required for off-line tests.
Advantages of Non-Destructive Tests
• Low risk of failure during test or immediately after being put back into service as test voltages are usually lower ($<2U_0$) than those used in withstand tests. • Tests are available to measure global or localized conditions. • Trending can be performed to give a better assessment of the cable system. • Off-line tests can be performed over a range of voltages from 0 to $3U_0$ or higher so that trends with voltage can be measured.
Disadvantages of Non-Destructive Tests
• Test equipment is more expensive than that needed for withstand testing. • Some test equipment requires considerable expertise to use equipment and run tests. • Test conditions may adversely affect the data (introduce noise or erroneous data). • Interpretation of data may be prone to error. • Limited criteria developed to assess cable circuit condition. • Outage required for off-line tests.

3

AGING, DEGRADATION AND FAILURE

Aging is the changes in properties that occur with time due to the electrical, thermal, mechanical and environmental stresses applied to the components of a cable circuit. An example of aging is oxidation of insulating materials. There may be one or more aging mechanisms that may be dependant on one another. More details on the mechanisms are given in Appendix A. As a comparison, when a person gets older, he or she cannot to do at 60 years of age everything that they could do at 25.

Degradation is permanent damage caused by the applied stresses that may eventually affect the ability of materials or systems to perform their normal functions. Examples of degradation are electrical trees in extruded insulation, tracking in PILC cables, and conductor corrosion. As equipment ages, it may become more susceptible to degradation. As a comparison, examples of degradation of a person are heart disease or cancer. In this report the term aging will also include degradation unless otherwise stated.

Failure, which occurs when the cable or accessory is no longer able to withstand the applied voltage, is usually the electrical breakdown between the high voltage conductor and ground causing a fault in the system.

The aging mechanisms depend on several factors that include the cable and accessory characteristics and the operating conditions. Thus, for any diagnostic testing, it useful to know:

- Type of cable: HMWPE, XLPE, TRXLPE, EPR (several types), PILC, voltage rating, jacketed or unjacketed, type of neutral or shield, date of manufacture and installation
- Details of circuit: cable length, number of splices, number of branches if any, mixed circuit (different types of cable in the same circuit)
- Type of accessory: heat shrink, cold shrink, premolded, or hand-taped
- Operating conditions: wet/dry location, direct-buried, duct or conduit installation, susceptibility to voltage transients, range of operating temperatures (load currents), possibility of hot spots
- Cable and accessory failure rates.

The aging and failure mechanisms are statistical in nature in that there may be considerable variations in how the mechanisms develop and progress (a) along the length of a cable and its accessories, and (b) between identical cable circuits operating in the same environment and under the same conditions. This will result in a scatter in the times to failure. For example, it is not uncommon in time-to-failure tests on cables in the laboratory that there is up to an order of

magnitude range in the times to failure for failures due to the same mechanism. In addition to the statistical behavior of the aging and failure mechanisms, the properties measured in diagnostic tests will also show statistical variations with the aging phenomena. Thus the statistical behavior, which must be taken into account when interpreting the test data, makes it very difficult to make accurate predictions of remaining life of cables and accessories. Remaining life should be expressed as a probability.

Making a comparison with the human population, it is very difficult to predict remaining life except in cases where a person has a terminal illness. Even then, when persons are given “one year to live”, a small percentage will survive for considerably longer or shorter than one year. The same statistical behavior is observed in the prediction of the future performance of cable circuits. In addition, when people reach a certain age, say 50 years old, it is recommended that they have regular checkups to monitor their health and possibly detect the early onset of a more serious illness. Performing diagnostic tests on older cables on a periodic basis to develop trends can have similar benefits as checkups on humans.

Aging and Diagnostics of Extruded Cable Systems

The aging of extruded cable insulations is mainly caused by the action of electrical, thermal, mechanical, and environmental stresses on defects in the insulation or in the semiconducting shields such as contaminants, protrusions, and voids (CPVs). These defects are usually introduced during cable or accessory manufacture, storage, transportation, or installation. Examples of defects are metal or dirt particles, which may be soluble or insoluble in water, particles of semicon in the insulation, semicon protruding into the insulation, delamination of the semicon from the insulation, interfacial voids between the cable and accessory insulations, and gas-filled voids in the insulation.

Table 3-1 lists the main mechanisms along with the main causes and the best methods to detect the aging and degradation. This table is a summary of the mechanisms listed in the tables in Appendix A. Not all defects (CPVs) will result in water or electrical trees, or partial discharges. For example contaminants with smooth edges and in intimate contact with the insulation will not create a high enough electrical field to initiate an electrical tree at typical test voltages ($<3U_0$), and the absence of any gas-filled space around the contaminant will prevent any partial discharges. However, after temperature-cycling due to load variations or excessive bending during installation, the contact between the contaminant and the insulation might be broken thus creating an air gap around the contaminant and the possibility of partial discharges. Thus the contaminants may not be detected during factory or after-laying tests, but could be a possible site for partial discharges during normal service operation. Water-soluble contaminants that also will probably not be detected by factory or after-laying tests are future sources of large water trees during service. The detection of voids will depend on their location, shape, and size, and the type of voltage applied in the diagnostic test, for example, DC voltage will usually only produce partial discharges during the raising and lowering of the voltage.

Table 3-1
The Main Aging Mechanisms of Extruded Cables

Aging Mechanisms	Cause	Detection Method
Water treeing (WT)	CPVs*, Water, Voltage	Dissipation Factor, recovery voltage, loss currents**
Electrical treeing (ET)	CPVs*, WT, Voltage	PD
Partial discharges (PD)	CPVs*, ET, Voltage	PD
Tracking	Surface contamination, Interfacial voids	PD, visual
Intrinsic breakdown	Lightning	none
Chemical changes, e.g., oxidation, hydrolysis	High temperature or direct contact with aggressive liquids	Dissipation Factor, recovery voltage, loss currents***
Thermomechanical	Current overloading	Visual, PD (if voids form due to mechanical deformation)
Thermal runaway, hot spots	Current overloading, dielectric heating	Visual (signs of overheating) Dissipation Factor, recovery voltage, loss currents***
Hardening/softening of insulation/shields/jackets	High temperatures, exposure to solvents, etc.	Visual, PD if voids form, otherwise none
Concentric neutral corrosion	Water, aggressive chemicals	Time domain reflectometry (TDR), resistance measurement

* Not all contaminants, protrusions and voids (CPVs) will result in water trees, electrical trees, or partial discharges

** High density of water trees necessary

*** Sensitive only if affected length of cable is relatively long

Table 3-1 makes reference to terms such as water treeing, electrical treeing, and partial discharges, which are three types of aging found in high voltage insulation systems.

A **water tree** is a tree-shaped collection of water-filled microvoids interconnected by oxidized tracks. Water trees can occur at protrusions, contaminants, or voids in polymeric materials subjected to electrical stress and when moisture is present. The insulation is degraded within the water tree, i.e., has a lower dielectric strength and a higher dielectric constant than the original insulation. Water trees grow very slowly with time and may reach a limiting length. Water trees from soluble contaminants can grow more rapidly.

An **electrical tree** is a tree-like growth, consisting of gas-filled or carbonized micro-channels, which can occur at electric field enhancements such as protrusions, contaminants, water trees, or voids subjected to electrical stress for extended time periods. The insulation is permanently damaged at the site of an electrical tree. Partial discharges cause the tree to grow and complete

insulation breakdown is only a question of time for non-laminated insulation. Electrical trees can initiate and grow in the absence of water.

A **partial discharge (PD)** is an electrical discharge that only partially bridges the insulation between conductors. It may or may not occur adjacent to a conductor. Partial discharges are local breakdowns either in regions of low breakdown field or as a result of electric field enhancement within or on the surface of the insulation.

Table 3-1 shows that the best diagnostic techniques for the insulations of extruded cable systems are:

- The measurement of the dissipation factor (loss factor or tan delta and $\approx$ power factor), recovery voltage, loss currents, which gives a global measurement of the insulation. A high density of water trees is needed for this type of measurement to be effective.
- Partial discharge measurements, which gives an indication of localized defects
- Visual inspection, which is limited to what can be seen in man-holes and the ends of the cables
- Time domain reflectometry (TDR) and resistance measurements can be used to check the condition of the concentric neutral or metallic shield.

After-laying tests performed prior to putting cable circuits into service are, in effect, diagnostic tests. Please note that after-laying tests of extruded cable systems are intended to detect gross defects such as severe contamination, large voids, or the incorrect installation of accessories. If the components successfully passed the factory tests, any defects are probably due to damage during storage, transportation, or poor installation. Thus a diagnostic test that detects only localized damage is required. Water treeing, thermal aging, and concentric neutral corrosion should not be factors in new cable installations. Thus, a DC, AC (power frequency or very low frequency (VLF)) withstand test is an adequate test. However, it would be beneficial for any utility wanting to develop a program to determine the health of their distribution cable assets to perform non-destructive tests on some new cable circuits that represent typical types of circuits being installed. This need not involve testing every cable installed but a small percentage of each particular type according to insulation, manufacturer, etc. The information from such tests will provide good baseline data and enables trends to be developed if periodic testing is performed, for example, every five years, to assess the condition of cable circuits.

Aging and Diagnostics of PILC Cable Systems

The aging of PILC cable insulations is mainly caused by the action of electrical, thermal, mechanical, and environmental stresses on the insulation or when contaminants such as water enter the cable through cracks or corrosion of the lead sheath. Table 3-2, which lists the main aging and degradation mechanisms of PILC cables, shows that suitable diagnostic techniques are dissipation factor, recovery voltage or loss current measurements (global assessment of the insulation), PD measurements (localized defects), and visual inspection. Table 3-2 is a summary of the tables in Appendix A. As for extruded cable systems, diagnostic tests that measure the global or bulk properties of the insulation give average values for the whole PILC insulation

system, cable plus accessories. PILC cables may have PD as part of their normal operation due to the presence of voids created by expansion of the lead sheath. These voids are not usually confined to one location but move around as the impregnant softens and flows with increasing temperature.

Table 3-2
The Main Aging and Degradation Mechanisms of PILC Cables

Aging/Degradation Mechanisms	Cause	Detection Method
Leakage of oil/Oil starvation leading to dry spots	Sheath corrosion/fatigue, Cracks at potheads/splices, Mechanical damage	Visual, PD, dissipation factor, recovery voltage, loss currents
Ingress of moisture	Sheath corrosion/fatigue	PD, dissipation factor, recovery voltage, loss currents
Thermal runaway	Insulation overheating due to high losses or current overloading	Dissipation factor, recovery voltage, loss currents

The two types of non-destructive tests, those that measure global properties and those that measure local properties, are sensitive to most of the aging mechanisms of both extruded and PILC cable circuits, so that it would be logical to assume that the same tests can be used on both insulation types. However, as different criteria for data interpretation apply for the different cable types, it is very difficult to interpret data for mixed circuits, either containing both extruded and PILC cables, or containing different extruded cables, XLPE, TRXLPE, or EPR, particularly data from tests that measure global properties. As an example, partial discharges of tens of picocoulombs may be of concern in XLPE cable circuits, whereas, PILC cables are tolerant of partial discharges of several hundreds of picocoulombs.

4

DIAGNOSTIC TECHNIQUES - GLOBAL PROPERTIES

The techniques that measure the general or average condition of the insulation of a cable circuit are dissipation factor (tan delta, loss factor, or loss tangent and $\approx$ power factor), dielectric spectroscopy, recovery voltage, and polarization/depolarization (short circuit) currents. The general principles of each type will now be discussed along with a brief description of the test methods commercially available.

Table 4-1 lists the advantages and disadvantages of global property diagnostic techniques

Table 4-1
Advantages and Disadvantages of Global Property Diagnostic Techniques

Advantages of Tests that Measure Global or Bulk Properties of the Insulation
• Measures the average property of the insulation • Accuracy in interpretation of the data is improved if measurements are repeated periodically, i.e., trending • Low risk of failure during the test if tests are limited to a maximum of $2U_0$
Disadvantages of Tests that Measure Global or Bulk Properties of the Insulation
• Considerable expertise needed to make the measurements • Specialized equipment needed that may be costly • Localized aging cannot be detected • Tests are performed off-line • Interpretation of data may be prone to error. • Corrosion of the neutral/shield or high contact resistance between the neutral/shield and the insulation shield will give artificially high DF values

Dissipation Factor/Dielectric Spectroscopy

Although cable insulation materials should ideally have an infinite resistance, in practice they have some resistance and thus have a small conduction current flowing through them. As the insulation ages with time, the conduction current tends to increase as a result of different aging processes.

For AC voltages the ratio of the conduction current to the capacitance current is called the dissipation factor (DF) and is given by:

$$DF = I_L/I_C = \epsilon''/\epsilon' \quad (1)$$

where I_L is the loss current, I_C is the capacitive current, and the complex dielectric permittivity is given by $\epsilon = \epsilon' - j\epsilon''$, ϵ' being the real part of the permittivity (dielectric constant) and ϵ'' representing the dielectric loss. The phase angle between the total (capacitive and loss) current through the insulation and the capacitive current is normally referred to as δ (delta), with $\tan \delta$ usually much less than 1. The dissipation factor can also be written as:

$$DF = \tan \delta = 1/(\omega CR) \quad (2)$$

where ω is $2\pi f$ (f is the frequency), C and R are the capacitance and parallel resistance of the insulation per unit length respectively. The capacitance C depends on the dimensions of the cable and accessories and the relative dielectric constant of their insulating materials. Typical values of the dielectric constant and dissipation factor for common cable insulations are given in Table 4-2. Note that there is at least an order of magnitude difference in the “as new” values of dissipation factor for the different types of cables and that one type of commercially available EPR has significant voltage dependence so that it is important to know the type of cable insulation being tested.

Table 4-2
Typical Values of Dielectric Constant and Dissipation Factor at 60 Hz for Cable Insulating Materials

Material	Relative Dielectric Constant	Dissipation Factor*
XLPE	2.2	~0.0004
TRXLPE	2.3	~0.0005
EPR	3.0	~0.003
PILC	3.5	~0.005

*Dissipation Factor is often expressed as $\%DF = 100 \times DF$

The dissipation factor can be measured at a single frequency, e.g., power frequency or VLF (~0.1 Hz), or over a range of frequencies (~0.001 Hz to ~100 Hz), which is known as dielectric spectroscopy. In dielectric spectroscopy, either discrete frequencies can be applied and the response measured [2], or a step voltage can be applied for a preset time, followed by a short period (2 to 5 seconds) when the cable is connected to ground through a resistor to discharge the cable capacitance, and the discharge current is then measured. This current, measured in the time domain, is converted into a dielectric loss in the frequency domain [3, 4].

The measuring equipment can either measure the phase angle between the total current flowing through the insulation and the capacitive current or measure directly the capacitive (proportional to ϵ') and loss (proportional to ϵ'') currents and calculate the dissipation factor. Knowledge of both I_C or ϵ' and I_L or ϵ'' can give more information about the insulation than the value of the dissipation factor alone. Both ϵ' and ϵ'' may increase with aging and if they increase at the same rate the dissipation factor remains constant and one could assume that there is no aging occurring. Usually ϵ'' increases more rapidly than ϵ' so that the dissipation factor will increase,

but a slowing down in the rate of increase of dissipation factor with aging is often a sign that the capacitance, (ϵ') is increasing more rapidly. This effect is sometimes more evident at the lower frequencies in dielectric spectroscopy measurements or VLF dissipation factor measurements.

The low values of dissipation factor at power frequency indicate that the conduction current can be over one thousand times smaller than the capacitive charging current, which in turn is only a few percent of the rated load current of the cable. Thus on-line measurements of the dissipation factor require sensitivity in the parts per million range or better; this sensitivity is very difficult to achieve in practice. Therefore, measurements are usually made off-line making use of techniques to balance out the capacitive current. This increases the sensitivity of the measurement needed for new XLPE or TRXLPE circuits.

DF measurements at low frequencies have some advantages over those at power frequency. Low frequency measurements effectively increases the sensitivity as the capacitive current, which is directly proportional to the frequency, is now reduced due to it being 600 times smaller at 0.1 Hz than it is at 60 Hz ($DF = \epsilon''/\epsilon'$). It must be noted that the terms ϵ' and ϵ'' , or C and R in equations (1) and (2) respectively will also vary with frequency. Low frequency dissipation factor measurements below 1 Hz also have an advantage in that some of the polar species generated by the aging (water trees in extruded cables and thermal aging byproducts in PILC cables) can rotate with a low frequency electric field and thus contribute to the loss current, whereas at power frequency they may not be able to oscillate and therefore not contribute to the measurements. The ability of polar species or mobile charges generated during the aging to oscillate or move in an applied alternating electric field will depend on their size and concentration. Larger species will not be able to follow the applied field at higher frequencies and thus will not contribute to the dielectric loss at these frequencies. This behavior can be modeled by the equivalent circuit shown in Figure 4-1. The capacitance C_{px} and resistance R_{px} represent the polarization caused by the aging. The number of polarization elements can vary but three elements are often used. The polarization elements have different time constants and represent the frequency response of the polar species in the insulation. Figure 4-1 shows a typical model circuit to represent the insulation with polar species.

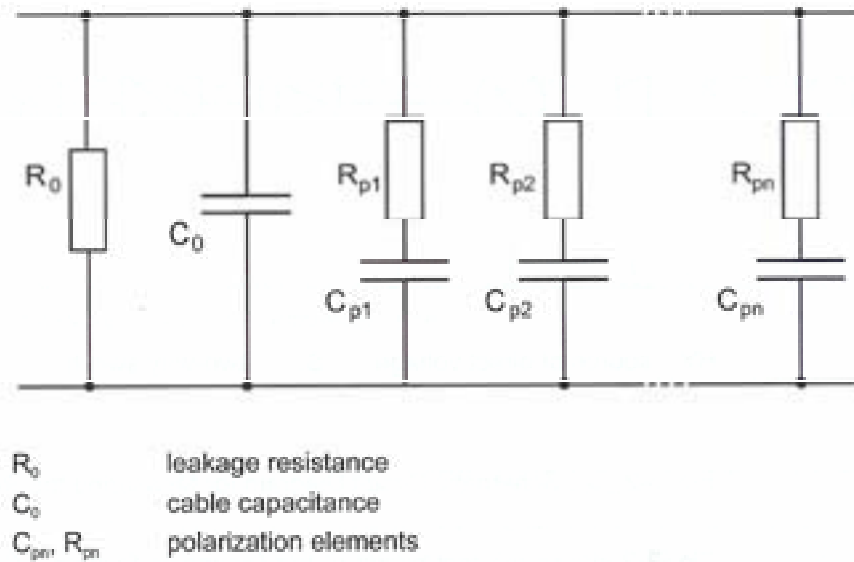


Figure 4-1
Model of cable/accessory insulation with polar species

Carrying out dissipation factor measurements/dielectric spectroscopy requires specialized equipment and expertise in low current measurements. Typical test voltages up to $2U_0$ are employed, so that all safety precautions when using high voltages must be followed. Great care must be taken to ensure that the measurement circuit does not detect any stray currents. Stray currents can be reduced by making the lead lengths connecting the measuring equipment to the test cable as short as possible. Also leakage currents over the surface of dirty termination or pothead surfaces can give artificially high loss currents and therefore incorrect dissipation factors. The surface leakage currents are usually reduced by cleaning the surfaces of the terminations or potheads, and are bypassed from the measuring circuit by adding a guard around the base of the termination or pothead to drain the current to ground. Ground connections are very important particularly when making measurements on cables with their neutrals (shields) that cannot be isolated from ground, e.g., unjacketed extruded cables. This type of cable circuit is tested by creating a “virtual” ground for the measuring circuit and power supply and connecting the “virtual” ground to the system ground by back-to-back diodes which provide transient ground rise protection in the unlikely event of a failure.

The higher loss currents in PILC and EPR cables make dissipation factor measurements/dielectric spectroscopy on these cables easier to make than on XLPE and TRXLPE cables, although stray currents must still be avoided. Most wet TRXLPE cables will have an order of magnitude or more greater DF than the corresponding XLPE cables, which again illustrates the great importance of knowing the type in cable insulation under test, otherwise an incorrect diagnosis could be made.

Typical dissipation factor measurements in the power frequency range or 0.1 Hz, are made at different voltages up to $\sim 2U_0$. In healthy PILC and extruded cables, the dissipation factor should not change or show only a small increase with voltage, the values being close to those listed in Table 4-2. It is important to know the type of cable being tested as there are differences in the “as

new” values of dissipation factor for the different types of cables and one type of commercially available EPR has a significant voltage dependence. As PILC and extruded cable systems age, they will show increases in the dissipation factor and also a significant increase with voltage, i.e., a “tip-up”. In general, the more severe the aging the greater the “tip-up”. The “tip-up” of the DF with voltage as an insulation ages is due to an increase in the number and size of the polar species, i.e., there is an increase in the polarization of the insulation. The sensitivity of the polarization to voltage also causes changes with the instantaneous value of sinusoidal voltage. This leads to an increase in harmonic content of loss current. In the laboratory the measurement of the loss current harmonics has been used to monitor the severity of water treeing in XLPE cables [5, 6]. A linear relationship was measured between the total harmonic distortion and tree length [5]. However, the technique has not yet been used in commercial diagnostic test equipment in North America, although it is now available in Japan [7], where it is used as a screening test to detect degraded cables, which are then subjected to additional withstand tests. No criteria are given to assess the condition of cables as degraded.

At the present time for tests at power frequency, there are no values of dissipation factor or magnitudes of the changes with voltage to assess the condition of a cable system specified in standards. Power frequency dissipation factor measurements in the field are not that common, particularly in North America so there is not a lot of data collected from which to determine either test voltages or dissipation factor values.

In dissipation factor measurements at VLF (0.1 Hz), the dissipation factor is measured at different voltages up to $\sim 2U_0$. As for the tests at power frequency, diagnosis is based on the value of the dissipation factor and the change in dissipation factor with voltage. The values measured will depend on the cable type, similar to power frequency measurements. Dissipation factor values to determine the condition of XLPE cable systems have been derived for 0.1 Hz tests [8]. XLPE cables in good condition should have:

$$DF@2U_0 < 1.2 \times 10^{-3} \text{ and } DF@2U_0 - DF@U_0 < 6 \times 10^{-4} \quad (3)$$

and cables should be considered for replacement if:

$$DF@2U_0 \geq 2.2 \times 10^{-3} \text{ or } DF@2U_0 - DF@U_0 \geq 10^{-3} \quad (4)$$

In dielectric spectroscopy measurements, the capacitive current, (proportional to ϵ'), and the loss current, (proportional to ϵ''), are measured at selected frequencies from 0.001 Hz to ~ 100 Hz at voltages from ~ 200 V up to $\sim 2U_0$. The dissipation factor can also be calculated from the measurements of ϵ'' and ϵ' according to equation (1).

Dissipation Factor/Dielectric Spectroscopy - Commercially Available Equipment

There are several companies that manufacture dissipation factor measuring/dielectric spectroscopy equipment and/or testing services. IMCORP now has the capability of measuring DF using a resonant power frequency supply. Baur and High Voltage have instrumentation to

measure DF at VLF (0.1 Hz), and HDW Electronics measures DF in the power frequency range using a damped AC. Dielectric spectroscopy (DS) equipment is available from GE; this equipment was formerly manufactured by Programma. KEMA uses this DS equipment as part of its diagnostic testing service. More details of the equipment, manufacturers and the diagnostic testing service providers is given in the section on commercially available diagnostic test equipment.

Dissipation Factor - Data Interpretation

As already mentioned it is important to note that diagnostic tests that measure the global or bulk properties of the insulation give the average condition of the insulation. For example suppose the DF of 10% of a cable circuit has ten times the DF of the other 90% of the circuit, which has a normal DF. This could arise if 10% of an XLPE cable with contaminants is sitting in water, or if a crack in the lead sheath of a PILC cable has allowed water to enter the cable. The measured DF will be slightly less than twice the normal value, which would not normally raise much concern when interpreting the data. Similarly the other diagnostic tests that measure bulk properties (dielectric spectroscopy, recovery voltage and leakage current measurements) will give average values and not be able to locate severely aged regions.

There can also be misinterpretation of data if the accessories are not taken into account [9]. Some accessories use non-linear stress grading materials to grade the electric field rather than geometric stress grading. Non-linear stress grading materials have a voltage dependent conductivity so that their loss current will increase more than linearly with voltage. This behavior is similar to that of a water treed XLPE cable. For example some terminations, splices and separable connectors with non-linear stress-grading material can give the same loss current at low frequency as over 1000 m (>3000 feet) of 28 kV cable [10]. Accessories with geometric stress grading have equivalent cable loss currents at low frequency of less than 50 m (150 feet) [10]. Thus it is essential to know the number and type of components in the system under test. Interpretation can be improved if data for individual new and aged components are known and can be subtracted from the total.

Global or bulk measurements of extruded insulations are also sensitive to the resistance of the conductors and semiconducting shields. Increased resistance of the semicons or neutral (shield) will also increase the DF readings. The semiconducting shields of extruded cables can become resistive, either through contact with aggressive chemicals, such as oils, or prolonged overheating. The neutral (shield) can corrode or have an insulating layer over its surface so that it is not in good contact with the insulation shield. The result is that there is now a higher resistance between the insulation and the measuring device which will increase the DF reading.

Although some criteria have been established for DF testing to assess the condition of XLPE cables, these criteria cannot be applied to other extruded cables, not even TRXLPE. This is because there is a significant difference in the DF values for the different insulations, see Table 4-2.

Recovery Voltage, Polarization/Depolarization (Short Circuit) Measurements

These tests also measure the global or bulk properties of the insulation. Laboratory tests on XLPE insulation show that the techniques are sensitive to different levels of water tree degradation [11]. For recovery voltage measurements the cable circuit is charged with a high DC voltage, between $0.5 U_0$ and $2 U_0$, for a preset time, typically 15 minutes, followed by a 2 to 5 second discharge to ground through a resistor to discharge the cable capacitance. The open circuit voltage, referred to as the recovery or return voltage, across the cable is then measured with a high-impedance voltmeter. For the polarization/depolarization current measurements the same charging procedure, although lower voltages are often used, is applied except that, after the discharge, the cable is short-circuited and the discharge (depolarization) current measured. The discharge current is also called the isothermal relaxation current. The charging (polarization) current can also be measured. The voltage or current measured after the charge and discharge procedure is due to depolarization, detrapping, and movement of charges. Aging of extruded insulation and oil-impregnated paper creates mobile charges and polar species so that the polarization will be greater. During the charging, or polarization period, the polar species will align with the electric field, charges will move through the insulation (DC conduction), or become trapped at interfaces or in trapping sites in the insulation. The polarization and charge motion contribute to the polarization current measured during the charging. During the measuring phase the recovery voltage or depolarization current is caused by the relaxation of the mobile and polarization charges with their characteristic time constants. Typically the recovery voltage rises to a maximum and then slowly decreases as the charges within the insulation relax.

As the test procedures are specific to a particular manufacturer, the procedure and the equipment will be described. Equipment to perform other tests is described in the section on commercially available diagnostic equipment.

Recovery Voltage

There are two commercially available instruments, the Cable Diagnosis System CD 32 made by HDW electronics suitable for extruded and PILC cables and the Tettex RVM 5462, which is designed to test oil/paper insulation systems, particularly power transformers but can be used on cables.

The two instruments have different operating procedures.

HDW (CD 31)

A voltage of $0.5U_0$ is applied for 5 minutes, followed by a discharge period of 2 seconds to discharge the cable capacitance. The recovery voltage is then measured for 10 to 40 minutes depending on the cable length. This procedure is repeated at voltages of U_0 , $1.5U_0$, and $2 U_0$. Cable circuit degradation is assessed by the ratio of the maximum peak recovery voltages at $2U_0$ and U_0 . The cable is considered to be very degraded if the ratio, referred to as the linearity factor is greater than 3. The cable circuit is considered to be in good condition if the linearity factor is 2.0 to 2.5, and moderately degraded for values between 2.5 and 3.0.

In the comparison test carried out in Norway, the technique correctly assessed the condition of four cable circuits tested out of seven. For the remaining three cable circuits, their condition was underestimated. However, further testing in the study indicated that if the charging current had been measured the correct diagnosis would have been made.

Advantages

- Test method is fully automated.
- Measuring time about one hour per phase.
- Manufacturer has developed condition assessment criteria for XLPE and PILC cables

Limitations and Disadvantages

- Reliability of assessment criteria not well established in North America
- Assessment criteria for TRXLPE and EPR cables not established.
- Cable should be completely discharged before each test.
- Some tests show that technique is not sensitive to all water trees but could be improved if charging current is monitored.
- Response of accessories should be taken into account to assess the cable condition.
- Data is needed on how certain types of accessories (non-linear stress grading materials) affect linearity factor.

Tettex (RVM 5462)

The instrument is intended to test oil/paper insulation systems particularly for power transformers. One of its first uses was to measure and even locate moisture in transformer insulation. The technique could, in principle, be used for PILC and extruded cables although no published data are available.

The test technique differs from that used by the HDW CD31 in that the maximum charging voltage is limited to 2000 V. The instrument is programmed to apply a series of DC voltages of constant magnitude but different time durations ranging from 0.020 s up to 10000 s. After each application of the DC “pulse” the cable is grounded through a resistor to discharge the cable capacitance for about two seconds, and the recovery voltage measured. The recovery voltage rises to a maximum and then decreases. A typical full program would be apply three voltage “pulses” per decade, i.e., 0.020, 0.050, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, and 10000 s. The instrument records the maximum voltage and the initial slope from each recovery voltage curve and then plots the maximum voltage vs. the voltage duration, see Figure 4-2 taken from the Tettex web site (<http://www.hipotronics.com/redirect/tettex.htm>).

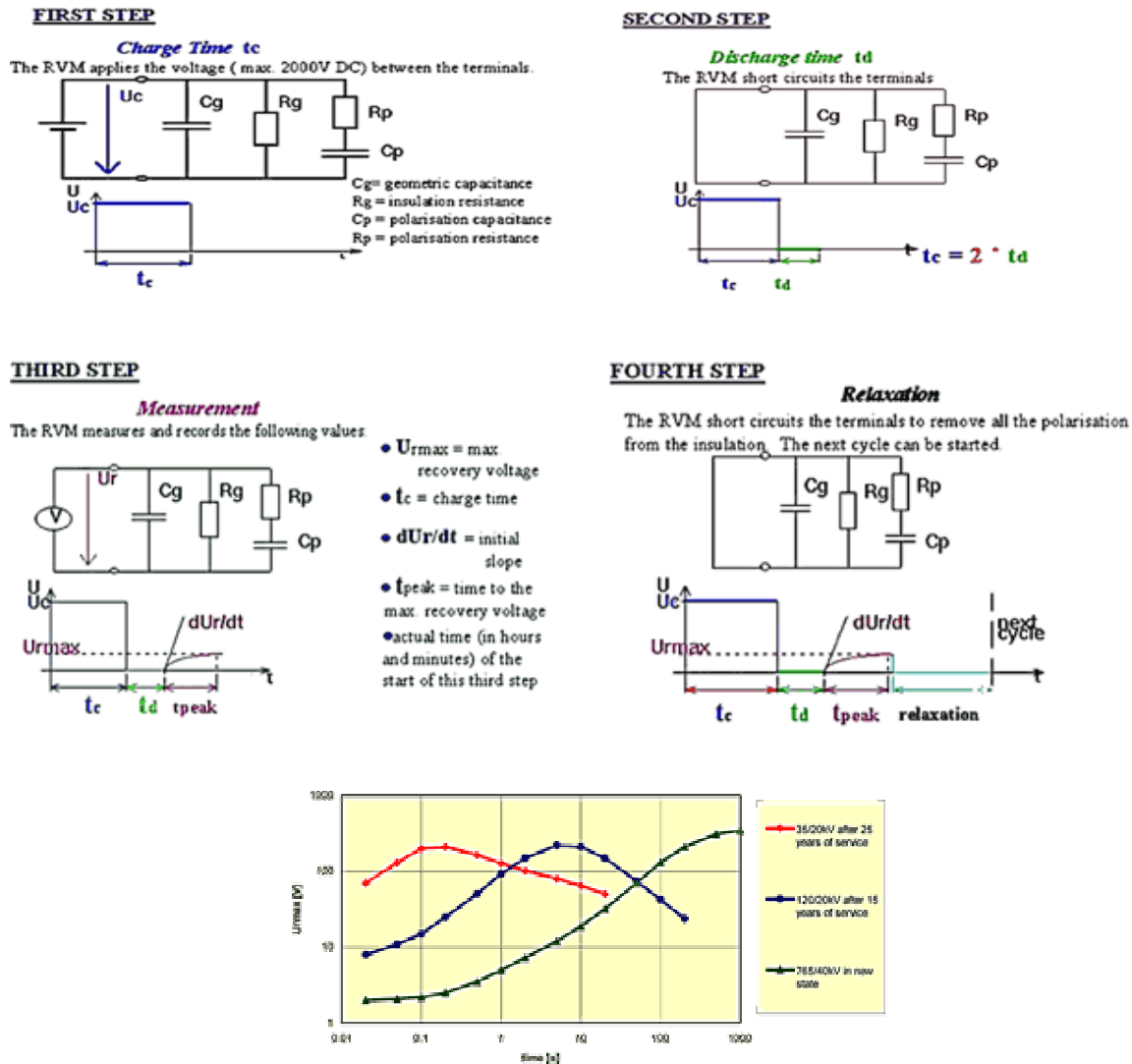


Figure 4-2
Examples of polarization spectrum curves: various ages of oil/paper insulation for transformer

As oil/paper insulation ages the time to reach the maximum voltage decreases indicating the increased loss of the insulation. Attempts to use this technique on XLPE cables with water trees showed differences between the “new” and “treed” insulation but the tests were very long, even when the longest charging time was limited to 1000 s due to the very long time for the charge to dissipate during the measurement phase. Thus the technique may be suitable for PILC cables although no data exists.

Advantages

- Test method is fully automated.

Limitations and Disadvantages

- Test method could be up to 2 hours per cable (assuming a maximum voltage application of 1000 s).
- Cable should be completely discharged before each test.
- Reliability of assessment criteria not established for either extruded or XLPE cables.
- Response of accessories should be taken into account to assess the cable condition.
- Data is needed on how certain types of accessories (non-linear stress grading materials) affect linearity factor.

Polarization/Depolarization Currents

These tests measure the global or bulk condition of the insulation. The test is relatively easy to perform. A DC voltage is applied to the cable for a predetermined time, usually 5 to 30 minutes. The cable is then discharged for a short time (~2 s) to discharge the cable capacitance and the short circuit current is then measured for 15 to 30 minutes, depending on the charging time.

Seba-Dynatronics KDA 1

The company refers to its technique as the Isothermal Relaxation Current (IRC) method. Typical test conditions are: charging voltage - 1 kV; charging time - 30 minutes; discharge time – 5s; measuring time 30 minutes. All switching is done automatically by the instrument.

The depolarization current is assumed to consist of three exponential components having different relaxation times, i.e., as per the equivalent circuit shown in Figure 4-1. Each component is associated with charge trapping/depolarization mechanisms for the cable insulation. What is unique about this instrument is that, for analysis, a plot is made of the product of the measured current and time (linear scale) vs. the time (log scale). An unaged cable shows an asymmetric curve with a single peak occurring at about 10 s [12]. Proprietary software deconvolutes the curve to show the three exponential components associated with the relaxation of the polarization/trapping processes caused by the aging (mainly water treeing). In healthy XLPE insulation, two of the components are small compared with the main component resulting in the single peak. As the insulation ages, the two smaller components increase in size so that the measured curve may have more than one peak and the main peak shifts to much longer times (~500 s). The instrument also contains a fuzzy logic algorithm to predict the residual strength of the insulation, expressed as a multiple of the operating voltage, U_0 .

The instrument was developed in Europe where XLPE cables of different designs are used to those in use in North America. Thus the software may have to be modified for North American cable designs.

In the comparison test carried out in Norway, the technique correctly assessed the condition of five cable circuits tested out of seven, The conditions of remaining two were underestimated. However further testing in the study indicated that if the charging current had been measured the

correct diagnosis would have been made. The field experience with this method in North America is up to now limited.

Advantages

- Test method is fully automated.
- Measuring time about one hour per phase.
- Manufacturer has developed condition assessment criteria for XLPE cables
- Maximum applied voltage is 1000 V.

Limitations and Disadvantages

- Reliability of assessment criteria not well established in North America.
- Assessment criteria for TRXLPE, EPR and PILC cables not established.
- Cable should be completely discharged before each test.
- Some tests show that technique does is not sensitive to all water trees but could be improved if charging current is monitored.
- Response of accessories should be taken into account to assess the cable condition.
- Data is needed on how certain types of accessories (non-linear stress grading materials) affect assessment criteria.

Powertech Labs LipATEST

(<http://www.powertech.bc.ca>)

The technique consists of measuring the charging (polarization) current during the application of DC voltages steps, from 1 to 4 kV, up to a maximum of $1.5U_0$ with one minute per step. The current, which is measured by a sensitive low-noise ammeter, is recorded at the end of each one minute step. The results are plotted as the normalized current (measured current divided by the cable capacitance) vs. the maximum electrical field. If the current increases more than linearly with the applied voltage, i.e., there is a “tip-up” in the current, the cable is assumed to be degraded. The system is automated.

There was good agreement in a comparison test between this method and recovery voltage, IRC and dielectric spectroscopy results carried out on aged PILC cables.

Advantages

- Test method is fully automated.
- Measuring time about ten minutes per cable.
- Maximum applied voltage is limited to $1.5U_0$ or less.

- Condition assessment criteria have been established (need to determine these for XLPE, PILC, etc).
- Good correlation with other global/bulk techniques.

Limitations and Disadvantages

- Reliability of assessment criteria not well established.
- Assessment criteria for TRXLPE, EPR, and PILC cables not established.
- Response of accessories should be taken into account to assess the cable condition.
- Data is needed on how certain types of accessories (non-linear stress grading materials) affect assessment criteria.

ALFF Engineering (PDC-Analyzer)

This instrument, which measures the polarization and depolarization currents, was developed by Prof. W. Zaengl from the Swiss Federal Institute of Technology (ETH) in Zurich in Switzerland. Primarily designed to evaluate the aging of oil impregnated paper it has also been used for medium voltage PE and XLPE cables [13, 14]. The instrument consists of a wide-range electrometer with special filters, an adjustable voltage source, switching devices, and measuring and analysis software.

Data are reported on tests on aged and unaged 20 kV PE and XLPE cables. Little difference was observed in the polarization currents for aged and unaged cable even when the aged cable had water trees up to 80% of the insulation thickness. This is in contrast to the findings from the Norwegian study. It was concluded that measuring the charging current was not useful. The depolarization currents were linear on a log vs. Current log time graph. The amplitudes of the current were directly proportional to the applied voltage for new cables but were non-linear for aged cables, i.e., the linearity factor was greater than 2 for currents measured at 20 and 40 kV. The linearity factor increased with temperature and disappeared when the cables were dried. The non-linearity of the current with applied voltage is similar to that observed in recovery voltage tests.

Techniques are available to convert measurements in the time domain into the frequency domain, for example, by performing a Fourier Analysis of the discharge current.

There is no experience of tests using this instrument on North American cables but since its operation is based on the same principles as other polarization/depolarization current measuring instrumentation, it is expected to yield similar data.

Advantages

- Test method is fully automated.
- Measuring time about one hour per cable.
- Maximum applied voltage is limited to $2U_0$ or less.

Limitations and Disadvantages

- Experience with the instrument is limited in North America.
- Reliability of assessment criteria not well established.
- Assessment criteria for TRXLPE, EPR, and PILC cables not established.
- Response of accessories should be taken into account to assess the cable condition.
- Data is needed on how certain types of accessories (non-linear stress grading materials) affect assessment criteria.

5

DIAGNOSTIC TECHNIQUES - LOCAL DEFECTS

As discussed in the section on aging mechanisms, aging in extruded cable systems is mainly caused by the action of electrical, thermal, mechanical, and environmental stresses on defects in the insulation. The defects are usually contaminants, protrusions, or voids that are introduced inadvertently, e.g., during manufacture, transportation, storage, or installation. Improved screening and handling polymer compounds has significantly reduced the size and number of contaminants in XLPE, TRXLPE, and semiconducting materials. However, cables manufactured in the 1960s and 1970s were not subject to the same industry standards that are in use today. Thus the older cables may contain higher levels of contamination that may be the source of aging. Defects in extruded insulation that initiate water trees cannot be detected unless the trees are numerous and sufficiently long so that they can be detected by global or bulk measurements. Contaminants that are not in good contact with the insulation so that a gas-filled void is formed will be source of partial discharges if the electric field in the gas is above the breakdown strength of the gas and an electron is available to start the breakdown process. Protrusions create local regions of high electrical field. If the local field exceeds 100 kV/mm (2500 V/mil) an electrical tree can initiate, which then becomes a partial discharge site.

In PILC cables aging is caused by the stresses on the insulation. Contaminants play less of a role unless cracks or corrosion of the lead sheath allow water to enter the insulation. Voids can also occur during normal operation, by thermal cycling; these voids tend to move with the thermal cycling so that the damage caused by the partial discharges is seldom localized. The voids can be a source of partial discharges that may exist under normal operation and are not considered harmful. When performing partial discharge tests on PILC cables sensitivity is not usually a problem. However at defects such as conducting protrusions at accessories, or moisture in the insulation the partial discharge site can be localized. Repeated discharges can then damage the paper insulation and permanent tracking (carbonization) will occur. These discharges are harmful to the insulation and will eventually cause failure. Thus the most common diagnostic test to detect local degradation is the partial discharge test. A guide for field partial discharge testing of medium voltage cables is being finalized the IEEE Insulated Conductors Committee WG C19W [16]. This guide describes the different techniques available and also discusses the difficult subject of the interpretation of test data.

Partial Discharge (PD) Testing

Partial discharges are local breakdowns that can occur in gas-filled voids in the insulation, at interfaces between the insulation and the semicon, along insulating surfaces or interfaces between components if the electrical stress exceeds the inception stress. The breakdown takes place in the order of a nanosecond and creates a fast rise-time pulse that propagates in both

directions along the cable, The frequency component of the PD pulse extends into the hundreds of megahertz. The high frequency components are attenuated more rapidly by the cable than the lower frequency components so that the upper bandwidth limit of PD detectors used in time domain systems is usually limited to less than 30 MHz. It should be noted that the frequency bandwidth of PD tests conducted in the factory is considerably less [18]. The propagation of a PD pulse along a cable and its reflection at the far end enables the PD to be located [19].

Partial discharges can be detected electrically by inductive or capacitive sensors, or acoustically. Electrical tests can be made in the time domain or frequency domain and also on-line [20] or off-line [21]. The advantages and disadvantages of on-line and off-line PD tests are listed in Table 5-1.

On-line measurements usually have greater external interference and so require greater noise rejection. This is achieved using a PD detection operating in frequency domain [20]. The technique makes use of a spectrum analyzer that sweeps a range of frequencies to detect the high frequency components of the PDs. By repeating the sweeps random noise is average out, which results in higher sensitivity. Signals in the time domain can be seen if the analyzer is set to operate in a fixed frequency (zero span) mode where the background noise is low.

Table 5-1
Advantage and Disadvantages of Off-line and On-line Tests

Advantages of On-line PD Tests
• No need to take an outage to perform the test • Measurements are carried out at normal operating temperatures of cable circuits • Periodic testing can give trends
Disadvantages and Limitations of On-line PD Tests
• Cannot measure PDIV, PDEV or voltage trends • May be difficult to identify type of defect • Can only measure short cable lengths
Advantages of Off-line PD Tests
• Tests can be performed over a range of voltages from 0 to $3U_0$ or higher so that trends with voltage can be measured • Inception and extinction voltages can be measured • Tests at different voltages may help identify type of defect • Some equipment can measure PD in branched circuits
Disadvantages of Off-line PD Tests
• Have to take an outage that could be expensive • Measurements cannot be made at operating temperatures

The application of digital techniques to PD detection and measurement systems has led to major advances in the parameters that can be measured and also in the detection sensitivity. While detection sensitivity is not a problem for PD measurements in PILC cables, high sensitivity is needed for PD measurements in extruded cables where typical PD magnitudes are usually in the tens of picocoulombs. A number of parameters are being measured to improve the interpretation of the data, i.e., to determine the type of defect (electrical tree, void, its location, surface discharge, etc.) and also to determine the risk of failure or what remedial action should be taken and when.

The PD characteristics that most commercial PD measurements systems can measure are listed in Table 5-2

Table 5-2
PD Characteristics Measured by Commercial PD Instruments

- PD inception voltage (PDIV) and extinction voltage (PDEV) (off-line tests only)
- PD magnitude (q)
- PD repetition rate (n)
- PD density (PILC cable only)
- Phase angle of PD pulse (θ)
- Phase resolved PD plot (n vs. θ vs. q)
- PD magnitude vs. voltage plot (q vs. V), (off- line tests)
- PD location

Data Interpretation

The PD characteristics depend on the type and location of the defect, operating or test voltage, insulation material. Accurate interpretation of the data requires a good knowledge base of the temporal PD behavior for typical defects in insulations operating at typical operating stresses. This requires a great amount of laboratory and field testing to acquire a complete data bank. Sadly many utilities are not collecting the necessary data and thus have a limited knowledge base in PD measurements. As a result they have to rely on the knowledge base of the PD service providers, who may have collected the data on particular cable and accessory types under accelerated test conditions that may not be completely representative of the service conditions of a particular utility. This could lead to potential errors in the interpretation. In addition as discussed earlier, there can be considerable scatter in PD data over time and also between identical defects so that the accuracy in quantifying the risk may not be very high.

The accuracy in data interpretation from PD measurements, as for other diagnostic tests on cables, may improve as more data are collected and the knowledge base is increased. This can be achieved by repeating diagnostic measurements on representative cable circuits every 2 to 5 years and correlating this data with failure statistics. This is not a popular concept in the present economic climate when cutting costs has become a major factor.

When a PD occurs at a defect in a cable a short duration pulse travels in both directions along the cable from the defect site. When the pulse reaches the termination it is reflected back along the cable. The source of PD can be located by measuring the time interval (Δt) between the first pulse arriving and the arrival of the pulse reflected from the far end. To convert the time interval into distance along the cable a calibration has to be carried out initially where a pulse injected into the cable and the time for reflected pulse from the termination to arrive is measured. This time is twice the travel time along the cable and the velocity of propagation (v) can be calculated if the cable length (L) is known. Then the distance to the partial discharge site (x) is given by:

$$x = L - v\Delta t/2 \quad (5)$$

Most commercial PD measuring instruments use the pulse travel time method just described. Errors in the measurement can occur due the dispersion of the pulses as they travel along the cable so that it becomes difficult to define exactly when the pulse begins. PD measurements made in the frequency domain make use of the attenuation of the frequency to locate the PD source.

At the present time there is no standard method to perform a PD test, i.e., there are no specified test voltage levels (up to $3 U_0$ is used) or test duration (either time or number of cycles). Too high a test voltage increases the risk of initiating PD at a defect that would be normally harmless at operating voltage, e.g., voids of specific size. The test voltage should ensure that the PD extinction voltage is above the operating voltage. For voids the extinction voltage can in theory be 50% of the inception voltage but in practice it usually between 70% and 80%. Thus to ensure that there are no discharges in voids, the inception voltage should be $>1.5 U_0$. PDs in spherical voids cause erosion of the cavity surfaces, pitting and the eventual formation of an electrical tree. This process can take thousand of hours (more precisely it depends on the number of AC cycles rather than time) so that the number of PD or the number of AC cycles in the diagnostic test is not critical for this type of void. However if the void is at an interface between a cable and its accessory, PDs can cause tracking which leaves carbon tracks at the interface. The tracks increase the local electric field and lead to more concentrated PD and increased damage. Similarly electrical trees, i.e., gas-filled channels have been created, will grow relatively rapidly with repeated PD, so that a limited number of AC cycles should be applied to limit the damage.

If an electrical tree has been initiated at a defect, in a test up to $3 U_0$, the PD inception voltage may decrease to less than 50% of the tree inception voltage, so there is high probability that the PD inception voltage will be less than the operating voltage. This means that PD will be present at that defect when the cable is put back into service, thus increasing the risk of failure at the defect within a short period of time. This explains why failures can occur within days or even weeks after a diagnostic test in which the test voltage was large enough to initiate an electrical tree (and PD) but the cable did not fail during the test. A similar behavior can occur during service after a lightning storm causes a transient overvoltage that initiates an electrical tree.

Although there are no PDs during water tree initiation and growth, water trees raise the electrical field at their tips, i.e., they act like protrusions or metal contaminants. The increase in the electrical field at the tip of a water tree depends on the shape and length of the tree, its location in the cable insulation, and the density of the water-filled microvoids within the tree. If the test

voltage in a diagnostic test or a transient overvoltage is large enough, an electrical tree will be initiated and PD will occur at the tip of the water tree. This could eventually occur at operating voltage. Once an electrical tree is initiated and PDs persist, there will usually be a failure within days or weeks. Thus testing older cables with water trees at voltages above $2U_0$ increases the risk of initiating electrical trees and causing failure either during the test or within a short time after the cable has been put back into service.

In summary, diagnostic tests should be limited to $1.5U_0$ to $2U_0$, particularly on older cables operating in a wet environment. Newer cable may be tested at higher voltage ($2.5U_0$ or $3U_0$) if the probability of long water trees is negligible. Also when PD is detected the number of cycles of the AC waveform should be limited to limit the number of PD pulses to that required for PD analysis.

Acoustic techniques can be used to probe accessories provided it is possible (and safe) to hold an acoustic rod in contact with accessory. The device is manufactured by Transinor [<http://www.transinor.no/>] and consists of an acoustic sensor embedded in a fiber glass rod. A microprocessor controls the data collection and does the data analysis. The instrument can give the magnitude (q) and phase (θ) of the PD. The sensitivity claimed is in the range of 5 to 50 pC.

There are several companies that manufacture PD detection and measurement systems and/or offer PD testing services and these are described in the next section. Most offer the option of measuring the parameters discussed above. The main differences between them is the type of voltage source, from a resonant power frequency supply (IMCORP), VLF (Baur and Kema), damped AC (HDW Electronics, HV Technologies) to on-line measurements (DTE, Transinor and HV Technologies). The latter detection system operates in the frequency domain while all the other operate in the time domain. Some companies supply only the PD detection system without any high voltage power supply (Transinor HV Technologies, TechImp). All techniques can locate the PD source and use different filtering techniques to reduce the background noise.

There is some debate about whether VLF PD measurements are as sensitive as those at power frequency for extruded cables. The PD inception voltage at some defects may be sensitive to the frequency of test voltage, for example, electrical tree initiation is up to two times greater for VLF than at power frequency [22]. However the PD inception voltage for voids is approximately the same at power frequency and at VLF [22]. There can be difference in the PD inception voltage for VLF and power frequency in voids if the surface conductivity of the cavity walls allows charge leakage at the lower frequency.

Test Experience

An assessment of aged 12 kV and 24 kV XLPE cables containing water trees using four techniques, recovery voltage (HDW) depolarization current (SEBA), dielectric spectroscopy (Programma, now GE) and VLF DF (Baur) has been reported [23, 24]. The cables were subjected to the diagnostic tests, then subjected to AC breakdown tests using 5 minute steps of U_0 , and finally water tree counts. Dielectric spectroscopy and VLF DF predicted correctly the state of the eight cables tested. The DC voltage test methods (recovery voltage and depolarization current) incorrectly underestimated the severity of the condition of two cables. It

is interesting to note that if the charging (polarization) current had been measured with the two latter methods, a correct diagnosis would have been made.

A comparison of the LIpATEST, recovery voltage, IRC and dielectric spectroscopy measurements on aged PILC cables showed that the techniques ranked the cables in good agreement with their AC breakdown strengths [25]. No attempt was made in this study to predict future performance. An interesting conclusion from this study was the lack of correlation between the results and the moisture content. This may not be too surprising if one remembers that the techniques are sensitive to polar species in general and not just moisture.

Two half day sessions were held at the Fall 2000 Insulated Conductors Committee (ICC) Meeting on diagnostic testing [26]. One session covered the fundamentals of field PD testing and consisted of seven presentations by the diagnostic test service providers. The other half day workshop was on the utility experience with PD testing of cable circuits with seven presentations by utility personnel. The main points from the workshop were:

- For on-line tests, about 80% of the PD sites were in the cables and about 20% in the accessories
- Off-line test data showed about 80% of the PD sites were in the accessories and about 20% in the accessories
- Utilities are now more cautious about replacing cables and accessories based solely on PD data. They now look at other factors such as cable history, and other tests.
- The causes of PD in accessories can be due to bad workmanship, silicone migration, insufficient pressure between splice body and cable, defects on surface
- For off-line tests, test voltages of $2U_0$ to $2.5U_0$ preferred as voltages above $2.5U_0$ can cause early failures, and voltages less than $1.5U_0$ might not detect incipient faults
- Not all PDs are harmful, thus interpretation is very important
- There is room for improvement in the interpretation of PD data
- Several utilities reported false positives and false negatives
- The reasons for the false positives were that the assessment was based solely on PD magnitude, PDs can become intermittent and cease, the measured signals might not be PD, and that the PDs were occurring in a location that caused no harm
- The reasons for the false negatives were that the PDs were dormant at the time of the test, the failure was initiated by a transient, and that the test voltage was too high and initiated degradation that caused failure
- There were advantages and disadvantages of on-line and off-line testing (see Table 5-1)
- The workmanship in installing accessories tends to improve when it is known that PD testing will be performed when the work is completed
- Interpretation is improved when there is detailed knowledge of the cables being tested, i.e., there are good records available

- The overall assessment of cables is better if PD tests are carried out in conjunction with other tests, such as a global assessment of the insulation and integrity of the neutral
- Trending (periodic testing) will give more reliable assessment
- Utilities were in general encouraged with the recent improvements in PD testing and interpretation.

Since the workshop was held almost five years ago, there is a general feeling that interpretation is slowly improving and that the expectations of the utilities have been lowered. There is a realization that aging and failure are statistical processes which make the estimation of the remaining life difficult to predict. Very good and very bad cables can be predicted with increasing confidence. It is the cables in between that are more difficult to evaluate. This should improve as more data are collected and if periodic measurements are carried on selected cables (trending). The improvement in the interpretation is due to the additional PD data available (however this is not generally available to the utilities) and more information is available about the cables.

Some utilities carry out their own testing and have developed their own assessment criteria. For example, PPL measures the resistance of the concentric neutral, PD level, and DF to assess their 15 kV direct buried unjacketed XLPE cables. The utility has limits on the three measurements to determine the cable circuit condition. For example, if a cable is below all three limits it continues in service. However, if the neutral is more than 50% corroded, the cable is replaced or repaired if the corrosion is localized. If the neutral is more than 50% intact, the values of the tip up in the DF measured at two voltages ($<1.5U_0$) and the PD level at $\sim 2U_0$ determine if the cable is a candidate for silicone fluid injection or if the PD site is repaired. About 50% of the cables tested are in good condition, about 20% need silicone injection and about 25% need to be replaced. Using this approach the utility expects to keep a constant cable failure rate, whereas prior to starting the diagnostic test program, the failure rate was continuously increasing.

There have been several studies of the effectiveness of damped AC (DAC) and VLF tests to detect defects in XLPE and EPR cables. These are reviewed in [27]. Most of the studies have compared withstand tests, i.e., breakdown voltages rather than diagnostic tests such as PD or DF measurements. The ratios of the breakdown voltages using DAC or VLF to power frequency depends on the type of defect (knife cut, void, or embedded needle). DAC is more effective in detecting interfacial defects such as voids but VLF is better at detecting knife cuts or protrusions. The breakdown voltages for both DAC and VLF were up to twice the corresponding values for power frequency.

6

COMMERCIALLY AVAILABLE DIAGNOSTIC TEST EQUIPMENT

As already mentioned diagnostic test equipment can be divided into two broad categories, equipment that measures global properties such as dissipation factor (DF) and equipment that measures and locates local defects such as partial discharges (PD). This section gives a brief description of the different equipment available and Table 6-13 lists the different manufacturers and their capability to carry out withstand tests and diagnostic tests to measure global and/or local properties. Equipment to carry out recovery voltage, polarization and depolarization current measurements has already been described in the section on Diagnostic Techniques – Global Properties and will not be reported here.

VLF (Very Low Frequency) Test Equipment

Very low frequency is defined in IEEE Guide 400.2 [16] as any frequency below 1 Hz although the most commonly used frequency is 0.1 Hz. VLF (0.1 Hz) testing was developed over 50 years ago to test the insulation of rotating machines. It has since been applied to testing medium voltage cables and is now being expanded to higher voltage cables. A major advantage of VLF testing is that the charging current at 0.1 Hz is 600 times smaller than that at power frequency. Thus the size of the test source is considerably smaller to energize the same length of cable. Although the most common test frequency is 0.1 Hz some test sets can produce waveforms as low as 0.01 Hz, which further increases the maximum length of cable that can be tested. There are two basic waveforms that are commonly used, the sinusoidal waveform and the cosine rectangular, which is a square wave that changes polarity every five seconds at the same rate of change of voltage as the power frequency. Please note that the peak value of a sinusoidal waveform is $\sqrt{2}$ times the rms value, whereas the peak and rms are approximately the same for the cosine/rectangular waveform. Thus it is important to find out if the sinusoidal voltage is measured in peak or rms values (IEEE 400.2 allows both measurements).

There are four manufacturers of VLF equipment, Baur, High Voltage and KEMA (sinusoidal voltage) and HDW Electronics (cosine-rectangular). The basic units of all four manufacturers can perform withstand tests according to the new IEEE Guide 400.2 [16]. The test equipment from Baur and High Voltage can be expanded to carry out dissipation factor measurements and Baur and Kema can also perform partial discharge tests. The HDW Electronics test set can measure the leakage current. The advantages and limitations of VLF testing are listed in Table 6-1.

Table 6-1
Advantages and Limitation of VLF testing

Advantages of VLF Testing
• Power supply required is much smaller in size than that for power frequency tests • Power requirements are similar to standard fault locating equipment • Electrical stress distribution is similar to that for power frequency • Non-destructive as well as withstand tests can be performed • Global and local condition of the insulation can be measured • Potentially dangerous space charges are less likely to form due to continuous polarity reversals of the voltage
Disadvantages and limitations of VLF Testing
• Diagnostic test data may not be directly comparable with power frequency test data (DF and PD) • Cables must be taken out of service for testing • Limited criteria to assess condition of most types of cable • Even though longer lengths can be tested PDs may not be detected as their attenuation increases with cable length

Baur

(http://www.baur.at/en_baur/_products/_hv.htm)

Baur makes a sinusoidal VLF test set that can perform withstand tests on extruded or PILC cable systems and components can be added to also make DF and PD measurements. Two units are available; their detailed specifications are given in the Baur web site and the main ones are listed in Table 6-2. The generator is programmable to give square wave or DC output voltages in addition to the sine wave output. The voltages are given in rms values.

Test criteria have been developed to assess the global condition of XLPE cables. Cables in good condition should have:

$$DF@2U_0 < 1.2 \times 10^{-3} \text{ and } DF@2U_0 - DF@U_0 < 6 \times 10^{-4} \quad (3)$$

and cables should be considered for replacement if:

$$DF@2U_0 \geq 2.2 \times 10^{-3} \text{ or } DF@2U_0 - DF@U_0 \geq 10^{-3} \quad (4)$$

Table 6-2
Specifications of Baur VLF Test Sets

	PHG 70	PHG 80
Max. voltage	38 kVrms/0.1 Hz	57 kVrms/0.1 Hz
Frequency	0.01 Hz to 1 Hz	0.01 Hz to 1 Hz
Load Capacity at max voltage	2.5 μ F	1 μ F
DF range	1×10^{-4} to 1	10^{-4} to 1
DF Resolution	1×10^{-5}	1×10^{-5}
PD background noise level	20 pC	20 pC
PD location accuracy	1% of cable length	1% of cable length

HDW Electronics

(<http://www.hdwelectronics.com/products.htm>)

HDW Electronics makes the cosine/rectangular test set in four voltage ranges, see Table 6-3. It is used for withstand testing but also has the capability of measuring the leakage current. The voltage waveshape is essentially a square wave except that the voltage switches from one polarity to the other at about the same rate of change of voltage as the power frequency at zero crossover. Please note that for a square waveform the rms and peak values of the voltage are the same.

Table 6-3
Specifications of HDW Electronics VLF Test Sets

	VLF 27	VLF 40	VLF 52	VLF 60
Max. Voltage cosine/rectangular	27 kV	40 kV	52 kV	60 kV
Output frequency	0.1 Hz	0.1 Hz	0.1 Hz *	0.1 Hz
Load Capacity at max voltage	5 μ F	2.5 μ F	5 μ F	1 μ F
Leakage Current		0 to 7 mA		0 to 5 mA

* 0.1 Hz trapezoidal waveform

High Voltage

(<http://www.hvinc.com/products.htm>)

High Voltage Inc manufactures VLF test sets with a sinusoidal voltage output. The specifications of the tests for medium voltage cable tests are listed in Table 6-4.

Table 6-4
Specifications of High Voltage Inc VLF Test Sets

	VLF-25	VLF-4022	VLF-50	VLF-6022	VLF-65	VLF-90
Max Voltage	17.5 kVrms	28 kVrms	35 kVrms	42 kVrms	46 kVrms	63 kVrms
Frequency	0.01 Hz to 0.1 Hz	0.01 Hz to 0.1 Hz	0.01 Hz to 0.1 Hz	0.01 Hz to 0.1 Hz	0.01 Hz to 0.1 Hz	0.01 Hz to 0.1 Hz
Load Capacity	0.4 μ F	5.5 μ F	50 μ F	5.5 μ F	22 μ F	2.2 μ F

High Voltage Inc also supplies an instrument that measures DF at 0.1 Hz. The specifications are listed in Table 6-5.

Table 6-5
Specifications of High Voltage Inc Dissipation Factor Measuring Instrument

	TDB-60
Max. Voltage	42 kV rms
Frequency	0.1 Hz to 0.2 Hz
Max. Current/load capacity at max voltage	35 mArms/1.3 μ F
DF resolution	5×10^{-4}

KEMA

(http://www.kema.com/high_and_medium_voltage/index.html)

KEMA provides off-line diagnostic test services of PD detection, measurement and location, utilizing a 0.1 Hz power source, to identify weak spots in the insulation. KEMA also has the capability to make dielectric spectroscopy measurements using the GE IDA. The PD characteristics that can be measured are listed in Table 5-2. KEMA uses its large database of test data and a set of knowledge rules to assess the severity of the identified defects and recommend a course of action.

Locating the source of PD when testing branched circuits is always complicated due to the multiple reflections that occur from the cable branches. KEMA has solved this problem by

installing sensors at more than two points in the circuit and measuring the arrival times of the pulses at the sensors using a satellite time signal as a reference. KEMA is also developing an on-line PD detection system monitor PD.

Typical classification of the assessment of a cable circuit is listed in Table 6-6.

Table 6-6
Typical Recommendations After PD tests (0.1 Hz) by KEMA

Class 1	Immediate replacement
Class 2	Replace within one year
Class 3	Repeat diagnosis
Class 4	Not expected to fail within 5 years due to PD

Power Frequency Test Equipment

Power Frequency test equipment produces a voltage waveform that duplicates service frequency. Thus values of DF and PD measured in diagnostic tests should be representative of in-service values. This is obviously an advantage of on-line testing. However for off-line power frequency tests, a large power capacity would be needed for long cables. One way to overcome this is to use a series resonant power supply, an approach taken by IMCORP.

IMCORP

(<http://www.imcorpotech.com/INDEX.HTM>)

IMCORP provides off-line diagnostic test services and equipment to detect local defects that uses a series resonant power supply to energize the cable system under test. The primary service offered by IMCORP is PD detection, measurement and location, although instrumentation to measure DF to assess the global condition is now under development. The DF measuring equipment is used in conjunction with the resonant power supply.

The specifications for PD measurements are listed in Table 6-7. The PD characteristics that can be measured are listed in Table 5-2.

Table 6-7
IMCORP PD Instrumentation Specifications

PD inception voltage	± 500 V
PD extinction voltage	± 500 V
PD resolution	5 pC
PD location accuracy	< 1% of cable length, typically ± 1 m
Cable assessment	Yes (see below)

A typical test procedure is as follows;

- Low voltage time domain reflectometry (TDR) is performed to map joints or cable anomalies (e.g., neutral corrosion) in cable circuit
- PD calibration is carried out to determine sensitivity of the measurement
- PD test is performed
- Data analysis to assess the severity of the defect and recommendations

As mentioned previously PD behavior is statistical in nature so that the severity of a defect is assessed by comparing the data with discharge patterns of known defects and acquiring as much knowledge as possible about the cable system under test.

Based on a statistical analysis of the data, IMCORP makes an assessment of the condition of the cable circuit tested. Table 6-8 is a list of typical recommendations by IMCORP, although other recommendations are possible.

Table 6-8
Typical Recommendations after PD Tests (60 Hz) by IMCORP

IMCORP Recommendation	Example Description
Immediate Repair	The circuit should not be put back in service until PD site has been repaired
Schedule Repair	The circuit can be put back in service but should be scheduled for a repair at the PD site within one year
Monitor/Retest 1yr	Cable system has a defect site that should be retested in one year to determine trending information.
Monitor/Retest 3yr	30 yr XLPE cable system has no severe* PD sites, but should be retested in 3 years to see if any new defect sites have started or currents sites have degraded
Monitor/Retest 5yr	15 year old cable system has no PD sites but should be retested in 5 years for trending purposes.

*On the basis of local statistics

Oscillating Wave (Damped AC) Test Equipment

There is some concern that diagnostic tests, particularly partial discharge tests, carried out at low frequencies may not have the same characteristics such as inception and extinction voltages as observed at power frequency. This led to an alternative test voltage waveform that did not require the large power source that a power frequency test set requires. The test waveform is a damped oscillation. There are two main suppliers of DAC test equipment, HDW Electronics and Hi Volt.

HDW

(http://www.hdwelectronics.com/OWTS_.htm)

The principle of the HDW Electronics test set is that the cable circuit under test is charged with a DC voltage to a specified voltage and then discharged via an electronic switch through an air-core inductor. The charging time is of the order of 20 seconds or less so that potentially harmful space charges do not occur. The inductor and capacitance of the cable forms a resonant circuit that produces a damped oscillatory sine wave. The frequency range is 50 Hz to 1 kHz. The instrument was developed at Delft University of Technology in the Netherlands [15]. Seitz Instruments AG in Switzerland commercialized the instrument and allows SebaKMT in Baunach, Germany (in North America, HDW Electronics is the official representative) to market worldwide the OWTS 25 system.

The specification of the oscillating wave test system (OWTS) is given in Table 6-9. The PD characteristics that can be measured are listed in Table 5-2. Although the test set is primarily designed to detect, measure and locate partial discharges, it can also measure the DF although its sensitivity is not as high as DF-specific measuring equipment. The rate of decay of the oscillation will depend on the resistance of the circuit, i.e., the DF of the insulation. Although the limit of the sensitivity of the DF measurement using the DAC (0.001) is about that for healthy XLPE insulation, it should be possible to measure the DF of aged XLPE cables. Typically up to 50 shots are applied at a specified voltage level. From one trace it is possible to determine the PD inception and extinction voltage, the pulse magnitude and dissipation factor.

Table 6-9
Specifications of OWTS

	OWTS 25
Max. voltage	36 kVDc/25 kVrms
Frequency range	50 Hz to 1 kHz
Load Capacitance	0.1 μ F to 2 μ F
DC charging current	12 mA
PD test range	1 pC to 100 nC
PD location	Yes
DF	0.001 to 0.1

HV Technologies

<http://www.hvtechnologies.com/ldg50.htm>

The test set manufactured by HV Technologies is known as the Complex Discharge Analysis (CDA) as the waveform applied to the cable is a heavily damped AC. A DC voltage charges the cable to a predetermine voltage and then the cable is discharged into an inductance and an auxiliary capacitance connected in parallel. The charging time is about 10 seconds to avoid unwanted space charge effects and the discharge time is about 10 ms, approximately the same as a half cycle of a power frequency cycle. The recommended test voltage is $2U_0$ and 10 shots applied at each voltage level. The specifications are given in Table 6-10.

Table 6-10
Specifications of the CDA-30 and CDA-50

	CDA-30	CDA-50
Max voltage	45 kV (peak to peak)	85 kV (peak to peak)
Max charging voltage	30 kV DC	50 kV DC
PD sensitivity		5 pC
PD location	Yes	Yes

HV Technologies also manufactures a hand-held PD probe (weight ~ 1 kg), the Differential Lemke Probe, Model LDP-5. It is suitable for detecting and measuring PD in cable accessories. It can be used with inductive, capacitive, UHF or ultrasonic sensors and the output from the probe can be fed into a computer to store and display the data, e.g., phase resolved discharge patterns.

Dielectric Spectroscopy

Dielectric spectroscopy is a global measurement of the insulation. It essentially measures the real and imaginary parts of the dielectric permittivity, see Eq. (1), and thus the DF over a range of frequencies, typically from 0.001 to 100 Hz. There is one commercial instrument available, manufactured by GE, which acquired the technology from Programma in Sweden. Table 4-1 lists the advantages and disadvantages of global measurement techniques such as DS.

GE

http://www.gepower.com/prod_serv/products/electrical_test/en/insulation_diag.htm

GE manufactures the Insulation Diagnosis Analyzer (IDA) 200™ which measures capacitance and dielectric losses at discrete frequencies (0.0001 Hz to 1000 Hz). It can operate at mains voltage or combined with a 30 kVpk (21 kVrms) high voltage amplifier. It has been used to detect water treeing in cables at frequencies from 0.1 Hz to 1 Hz.

Field and laboratory testing has led to 3 different conditions for XLPE cables with water trees. The conditions are listed in Table 6-11.

Table 6-11
Assessment Conditions of XLPE Cables Given by Dielectric Spectroscopy (DS)

Assessment Class	ϵ' , ϵ'' Behavior	ϵ' , ϵ'' values	Cable BD Values	Strategy
As new cables	ϵ' & ϵ'' relatively constant with Freq. & do not vary with voltage	$\epsilon'' < 8 \times 10^{-4}$ at U_0	$> 4U_0$	Retest in 5 to 10 years
Significantly aged	ϵ' & ϵ'' relatively constant with Freq. & but increase with voltage	$\epsilon'' \geq 8 \times 10^{-4}$ $\Delta\epsilon''^* \geq 1 \times 10^{-4}$ $\Delta\epsilon' \geq 2 \times 10^{-4}$	$> 2.5U_0$ $< 4U_0$	Retest in 2 to 5 years
Severely aged	ϵ' & ϵ'' increase with voltage. $\epsilon'' \propto 1/f$		$< 2.5U_0$	Replace as soon as possible

$$\Delta\epsilon''^* = \epsilon''(U_0) - \epsilon''(0.5U_0) \text{ \& } \Delta\epsilon' = \epsilon'(U_0) - \epsilon'(0.5U_0)$$

The increase in the harmonic content (harmonic distortion) of the loss current was also found to be a good indicator of the cable condition.

Partial Discharge Measurements

Partial Discharge measurement equipment is not normally integrated with the high voltage power supply and can be purchased separately. Several manufacturers manufacture PD measuring systems without providing a power supply. Additional companies that supply PD detection equipment for cable systems, other than those already mentioned in this section, are DTE, TechImp and Transinor.

DTE

(www.dtetech.com/technologies/cablewise/)

DTE provides a PD testing service and does not sell their detection system. The system is different from all the other commercial PD detection systems for cables as it operates in the frequency domain rather than the time domain. It detects the frequencies of the PD pulses using a spectrum analyzer. DTE uses the technique to make on-line measurements so that no outage is required. The high sensitivity of the technique allows measurements to be made on-line. DTE has developed a condition assessment rating, Table 6-12, based on the test data, knowledge of the cable system under test, and their data bank.

Table 6-12
DTE Cable Assessment Rating

Condition Level	Action Recommended
1	No action need be taken
2	Repeat test every two years
3	Low probability of failure in 2 years, repeat test in 1 year
4	Medium probability of failure in 2 years. Consider replacement or other remedial action
5	High probability of failure. Consider replacement

Table 5-1 lists the advantages and disadvantages of on-line testing vs. off-line testing.

TransiNor

(<http://www.transinor.no/>)

TransiNor manufactures the Acoustic Partial Discharge Analyzer (APDA) that uses a glass fiber rod that acts as wave guide to transfer acoustic signals from internal defects in cable accessories. The rod, which is in contact with the accessory, is moved slowly over the surface to detect PD. The results are presented on an LCD screen and can be stored on a computer. The instrument can operate in two modes, continuous mode to detect the PD, and phase mode to give the phase angles of the PD pulses. The sensitivity of the technique is in the range of 5 to 50 pC depending on the type of accessory and the location of the discharge site.

TechImp

(<http://www.techimp.com/eng/products.html>)

TechImp manufactures PD diagnosis system that can be used on cables as well as other high voltage equipment. The digital PD detection system uses special instrumentation to record the PD pulses to overcome the need for a large computer memory buffer to collect the large amount of data accumulated when discharge pulses are sampled at a rate sufficient to record its waveshape. The pulses are sorted according to their shape and fuzzy logic applied to separate the pulses into clusters on the applied voltage waveform. By this means different sources of PD pulses and noise can be identified. For example, PD in voids, electrical trees, and surface discharges can be identified even if they are occurring simultaneously. The technique requires the signal to be measured without much attenuation which means that the discharge source has to be near the sensor. The technique has been used to detect PD in transmission cable systems but little data is available for medium voltage cables.

Table 6-13
List of Suppliers of Diagnostic Test Equipment/Services

Name	Voltage Source*	Tests**	Bulk	Loc	Criteria	Web Site
Baur	VLF (sin)	W, DF, PD	X	X	Y	Y
HDW	VLF (cos/rec)	W,PI	X			Y
High Voltage	VLF (sin)	W, DF	X		N	Y
KEMA	VLF (sin)	W, PD, DF	X	X	X	Y
GE/Programma	0.001-1000 Hz	DS	X		Y	Y
Tettex	DC	RV	X			Y
HDW	DC	RV	X		Y	Y
SEBA	DC	DI	X		Y	Y
ALFF	DC	PI/DI	X			Y
Powertech	DC	DI	X		Y	Y
HDW	DAC	PD, DF	X	X	?	Y
HV Technologies	DAC	PD		X	?	Y
IMCORP	60 Hz	W, PD,(DF)	(X)	X	Y	Y
Cutler/Hammer	60 Hz	W, PD		X	?	?
TechImp	60 Hz?	W, PD		X	?	Y
Hipotronics	60 Hz	W, PD		X	?	Y
DTE	On-line	PD		X	Y	Y?
TransiNor	On-line	PD acoustic		X		Y
HV Technologies	On-line	PD, acoustic, electromag.		X		Y

* VLF – very low frequency, typically 0.1 Hz

DAC – damped AC

**W – withstand

DF – dissipation factor

DS – dielectric spectroscopy

PD – partial discharge

PI – polarization current

DI – depolarization current

RV – recovery voltage

7

CONCLUSION

There is continuing improvements in the diagnostic testing of cable systems, both in systems that measure the global condition of the insulation and in systems that measure localized defects, i.e., partial discharge measurements.

There is also continuing improvement in the interpretation of data from the diagnostic tests. The more information known about the cable circuit under test (type of cable, accessories, year of installation, etc) the better the interpretation will be.

Interpretation should improve as the knowledge base is increased for the different diagnostic techniques. At the utility level this can be done by repeating tests on selected circuits periodically, i.e., trending, and correlating the data with actual performance. This requires the collection of failure statistics.

Assessment of cable circuits is improved if several diagnostic tests can be performed, for example, tests to assess the condition of the neutral of extruded cables, a global measuring diagnostic, e.g., dissipation factor test, and a partial discharge test.

Most diagnostic techniques can identify good and really bad cable systems. The statistical nature of the aging and failure mechanisms makes it extremely difficult for diagnostic tests to predict remaining life. Diagnostic tests should be able to give an assessment of the risk of failure.

Cable systems between very good and very bad condition are more difficult to assess. Periodic testing (trending) of some of these cable circuits will improve the interpretation of data.

Care must be taken in performing any diagnostic test to prevent misleading results (leakage or stray currents affecting global measurements, or external noise giving false PD readings).

Most of the PD data indicate that the major source of PD is at the accessories, i.e., the problems are probably due to poor workmanship.

The maximum test voltage for off-line tests should not exceed $2U_0$, particularly for older cable circuits. Newer cable circuits may be tested up to $2.5 U_0$. Testing at $3U_0$ runs a greater risk of a failure during the test or shortly after the cable has been restored to service.

The different diagnostic test service providers use different test methods so that it is difficult to compare data. Utilities would benefit if some comparison tests could be carried out or some standard tests developed.

8

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A

AGING AND DEGRADATION MECHANISMS

Water trees, which are collections of water-filled microvoids, grow from contaminants, protrusions and water-filled voids in the insulation. Water trees that originate from a protrusion or contaminant at the insulation/semicon interface are known as vented or streamer trees and those that originate from water-filled voids within the insulation are called bow-tie trees due to their shape. Water trees tend to grow in the direction of the electric field. A typical water tree is shown in Figure A-1.

Some properties of water are:

- No PD
- Do not normally produce breakdown even when bridging the insulation
- Create stress enhancement from which electrical tree initiates
- Convert to electrical tree to cause failure due to overvoltage, lightning or surge
- Partial discharge occur when electrical has formed
- Become invisible when allowed to dry
- BD strength of dried cable increases but quickly decreases when rewetted
- Grow at low fields (2 kV/mm (50 V/mil))
- Growth rate is slow and many trees reach a limiting length
- Trees initiated at soluble contaminants grow faster than trees from voids and do not tend to reach a limiting length, i.e., they keep growing
- Can be neutralized by chemical reaction (cable rejuvenation)
- Large density of water trees can be detected by DF, RVM, leakage current.
- Growth rate depends on material and electric stress
- Can grow in some EPRs



Figure A-1
Typical vented water tree growing from conductor shield. Note bow-tie tree on left hand side

Electrical trees are tree-like growths of gas-filled or carbonized microchannels, typically 0.1 to 10 μm diameter, that originate at electric field enhancement such as water trees, protrusions at the semicon /insulation interface or sharp contaminants in the insulation. The growth of electrical trees is caused by partial discharges within the microchannels. The initiation of an electrical tree can take several years and involves the repeated injection and extraction of charges at the tip of the protrusion into the insulation. The initiation stage of an electrical tree cannot be detected in cables. The growth stage can be detected by PD measurements.

- Local stress to initiate an ET is $\geq 100 \text{ kV/mm}$ (2500 V/mil)

- Once initiated ET can propagate at stresses as low as 2 kV/mm (50 V/mil)
- Growth rate varies with electric stress ranging from some $\sim 10 \mu\text{m/h}$ to 100 mm/h in XLPE
- Some materials more resistant to ET than others
- Growth rate can be large for small magnitude PD
- Can initiate from water trees, as can be seen in Figure A-2.

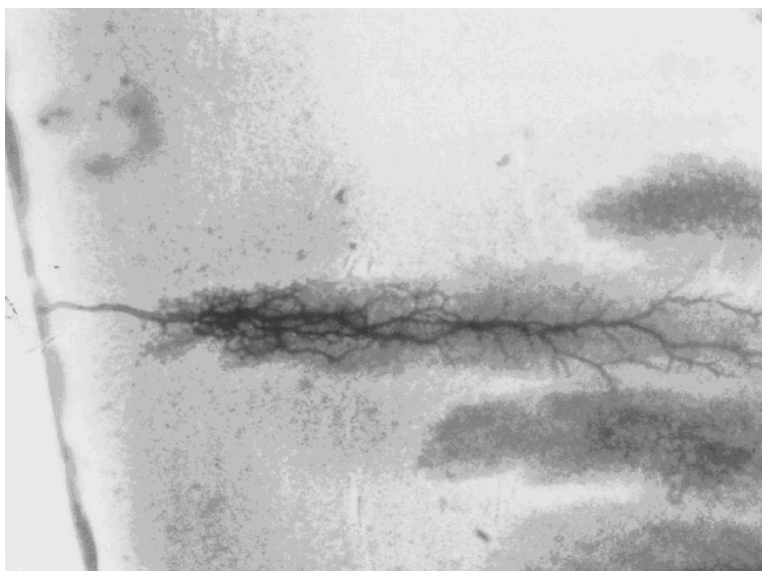


Figure A-2
Electrical tree growing into a water tree

As already mentioned the mechanisms of aging and degradation depend on the type of cable and accessories and the operating conditions of the circuit. Tables A-1 to A-4 list the different aging and degradation mechanisms of cable circuits for thermal, electrical, mechanical and electrical stresses respectively. Each table shows the stresses, the aging and degradation mechanisms, and the effects of these mechanisms.

Table A-1
Possible Thermal Aging and Degradation Mechanisms of Cable Systems

Thermal Factors	Aging and Degradation Mechanisms	Effects
High temperature, Hot spots	- Chemical reactions (PILC & extr.) - Incompatibility of materials	- Increased dielectric losses → DF - Increased dielectric losses → DF
Temperature cycling	- Thermal expansion/contraction (radial and axial) (PILC & extr.)	- Formation of soft spots/voids, wrinkles → PD, DF, ET, tracking
Low temperature	- Thermomechanical (PILC & extr.) - Diffusion/migration of greases, etc. - Anneal locked- in mechanical stresses - Melting/flow of insulation (extr.) - Hardening, cracking, softening, loss of mechanical strength, embrittlement of sheath, jacket and insulation (PILC & extr.) - Shrinkage, loss of adhesion, separation, delamination at interfaces (extr.) - Swelling, softening, loss of mechanical strength, (extr.)	- Formation of voids → PD - Movement of accessories → PD - Conductor movement/penetration, rotation of cable → voids → PD - Movement of accessories → PD - Formation of voids → PD - Formation of voids → PD - Conductor movement → PD - Loss of oil → voids → PD, DF - Ingress of water → increased loss (DF), PD - Formation of voids → PD - Formation of voids → PD - Conductor movement/penetration, → voids → PD - Movement of accessories → PD - Increased dielectric losses (DF)

extr. extruded cables

PILC paper insulated lead covered

DF dissipation factor ($\tan \delta$) $\approx$ power factor

PD partial discharge

ET electrical treeing

WT water treeing

Table A-2
Possible Electrical Aging and Degradation Mechanisms of Cable Systems

Electrical Factors	Aging and Degradation Mechanisms	Effects
Voltage, AC, DC, Impulse	- Partial discharges (PD) at contaminants, voids (extr.) - PD in voids, protrusions, and wet paper (PILC) - Electrical treeing (ET) at protrusions, voids - Water treeing (WT) in presence of water at contaminants, voids (extr.) - Dielectric losses and capacitance (PILC & extr.) - Intrinsic breakdown (PILC & extr.)	- Erosion of insulation → ET - increased losses, Tracking - Formation of gas-filled channels → PD - Increased losses (DF), ET → PD - Increased temperature, thermal aging, thermal runaway - Immediate failure
Current	- Overheating (PILC & extr.) - Thermomechanical (see thermal aging)	- Increased temperature, thermal runaway

extr. extruded cables

PILC paper insulated lead covered

DF dissipation factor ($\tan \delta$) $\approx$ power factor

PD partial discharge

ET electrical treeing

WT water treeing

Table A-3
Possible Mechanical Aging and Degradation Mechanisms of Cable Systems

Mechanical Factors	Aging and Degradation Mechanisms	Effects*
Tensile, compressive, shear stresses Fatigue, cyclic bending, vibration	-yielding of materials (PILC & extr.) -Cracking (PILC & extr.) -Rupture -Thermomechanical (see thermal aging)	-Rupture of components -Loss of adhesion, separation, delamination at interfaces → PD -Loss of oil → PD, DF -Ingress of water → PD, DF

extr. extruded cables

PILC paper insulated lead covered

DF dissipation factor ($\tan \delta$) $\approx$ power factor

PD partial discharge

ET electrical treeing

WT water treeing

Table A-4
Possible Environmental Aging and Degradation Mechanisms of Cable Systems

Environmental Factors	Aging and Degradation Mechanisms	Effects*
Water/humidity Liquids/gases Contamination	-Increased losses in paper and extruded insulations (PILC & extr.) -Electrical tracking along external insulation surfaces (PILC & extr.) -Water treeing (extr.) -Corrosion of conductor, shield, and sheath (PILC & extr.)	-Increased capacitance, losses (DF), PD -Increased temperature, thermal aging, thermal runaway -Flashover -Increased losses (DF) and ET -Loss of continuity of shield (resistance measurement) -Loss of continuity of conductor -Loss of oil → PD, DF -Ingress of water → PD, DF
Radiation	- Hardening, cracking, softening, loss of mechanical strength, embrittlement	-Formation of voids → PD -Increased losses (DF),

extr. extruded cables

PILC paper insulated lead covered

DF dissipation factor ($\tan \delta$) $\approx$ power factor

PD partial discharge

ET electrical treeing

WT water treeing

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