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Art. nr. 821-071, version 4.1, 11/2019 Information subject to change. Subject to modifications.

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Cable diagnostic in MV underground cable networks

Diagnostic Handbook / Theoretical background and practical application

- VLF testing
- tan delta loss factor measurement
- Partial discharge localization and measurement

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Testing and Diagnostics

on Medium-Voltage Underground Cable Networks

Based on VLF

truesinus®

1. Introduction

As an introduction we want to show how cable testing and diagnostics allow you to plan the maintenance of cable routes, thus preventing expensive power failures and significantly reducing maintenance costs for cable networks. We also list tried-and-tested measurement methods, describe these in detail and introduce various options for their use. Finally, we provide guidance on how to successfully implement diagnostics.

1.1 Economic background to cable diagnostics

Every network operator understands the importance of cable networks. When planning the maintenance of these networks, distribution network operators have to manage the conflicting requirements of scarce resources, high standards in terms of security of supply, and the issue of networks that are becoming older and more complex.

On the one hand, the budget available for maintenance is being steadily eroded and, on the other, lower grid charges caused by deregulation are leading to higher pressure on the cost side. Another issue is the reduction in personnel capacity. At the same time, customer expectations regarding network quality and security of supply are rising. This results in a demand for cable networks that are always intact and fault free, and for failure prevention. Medium-voltage networks are also becoming increasingly complex due to their interlinking and frequent modification. This gives rise to cable routes that incorporate a wide range of cable types, joints and terminations. It also leads to different degrees of ageing, depending upon the cable segments in question. These conflicting requirements can be resolved using condition-based maintenance. The data for this are supplied by cable diagnostics. So what do we already know about cable diagnostics?

There is a myth that cable diagnostics is expensive, complex and not worthwhile because only very few cable faults occur. Let's take a closer look at these assertions. In what follows, we wish to further illustrate the benefits of cable diagnostics from a technical and financial point of view.

Cable diagnostics is widely used in the acceptance testing of new cable routes. More and more power supply companies are replacing the simple voltage test with intelligent voltage testing, called "Smart Testing". This means that in the Monitored Withstand Test, voltage testing and diagnostic measurement are performed at the same time. This saves time and supplies valuable information for asset management. This is because it gives users a very clear idea of the quality of the assembly work. Assembly errors are thus highlighted at an early stage and can be eliminated during the warranty period. During cable testing on worn cables, a distinction is made between a general condition evaluation of critical cables and the inspection of cables after repairs. The general inspection supplies information about the condition of the network status, which facilitates maintenance planning. Testing after repairs has two purposes:

- firstly, to check the assembly quality and
- secondly, for condition detection and to check whether the problem has been rectified. This allows claims to be asserted with the company that has performed the repairs during the warranty period, the quality of the cable route to be improved and consequential costs to be avoided.

In the following paragraphs, we will compare the investment costs with the benefits of diagnostics in numerical terms. The figures mentioned in the calculation below refer to common values derived from a German power utility and shall be used as an example only.
When considering this subject from a financial perspective, the following investment costs should be planned over a 10-year period. Engineers and technicians are required for cable testing and diagnostics. Initially, costs start at around € 50,000 per year. Then the costs of training and the investment in building staff experience must be added to this. The costs for staff and expertise add up to around € 54,000 per year. In addition, expenditure of between € 9,000 and € 30,000 per year must be allowed to cover the required equipment, which gives rise to a total budget for testing and diagnostics of € 63,000 to € 84,000 per year. This represents costs of € 250 – € 840 per cable route, depending on the number of measurements conducted.
This compares to the following savings that can be achieved by using cable testing and diagnostics:

Failures that occur after the warranty period has expired can be significantly reduced by checking assembly quality, resulting in savings of at least € 2,000 – € 5,000 per component.
Condition-based maintenance makes it possible to strategically replace components before they fail. This gives a saving of at least € 2,000 – € 5,000 per component.
Evaluating the condition of cable routes makes it possible to strategically plan for maintenance projects. For example, if a weak spot is detected, the repair can be scheduled for the next time excavation is necessary in this area. If this is not discovered in time and subsequently leads to a fault, an additional excavation must be commissioned, which can be complex and expensive, especially in an urban area. The savings in such a case are at least € 10,000.
Diagnostics also help when worn cable routes are being replaced. Once cables have reached a certain age, they are often replaced on a precautionary basis to prevent failures. In this situation, diagnostics can be used for condition evaluation, which can extend the service life of a cable if it turns out that the cable is still in good condition despite reaching the end of its expected service life.
Let's assume the costs for laying a new cable route are € 300,000 and the normal service life of a cable is 40 years. With the aid of diagnostic measurements, it is now possible to establish that the cable is still in very good condition and can therefore remain in place within the network for a further 10 years. This measurement therefore extends the service life of the cable route by 25%. If this is the case for several cable routes, savings of over € 100,000 per year are possible. Furthermore, sections of the cable route can be replaced instead of replacing the entire route. This has proved its value several times, with one example being a user of BAUR VLF truesinus® technology. Instead of replacing the entire cable with a length of nearly 2,000 m, he was able to replace a section of just 618 m, thereby saving € 131,960. Comparing the required investment costs with the benefits, we see the return on investment attained by testing and diagnostics. It is clear that the potential savings are not as may be assumed when restricted only to the elimination of cable faults. There are also enormous savings to be made by extending the service life of cables, and by replacing segments rather than entire routes. We can therefore refute the myths that cable diagnostics is expensive and not worthwhile.

1.2 Standards and methods overview

Standards

More and more committees are taking up the subject of cable diagnostics, which has led to some changes and progress in this area. All of the standards that have been revised in recent years now cover the subject of diagnostics and this has become an instrument used by network operators in the maintenance of their networks.
IEC, IEEE, DIN VDE and CIGRE represent the most important standards and committees on the subject of cable diagnostics. So what is in the standards and what changes have taken place in recent years?

IEC 60502-2014 covers, among other things, testing and diagnostics for distribution networks in the medium-voltage range from 6 kV to 30 kV. An update to the standard led to the inclusion of the 0.1 Hz sinusoidal VLF test method and the recommendation of tan delta and/or partial discharge testing to accompany cable testing. The simple DC test for plastic cables was removed from the standard.

IEEE: Following the introduction of IEEE 400-2012, the VLF (Very Low Frequency) test method with sinusoidal 0.1 Hz is now also listed in the standard; this is the only method listed for which sufficient experience exists on the market and that is classified as "useful" or "potentially useful" for all application cases. Moreover, the HV DC testing of XLPE cables is no longer recommended due to bad experiences. Following the introduction of **IEEE 400.2-2013**, the tan delta Monitored Withstand Test was introduced onto the market. This means performing the VLF sinusoidal voltage test with simultaneous diagnostic measurement.

CIGRE: The committee of CIGRE (WG B1.58) has also set up a working group on the subject of cable diagnostics in the medium-voltage range, thereby assigning more importance to this area.
DIN VDE: The DIN VDE recommendation for commissioning testing of medium-voltage cables includes a VLF voltage test with accompanying PD testing that permits a reduction in the test level and test duration.

It is clear that all the listed standards include and recommend tan delta and/or partial discharge testing to accompany the VLF 0.1Hz voltage test.

Measurement methods

Cable testing technology has been in a state of continuous development over the last few decades. DC voltage withstand testing was used initially but has been replaced by Very Low Frequency (VLF) testing, which only provides information on whether the cable is OK at the time of the test or whether a fault or breakdown has occurred during the test. It provides no information about the cable's condition or its remaining service life. For this reason, the simple cable test is falling out of favour and it is increasingly being replaced by the Monitored Withstand Test, which arose from cable testing. In addition to cable testing, this also includes a tan delta and/or partial discharge measurement and therefore provides more in-depth information about the condition of the cable and its joints and terminations. The current state of the art permits a protective test with simultaneous diagnostics plus a well-founded, predictive statement about the condition of the cable.

VLF

BAUR technology covers every measurement method from VLF cable testing, through tan delta and partial discharge testing, to Monitored Withstand Testing. The market-leading truesinus® technology developed by BAUR provides a precise basis for significant and reproducible cable tests or condition evaluations based upon tan delta or partial discharge testing, even for simultaneous measurements such as MWT or Full MWT. It permits the least destructive cable testing and condition evaluation of medium-voltage cables in compliance with VDE, IEC and IEEE.
BAUR's VLF or Very Low Frequency test is based upon a sine curve with a frequency of 0.1 Hz, and can be shown to be comparable with the results of the 50 Hz sinusoidal testing and diagnostics.

This comparability has been comprehensively tested in practical, everyday situations by field measurements and has proven its value in numerous studies and field tests. The most important factor in VLF testing is the reproducibility of the measurement results. This means that the influence of the measurement system upon the measurement result is minimised and the results are therefore load independent, representing a clear advantage compared with other methods. VLF sinewave test voltage is the only available test voltage that allows simultaneous measurement of PD and TD.

Tan delta

The tan delta measurement provides information about water trees, damp and wet joints, and thermal and chemical cable ageing, and indicates the presence of partial discharges. Three parameters are needed for the tan delta measurement:

- Mean TD (MTD)
- Standard deviation (STD)
- Delta tan delta (DTD)

The standard deviation, in particular, provides a great deal of information. Prerequisites for the success of this are a high tan delta precision of 1E-4 and a high resolution of 1E-6. Particular care should be taken to ensure the layout is the same as for the simple VLF test, and that it is possible to display the measurement results during the measurement, which allows diagnostics to be performed easily. The combination of the results of mean tan delta, standard deviation, and delta tan delta allow a detailed analysis of cable condition and indicate reasons for degradation.

Partial discharge

The partial discharge testing provides information about the quality of installation work, locates partial discharges in joints and cable terminations, and locates "electrical trees" and paper-insulated cables.
The following equipment is required to perform partial discharge testing:
A VLF voltage source, an appropriate coupling capacitor and a PC to control the whole process. With this combination of measuring devices, the information can be found and the measurement results supplied as in the example given. Even the smallest of faults – for example an air pocket between the insulating body and the field control – can be highlighted using partial discharge testing.
The partial discharge testing also provides a phase-resolved representation, which provides information about the type of fault. This phase-resolved representation of the air pocket in the picture leads us to suspect that the cable contains a non-conducting material that is not in direct contact with the metal electrode.

Monitored Withstand Test

VLF cable testing provides information about whether the cable is OK and is used during the commissioning of new or repaired cables for use with a voltage of up to 3x U_0. It is increasingly being replaced by the Monitored Withstand Test. The tan delta measurement diagnoses the condition of the cable in terms of ageing and moisture. The PD testing locates partial discharges, uncovers installation faults and provides initial information about the type of fault.

BAUR diagnostics systems

BAUR diagnostics systems include a VLF sinusoidal voltage source, ideally with integrated tan delta function, a coupling capacitor for the partial discharge testing and BAUR VLF truesinus® technology. These systems range from smaller variants such as the frida TD or viola TD with PD-TaD 62 coupling capacitor and a PC for controlling the system, through alternative VLF voltage sources such as the PHG for higher voltages and longer cables, to fully integrated diagnostics in the titron or transcable® cable test vans.

1.3 VLF testing versus VLF diagnostics – the fundamental differences

In the past, many utilities have struggled to implement VLF testing and diagnostics in a successful way, mainly because they started to implement VLF testing as the ultimate tool for application on XLPE cable networks. At that time, cable diagnostics was either not yet available or there was no experience to draw on.
If VLF testing is applied to aged cables in a similar way to which it is applied to new cables, it is understandable that the outcome is not satisfactory. A simple VLF test should only be applied to aged cables if the ageing condition suggests it is required.
The most important experience gained has been an understanding of the fundamental difference between VLF testing versus VLF diagnostics.

VLF testing
Before new cable routes are commissioned, VLF testing is mainly used to check the assembly quality. Quality defects can be detected in good time, thereby avoiding high consequential costs. In addition, newly laid cables are tested for safety-related defects by a simple cable test. The new standards and utility experience even combine diagnostics along with a simple withstand test.

A further field of application is testing on worn cables after repair. If a repair was necessary to a cable route, the assembly quality is checked after its completion to establish whether the repair was performed properly and the problem rectified, or whether there are further faults on the cable route. At the same time, the general condition of the cable route is ascertained. Nowadays, most utilities follow the IEEE standard and combine the simple Withstand Test with diagnostics.

VLF testing	Aim: ▪ Intentional stress to the cable under test ▪ Stress to the entire cable to verify its suitability for service	Test voltage: 2.0 – 3.0 x U_0	Test duration: 15 – 60 min.

VLF diagnostics
When evaluating the condition of worn cables, the focus is on checking critical or susceptible cable routes. It is important to understand that the voltage level is deliberately kept low during condition evaluation or cable diagnostics to avoid test loads. Cable testing is only considered when there is a need for this. Diagnostics provides important information that helps to optimise the costs of network planning, as highlighted in the sections above.

VLF diagnostics	Aim: ▪ Keep voltage low to avoid test load ▪ Diagnostics without stress	Test voltage: 0.5 – 1.7 U_0	Test duration: Short < 5 min.

Measurement with a sinusoidal voltage of 0.1 Hz forms the basis for efficient and meaningful cable diagnostics in all fields of application. Since this represents the same voltage shape as that used in actual mains operation, measurement results have proven to be extremely comparable. This is a significant advantage of the VLF 0.1 Hz sine method. Furthermore, the cable route is not exposed to unnecessary loading – in comparison to square wave or similar voltage shapes, for example. This is a particularly important and beneficial aspect in the case of worn components.

Despite the advantages and disadvantages of each of the different testing and diagnostic methods such as 50 Hz sine, 0.1 Hz sine, damped AC (DAC) and 0.1 Hz cos square wave (or 50 Hz slope), the 0.1 Hz voltage shape has the decisive advantage of delivering reproducible and comparable measurement results. This is due to its load independence, which can only be achieved by the truesinus® 0.1 Hz sinusoidal voltage. Thanks to the comparability of the measurement results, the operator can build up empirical and reference values in the field of dissipation factor measurement (tan delta) and partial discharge testing. This comparability of diagnostic results massively increases the benefits of cable diagnostics. A further advantage is the fact that sine 0.1 Hz technology can be used for all meaningful measurement methods, such as dissipation factor measurement and partial discharge testing. Comprehensive cable testing and diagnostics is thus based upon **one** unified technology with 0.1 Hz sinusoidal voltage.

An Example: Benefits and significance of diagnostic measurement methods based upon 0.1 Hz sine

The condition of a three-phase 11 kV plastic cable is to be assessed with the aid of cable diagnostics. The cable is 3,099 m long and has 32 joints within this route.

The dissipation factor measurement performed at the start supplies information on the general condition of the cable. This allows the detection of damp joints and joints subject to the tracking effect, water-tree ageing or thermal leakage currents. A high level of accuracy and a high overall resolution of $1E^{-6}$ are necessary for identifying damp joints. In our example, the dissipation factor measurement shows a deviation between phase 2 and the normal value, which leads to the conclusion that there is moisture in at least one of the joints.

The subsequently performed partial discharge testing identifies partial discharges on phase 2 after a length of 669 m. The partial discharge level of 2,000 pC leads to the conclusion that the cable does not require immediate action. The final information on the real condition of the cable and the joints can only be determined with an overall consideration of the correlation of PD results in combination with the dissipation factor measurement results.

The TDR measurement, which is also used to locate moist joints, shows that the moisture in joint 4 lies at 672 m. The fault location identified in the example coincides with that from partial discharge testing. The partial discharge measurement of 2,000 pC is therefore a distorted result influenced by the moisture in the joint. The joint is more severely damaged than can be seen from partial discharge testing and should be replaced immediately to prevent a failure during operation.

The subsequently exposed joint exhibits clear traces of partial discharges as well as moisture. The decision to replace the joint immediately was therefore appropriate.

The combination of TD and PD is technically possible by using the state-of-the-art diagnostics system PD TaD 62 in combination with a VLF TD system. Further time can be saved, as the dissipation factor measurement and partial discharge testing can be performed in parallel. Comprehensive checking of newly laid or repaired cables or a general condition evaluation can therefore be performed quickly and simply in a single operation without significant extra expense.

Fact box

- PD result shows 2,000 pC at a particular joint
- TD result confirms the signs of water ingress in at least one of the joints
- The PD result is therefore most likely influenced by humidity
- TDR result confirms the irregular impedance change at the suspicious joint
- Joint dissection confirms the presence of humidity

- The severity of a joint with PD is related to the tan delta result
- Tan delta result can identify presence of water along the cable

2. VLF testing

2.1 Why should VLF be used for testing MV underground cables?

Very Low Frequency test voltages were introduced for testing high-power generators. Later, having recognised the danger of DC testing PE/XLPE cables, VLF was identified as one of the possible alternatives. VLF was used as a possible withstand at typically 3 U_0 for one hour. Later, dissipation factor (DF) measurement (tan δ) and partial discharge (PD) measurements were introduced as diagnostic tools. [1]

It is necessary to test the withstand strength of the equipment and cable with a stress similar to or greater than the stress in operation. Diagnostic procedures put the insulation under minimal stress. The first requirement is not to damage the insulation, and the second is to achieve sufficient recognition of the status of the test item. DC testing conflicts with both requirements when testing PE-/XLPE-insulated power cables, and VLF based testing fulfils these needs.

2.1.1 Withstand Test with VLF

VLF Withstand Tests were successfully introduced and standardised for power cables [VDE]. Experience such as that described in [Moh, 2003] and according to [Goc, 2000] (see Fig. 1) explain that the withstand voltage of non pre-damaged insulation at VLF (0.1 Hz) is two times higher compared to that at PLF (50 Hz). In other words, even if higher test voltages are used, non pre-damaged parts of the insulation are not endangered during these VLF tests. [1], [2]

Several advantages can be noted as reasons to test the underground cable system network with VLF.

- Effective tree growth rate with VLF > 1.7 U_0
- Symmetric waveform with truesinus®
- No DC charge – polarisation effect

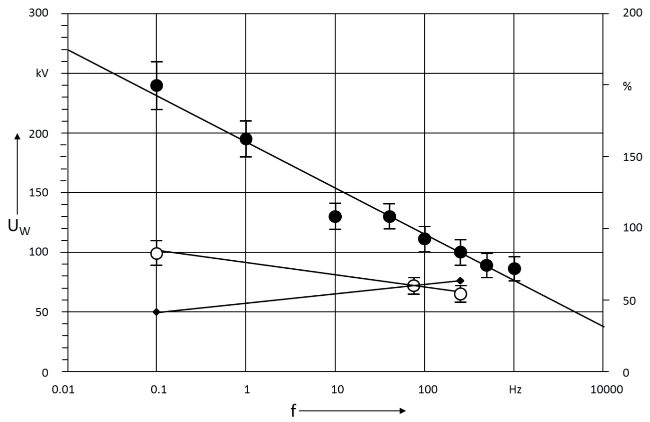


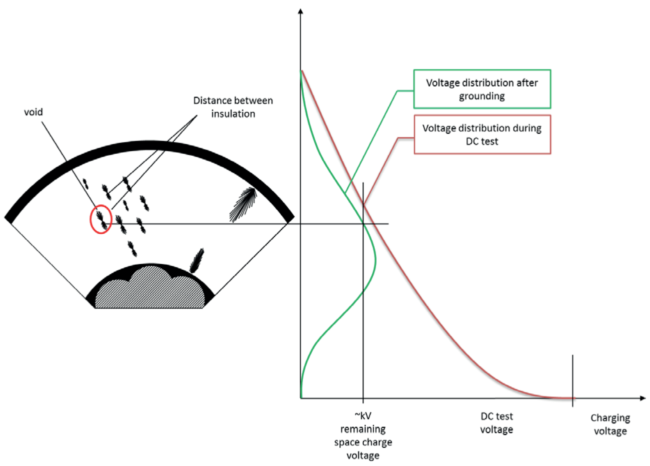
Figure 1:
Withstand voltage as a function of the frequency for model cables without and with mechanical damage [Goc, 2000]: [2]
● Withstand voltage without mechanical damage,
○ Withstand voltage with mechanical damage,
♦ Ratio between withstand voltage with and without mechanical damage [6]

2.1.2 Why should DC test not be used for XLPE cables?

Many power utilities had been using DC voltage for the on-site testing of cables. The same practice was retained when XLPE cables were introduced into the system in the early 1980s. However, studies on cable failures in developed utilities revealed the fact that DC withstand voltage cable testing, which is reasonably reliable on PILC cables, is ineffective in detecting hidden defects in XLPE insulation and conversely that VLF testing exposed those defects. Under laboratory evaluation, DC test voltages as high as 10 x U_0 still did not expose defects.
Additionally, it was found that DC voltage testing can induce trapped space charges in the polymeric material, which are detrimental to the dielectric strength of the cables. In this case, it would appear that cables may successfully pass a DC voltage test, but these cables would breakdown shortly after being re-energised. [3]

IEEE 400.2-2013 even states that "The use of the high-voltage DC (HVDC) Withstand Test for extruded cables has been the source of much discussion. **HVDC is not effective** in detecting certain types of insulation defects in a cable system when compared with AC. A majority of cable manufacturers have discontinued the use of HVDC withstand in their production tests. In the past two or three decades, **evidence has surfaced indicating the likely adverse effect that HVDC test has** on aged XLPE insulations. Subsequently, numerous experiments and discussions have led to the accepted belief that **HVDC voltage does indeed cause space charge** build-up in aged XLPE insulation, which, if remaining in the insulation, can result in cable failures when an AC voltage is reapplied." [4, p. 14]

Space charges can be visualised by plotting the voltage distribution during a DC test between the sheath and core over the distance of insulation. The voltage distribution indicates that voids are acting as small capacitors at particular positions and can store energy. Depending on its position across the diameter, the voltage can reach high levels after several minutes of DC testing. After the test has been completed, the core is discharged and remains earthed, but the voltage distribution along the insulation will remain for a time. Voids that are charged keep their charge due to the surrounding highly insulating XLPE material.
When cables in this state are re-energised, the locations around the voids receive the system voltage plus the charge voltage, causing over-stress and degradation of the insulation.



↗ Figure 2: Space Charges in voids of XLPE during DC testing [5]

2.1.3 Requirements for cable testing and standards

New standards, such as IEC 60060-3 – 2006, define the VLF voltage source as an appropriate waveform for HV field testing; it represents today's state of the art of different HV excitation voltage sources. In fact, based on the aforementioned standard, the VLF cable field test has become a worldwide accepted field test and diagnostic method for commissioning and maintenance work within medium- and high-voltage applications.
Furthermore, the given standards are minimum requirements. The operators are free to choose higher levels of criteria than the standard requirements, such as IEC 60060-3, IEEE STD 400.2 or VDE 0267 or Cenelec HD 620 S1.
Conforming to a standard motivates the suppliers and the users of underground cable systems to improve system reliability. Regular condition monitoring can provide excellent support for avoiding incipient failures on underground distribution systems. In the event of faults and damage related to liability or guarantee procedures, the user or supplier is protected (insured) if the cause of failure can be analysed and localised in a non-destructive way. [6]

2.1.4 Technical reasons for using VLF

- Weight and volume of test equipment
- Mobility for field application
- Higher efficiency in finding insulation defects compared to DC
- Higher sensitivity and precision on TD measurement compared to power frequency or oscillating wave
- Diagnostic efficiency, using truesinus® HV source for PD measurements
- Fault distance monitoring during commissioning and proof tests with PD monitoring
- **VLF testing is far more effective than DC**
- **DC may produce space charges in the dry cable insulation with long term damage to the cable** [6]

2.1.5 General strategic reasons for using VLF

- Improve wide-scale system reliability
- Reduce hours / minutes lost
- Condition based maintenance (use available budget in the most efficient way / decisions on partial cable replacements can be done / costs can be reduced dramatically compared to a complete cable replacement)
- Preventive maintenance (avoid outages, costs can be minimised)
- Realise the full planned network life with high reliability [6]

2.2 Standards for high-voltage field testing for HV cables

In the mid-1980s, for XLPE cables constructed with solid dielectric material, alternative field test methods were developed and presented which use very low frequency (VLF) in the range of 0.01 Hz to 1 Hz. VLF is an AC test, an alternative to using the power frequency of 50 Hz or 60 Hz. Extensive field and laboratory tests have clearly proved not only the practicability of VLF, but also the benefits of the new testing equipment. The most common VLF high-voltage-waveform worldwide is **sinusoidal according to IEC 60060-3.**
VLF testing started to be defined by standardisation committees in 1996. The European Committee for Electrotechnical Standardization, CENELEC, released the first standard HD 620 S1 field testing for MV cables in the range of 6 kV to 36 kV. In 2004, the IEEE published a first field testing guide, IEEE STD 400.2-2004®, for VLF field testing on high-voltage MV cables. [6]

In 2014, the CENELEC HD 620 S1 was finally implemented in the new IEC 60502 standard. VLF testing has now been officially named the recommended testing standard, especially for extruded XLPE underground cables. **The Monitored Withstand Test is further mentioned as a recommended approach for advanced VLF testing.**
The overall field guide IEEE 400-2012 for the application of field tests explains the different available technologies for testing and evaluating the insulation of shielded power cable systems rated 5 kV and above. VLF testing in particular is described in the technology-specific field guide IEEE 400.2 in its latest version from 2013.

The latest IEC 60060-3 standard, released in 2004, deals with test equipment especially for on-site testing and includes VLF test equipment. IEC 60060 standards are so-called horizontal standards.
This means their validity covers all components (such as cables, transformers, rotating machines, etc.) and all voltage ranges above 1 kV. As a horizontal standard, IEC 60060-3 does not define values. The test levels are left to the component-relevant standards (such as IEC 60502-2014, CENELEC HD 620 and 621, VDE 0267 or IEEE 400.2 for cables).

Therefore, the diagnostic approach with VLF can be described as **"testing and diagnostics according to standards!"**

The most important new features of IEC 60060-3 are:
- Inclusion of VLF test equipment
- Provision of accuracy levels for test voltages on site
- Introduction of performance recording for on-site test equipment
- Definition of performance test and performance check for on-site test equipment

The benefit for the customers is that they get and maintain reliable on-site test equipment of certified accuracy and performance. The values for accuracies for on-site equipment are adapted to the needs and the cost structure of on-site equipment. [7]

2.3 Testing and diagnostics according to standards

Medium-Voltage Cables 6 – 69 kV				
	IEC 60502-2 2014	CENELEC HD 620 – 1996	IEEE 400.2-2013	Example Utility Standard
Commissioning testing	3 x U_0 15 min ▪ **VLF 0.1 Hz** ▪ ACRT 15 min, 20-300 Hz ▪ No-load test, 24 h, 1.0 U_0 50/60 Hz ▪ **TD/PD recommended** ▪ 4 x U_0, 15 min, DC	2.0 x U_0 60 min ▪ 45-60 Hz 3 x U_0 60 min ▪ **VLF 0.1 Hz** Oversheath testing	**Testing** 2.2 – 2.8 U_0 15 – 60 min ▪ **VLF** ▪ **VLF MWT** (TD/PD) **Diagnostics** max. 2.0 U_0 ▪ **VLF TD** ▪ **VLF PD**	**Testing** 3 x U_0 30/60 min ▪ **VLF 0.1 Hz** 3 x U_0 5 min ▪ **VLF + PD**
Maintenance testing			**Testing** 1.8 – 2.2 15 – 60 min ▪ VLF ▪ VLF MWT **Diagnostics** Max. 1.5 U_0 ▪ VLF TD ▪ VLF PD	**Testing** 3 x U_0 10 min VLF 0.1 Hz **Diagnostics** Max. 2.0 U_0 ▪ VLF TD ▪ VLF PD

↗ Table 1: Overview of testing and diagnostics standards for MV cables

	High-Voltage Cables 30 – 150 kV		Extra High-Voltage Cables 150 – 500 kV	
	IEC 60840	IEC 60229 Sheath test	IEC 62067-2000	IEC 60229 Sheath test
Commissioning testing	1.7 -2.0 U_0 ▪ ACRT 60 min, 20-300 Hz ▪ No-load test 24 h, 1.0 U_0 50/60 Hz Oversheath testing	4 kV/mm Max. 10 kV 1 min	1.1 – 1.7 U_0 ▪ ACRT 1 h, 20-300 Hz ▪ No-load test 24 h, 1.0 U_0 50/60 Hz	4 kV/mm Max. 10 kV 1 min

↗ Table 2: Overview of testing and diagnostics standards for HV and EHV cables

2.3.1 IEC 60502-2 Edition 3.0 / 2014-02

The new standard IEC 60502 was released in 2014 and is considered a horizontal standard that defines the applicable testing standards for power cables with extruded insulation and their accessories.
Beside the conductor test, the standard also defines the sheath test for the outer protective layer.

IEC 60502-2

Edition 3.0 2014-02

INTERNATIONAL STANDARD

Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 36 kV) –
Part 2: Cables for rated voltages from 6 kV (Um = 7.2 kV) up to 30 kV (Um = 36 kV)

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60038, IEC standard voltages
IEC 60060-1, High-voltage test techniques – Part 1: General definitions and test requirements
IEC 60060-3, High-voltage test techniques – Part 3: Definitions and requirements for on-site testing
IEC 60183, Guide to the selection of high-voltage cables
IEC 60228, Conductors of insulated cables
IEC 60229:2007, Test on cable oversheaths which have a special protective function and are applied by extrusion
IEC 60230, Impulse tests on cables and their accessories
IEC 60287-3-1, Electric cables – Calculation of the current rating – Part 3: Sections on operating conditions – Section 1: Reference operating conditions and selection of cable type
IEC 60332-1-2, Tests on electric and optical fibre cables under fire conditions – Part 1-2: Test for vertical flame propagation for a single insulated wire or cable – Procedure for 1 kW premixed flame
IEC 60811 (all parts), Electric and optical fibre cables – Test methods for non-metallic materials

↗ Table 3: Extract from IEC 60502-2, [8, p. 12]

The new version of IEC 60502 states that VLF testing shall be applied.
"Note 1" applies for VLF testing. It is emphasised that TD and PD may be monitored. According to IEEE 400-2012, this is described as Monitored Withstand Testing.

20.2 DC voltage testing of the oversheath

The voltage level and duration specified in Clause 5 of IEC 60229:2007 shall be applied between each metal sheath or metal screen and the ground.

For the test to be effective, it is necessary that the ground makes good contact with all of the outer surface of the oversheath. A conductive layer on the oversheath can assist in this respect.

20.3 Insulating test
20.3.1 AC testing

By agreement between the purchaser and the contractor, an AC voltage test in accordance with IEC 60060-3 and in accordance with item a), b) or c) as below may be used:

a) test for 15 min with the phase-to-phase voltage U, at a frequency between 20 Hz to 300 Hz shall be applied between the conductor and the metal screen/sheath;
b) test for 24 h with the normal rated voltage U_0 of the system;
c) test for 15 min with the RMS rated voltage value of 3 U_0 at a frequency of 0.1 Hz applied between the conductor and the metal screen/sheath.

NOTE 1: During the AC, test, tan and/or partial discharge may be monitored.
NOTE 2: For installations which have been in use, lower voltages and/or shorter durations may be used. Values should be negotiated, taking into account the age, environment history of breakdowns and the purpose of carrying out the test.

Table 4: Extract from IEC 60502-2, [8, p. 43]

2.3.2 IEC 60060-3

The IEC 60060-3 standard was released in 2004 and is also considered a horizontal standard that defines the characteristic and requirements for VLF testing voltage.

9.3 Test voltage
9.3.1 Voltage wave shape

The test voltage should be an alternating voltage having a frequency between 0.01 Hz and 1 Hz.

NOTE: With respect to the wide frequency range the relevant Technical Committee should specify the frequency dependent on the test object, the test duration and the voltage value.

Sinusoidal VLF voltage waveshape shall approximate a sinusoid with both half-cycles closely alike. The result of a high-voltage test is thought to be unaffected by small deviations from a sinusoid if the ratio of the peak to r.m.s values is within $\sqrt{2} \pm 15\%$.

NOTE: If the ratio of peak r.m.s values is not within $\sqrt{2} \pm 5\%$, it should be verified that positive and negative peaks do not differ by more than 2%.

Rectangular VLF voltage wave shape shall approximate a rectangular wave with both half-cycles closely alike. The polarity change should be controlled to avoid overvoltages caused by transients. The ratio of peak to r.m.s value shall be within 1.0 ± 5%.

9.3.2 Tolerance
The measured value of the test voltage shall be within ± 5% of the specified value unless otherwise specified by the relevant Technical Committee.

Table 5: Extract from IEC 60060-3 definition of maximum distortion value of ± 5% [9]

Definition according to IEC 60060-3:
The VLF waveform is defined as an alternating voltage with a frequency of 0.01 Hz to 1 Hz. The waveform can vary from sinusoidal to rectangular. The tolerance of the measured value shall be within ± 5%. This value is limiting the acceptable distortion value.

2.3.3 CENELEC HD 620 (S1), VDE 0267 HD S1 (1996)

The CENELEC Harmonization Document HD 620 S1 used to be defined as a pre-version of the internationally released IEC standard. The harmonisation document was released in 1996. In Europe, this harmonisation document is already being used as a VDE standard, VDE 0267 HD 620S1 (1996), and is treated as a common standard for Cable After-Laying Testing. IEC 60502 has been released and takes precedence over the harmonisation document.

			Page 5-C-19 HD 620 S1:1996 Part 5 Section C
3. Test requirements (concluded) **5. Recommended test after installation, if required**			
	Test	Requirements	Test method
1.	Voltage test on insulation 1) 2)		
1.1.	AC test voltage 45 to 65 Hz ▪ test voltage (r.m.s) $2\ U_0$ ▪ test duration 60 min	 no breakdown	AC
	Alternatively:		
1.2.	AC test voltage 0.1 Hz ▪ test voltage (r.m.s) $3\ U_0$ ▪ test duration 60 min	 no breakdown	VLF

↗ Table 6: Extract from CENELEC HD 620 (S1) or VDE 0267 HD 620 S1 (1996) [10]

2.3.4 IEEE STD. 400.2

There is some discussion concerning the testing voltage levels due to the unknown ageing level of the cable insulation and possible damage and degradation [6]. Therefore, a testing standard with 3 U_0 is recommended to apply **only for commissioning and after-laying tests.** [6]

Looking at the long term security of the distribution network, reliability and performance tests using VLF HV field tests related to the recommended standards can avoid incipient faults in the URD (Underground Distribution) system [3, 4]. Today, there is adequate portable VLF test equipment available on the market. The latest research results comparing power frequency diagnostic results with VLF diagnostic results support the idea of Very Low Frequency. Newly designed state-of-the-art VLF high-voltage sources use solid state high precision amplifiers.
The technique of producing a true-sinusoidal high-voltage output signal makes it possible to deliver high-precision partial-discharge-free and harmonic-free sources that can be used as a basis for reliable TD and PD diagnostic measurements [10, 11]. [6]

IEEE 400.2-2001 / IEEE 400.2-2004 / IEEE 400.2-D12 Jan 2012 / IEEE 400.2-2013
The IEEE committee is essentially a committee of experts from power utilities, universities and equipment manufacturers. Together, they summarise guidelines for the practical application of testing methods. These guidelines recommend applying different test voltage levels for different tests. The applications are categorised under Installation Test, Acceptance Test and Maintenance Test.

1.2 Purpose This guide is intended to provide troubleshooting and testing personnel with information to test shielded medium- and high-voltage cable systems rated from **5 kV through to 69 kV** using VLF AC techniques.

↗ Table 7: Definition of the purpose of IEEE 400.2-2013, [11, p. 2]

According to IEEE 400.2-2013, these tests are defined as follows: [11, pp. 3, 4]

Installation test:
A field test conducted after cable installation but before jointing (splicing), terminating or energising. The test is intended to detect shipping, storage, or installation damage. It should be noted that temporary terminations may need to be added to the cable to successfully complete this test, particularly for cables rated above 35 kV.

Acceptance test:
A field test made after cable system installation, including terminations and joints, but before the cable system is placed in normal service. The test is intended to detect installation damage and to show any gross defects or errors in installation of other system components.

Maintenance test:
A field test made during the operating life of a cable system. It is intended to detect deterioration and to check the serviceability of the system.
These test voltage levels are defined differently for cosine-rectangular waveform (defined with peak value) and sinusoidal waveform (defined with RMS value). The Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) [11] defines test levels related to Peak or RMS voltages.

In the tables below, clear test voltage levels are defined for particular voltage levels. The voltage levels are based on US network values. Other voltage levels such as BS standards need to adapt the linear factor of the closest voltage rating mentioned in the standard.
Two testing tables are provided below. The first table shows the test voltage with VLF sinusoidal waveform and the second table shows the test voltage for rectangular waveform. It is important to mention that the r.m.s values of the rectangular test voltage are always a factor of 1.41 higher compared to sinusoidal values.

Table 3: VLF withstand test voltages for sinusoidal and cosine-rectangular waveforms

Waveform	Cable System Rating (Phase to Phase) [kV]	Installation (Phase to Earth)		Acceptance (Phase to Earth)		Maintenance (Phase to Earth)	
		[kV rms]	[kV peak]	[kV rms]	[kV peak]	[kV rms]	[kV peak]
Sinusoidal	5	9	13	10	14	7	10
	8	11	16	13	18	10	14
	15	19	27	21	30	16	22
	20	**24[3]**	34[3]	**26**	37	**20**	28
	25	29[3]	41[3]	32	45	24[3]	34[3]
	28	32	45	36[3]	51[3]	27	38
	30	34	48	38	54	29[3]	41[3]
	35	39	55	44	62	33	47
	46	51	72	57	81	43	61
	69	75	106	84	119	63	89

Waveform	Cable System Rating (Phase to Phase) [kV]	Installation (Phase to Earth)		Acceptance (Phase to Earth)		Maintenance (Phase to Earth)	
		[kV rms]	[kV peak]	[kV rms]	[kV peak]	[kV rms]	[kV peak]
Cosine Rectangular	5	13	13	14	14	10	10
	8	16	16	18	18	14	14
	15	27	27	30	30	22	22
	20	**34**	34	**37**	37	**28**	28
	25	41	41	45	45	34	34
	28	45	45	51	51	38	38
	30	48	48	54	54	41	41
	35	55	55	62	62	47	47
	46	72	72	81	81	61	61
	69	106	106	119	119	89	89

↗ Table 8: Table 3 of IEEE 400.2-2013, testing tables for sinusoidal and rectangular VLF test voltage, [11, p. 11]

Note 1: If the operating voltage is a voltage class lower than the rated voltage of the cable, it is recommended that the maintenance test voltages should be those corresponding to the operating voltage class unless it is known that the accessories are the same class as the cable, in which case the test voltages should be those corresponding to the rated voltage.
Note 2: The maintenance voltage is about 75% of the acceptance test voltage magnitude.
Note 3: Some existing test sets have a maximum voltage that is up to 2 kV below the values listed in the Table. Test sets with this characteristic are permitted to be used.

VLF ac voltage testing methods utilise ac signals at frequencies in the range of 0.01 Hz to 1 Hz. The most commonly used, commercially available **VLF ac voltage test frequency is 0.1 Hz.** VLF ac voltage test voltages with cosine-rectangular and the sinusoidal wave shapes are most commonly used. While other wave shapes are available for the testing of cable systems, recommended test voltage levels have not been established.
Other commercially available frequencies are in the range of 0.001 Hz up to 1 Hz. Frequencies lower than 0.1 Hz may be useful for diagnosing cable systems where the length of the cable system exceeds the limitations of the test equipment at 0.1 Hz. However, if tests at frequencies below 0.1 Hz are carried out, consideration should be given to extending the test duration to ensure that there are a sufficient number of cycles to cause breakdown if an electrical tree is initiated.
Some comments on reliability can be made based on data collected from approximately 16,000 km (10,000 miles) of cable systems since 2000 from several North American utilities. VLF Withstand Tests can be performed on a large range of cable lengths (~75 m to ~4.5 km). Thus the risk of failure on test can be considered on two levels as shown in Table 4 of [12]:
1. risk of failure on test as a function of cable length.
2. risk of failure on test for a specific length of cable, e.g., 300 m.

↗ Table 9: Table 3 of IEEE 400.2-2013, [11, p. 11]

The practical experience of power utilities following these recommendations confirmed the findings of published technical papers containing case studies.

Diagnostics is today's alternative solution!

Without any unnecessary pressure test, all performance details can be analysed by TD tangent delta dissipation factor measurement (TD or DF) and PD partial discharge diagnostics.
Besides recommending test voltage levels, since 2001, "IEEE 400.2-2001 Guide for Field Testing of Power Cables" has published recommended evaluation criteria for tan delta dissipation factor values for XLPE cables. [13, p. 23]. In 2013, "IEEE 4002.-2013 Guide for Field Testing of Shielded Power Cable Systems" summarised the practical experience in new criteria values gleaned over a decade.

9.3 Method

The dissipation factor (tan δ) test is a diagnostic test that allows an evaluation of the cable insulation at operating or test voltage levels. The test is conducted at operating frequency or at the VLF frequency of 0.1 Hz. When the tan δ measurement exceeds a historically established value for the particular insulation type, the cable is considered to be defective and may have to be scheduled for replacement. If the tan δ measurements are below a historically established value for a particular insulation type, additional tests have to be performed to determine whether the cable insulation is defective.

Tests conducted on 2,400 km of XLPE-insulated cables have established a figure of merit for XLPE, tan δ = 2.2 x 10^{-3}. If the cable's measured tan δ is greater than 2.2 x 10^{-3}, the cable insulation is contaminated by moisture (water trees). The cable may be returned to service, but it should be scheduled for replacement as soon as possible. [10]
If the cable's measured tan δ is less than 2.2 x 10^{-3}, the general condition of the insulation is probably good; however, the cable insulation could have many small defects; in which case, the cable may operate satisfactorily for many more years. The tan δ should be monitored regularly, and upon further deterioration of the dissipation factor, proper action should be taken. However, the cable could have only a few isolated large defects, which could cause it to fail upon returning it to service or within days after it has been re-energised. Therefore, if the measured tan δ is greater than 2.2 x 10^{-3}, it is recommended that a VLF test at 3 V_0 be performed to identify the large defects, remove them, and repair them.

↗ Table 10: Extract from IEEE 400.2-2001, 9.3 Method of TD evaluations [13, p. 23]

The new version of the field guide "IEEE 400.2-2013" summarised the experience collected over the past decade with the definition of different evaluation criteria for PE, XLPE, TRXLPE, EPRs and paper-type insulations. It differentiates between the diagnostic evaluation criteria between new and aged cables. In addition, the criteria for TD evaluation have been extended to include the value of tangent delta stability (VLF-TDTS).

5.4 Tangent delta / differential tangent delta / tangent delta stability / leakage current / harmonic loss current tests with VLF sinusoidal waveform

5.4.1 Measurement and equipment

VLF tangent delta, differential tangent delta, tangent delta stability, leakage current, and loss current harmonics measurements may be used to monitor ageing and deterioration of cable systems (Werelius [B35]). However, **tangent delta (VLF-TD), differential tangent delta (VLF-DTD),** and **tangent delta stability (VLF-TDTS)** measurements are the most commonly used methods in the field. A correlation between an increasing 0.1 Hz tangent delta and a decreasing insulation breakdown voltage level at power frequency has been reported (Bach, Kalkner, and Oldehoff [B3]; Hvidsten, et al. [B24]; Hernandez-Mejia, et al. [B21] for PE and cross linked polyethylene (XLPE) cables. The 0.1 Hz tangent delta, differential tangent delta, and tangent delta stability are mainly determined by **degradation of the cable insulation (water-trees), corroding metallic shields, insulation moisture, and degraded accessories**. The measurement of the tangent delta, differential tangent delta and/or tangent stability with a 0.1 Hz sinusoidal waveform offer comparative assessment of the **ageing of PE, XLPE, TRXLPE, EPRs, and paper-type insulations and can be used as a diagnostic test.** The test results permit differentiating between new, defective, and highly degraded cable systems (Baur, Mohaupt, and Schlick, [B6]; Hernandez-Mejia, et al. [B21]; Hampton, et al. [B20]; Hampton and Patterson [B18]).

Cable systems can be tested in preventive maintenance programs and returned to service after testing. The measurements at VLF can be used **to make decisions on cable/accessory replacement, cable rejuvenation, or repair expenditures.**

↗ Table 11: Extract from IEEE 400.2-2013, 5.4 VLF-TD, VLF-DTD, VLF-TDTS with VLF sinusoidal waveform [11, p. 15]

Table 2 – Usefulness of VLF AC voltage testing methods for selected cable and/or insulation conditions

Cable condition	Diagnostic test method				
	Simple withstand test methods	VLF-MW	VLF-TD VLF-DTD VLF-TDTS VLF-DS	VLF-PD	VLF-LC VLF-LCH
Cables with metallic shield corrosion	Acceptable	Acceptable	Acceptable	Poor (see Note 1)	Poor
Extensive water treeing	Acceptable	**Good**	**Good**	Poor (see Note 2)	Good
Few large defects or few localised electrical trees	**Good**	Acceptable/ **Good** (see Note 3)	Acceptable/ **Good** (see Note 2)	Acceptable/ **Good**	Acceptable/ Good (see Note 3)
Defective splices and terminations	Acceptable/ **Good** (see Note 4)	Acceptable/ **Good** (see Note 3)	Acceptable (see Note 3)	Acceptable (see Note 2)	Acceptable (see Note 3)
Mixed insulation (extruded and/ or laminated)	**Good**	**Good** (see Note 4)	Poor/**Good** (see Note 4)	**Good** (see Note 5)	Poor/Good (see Note 4)

Note 1: PD testing can be less sensitive on aged taped shielded cables due to corrosion of the shield overlaps and the resulting changes of current distribution within the tape.

Note 2: PDs are detectable only if there are one or more active electrical trees or tracking sites or there are voids in the cable insulation or accessories. Moreover it should be noted that PD inception conditions at VLF can be different to those at other frequencies.

Note 3: Supplemental testing is recommended to distinguish a severe localised defect from general overall deterioration.

Note 4: As this test technique measures the average of all the insulations under test, supplemental testing is recommended to measure individual sections of the insulation. VLF-TD, VLF-DTD, VLF-TDTS, VLF-DS or non VLF techniques can be used to differentiate mixed cable insulations. If individual sections cannot be measured, the usefulness may be poor.

Note 5: The different propagation characteristics of the various cable sections (different sizes and/or insulations) may make localisation difficult.

↗ Table 12: Table 2, page 9 of IEEE 400.2, 2013, [11, p. 9] Usefulness of VLF TD PD testing and diagnostic methods

3. Monitored Withstand Test (MWT)

NEETRAC has been working on extensive practical research projects for many years. One of its latest projects involves investigating the **dielectric parameters during the Simple Withstand Test.**
The National Electric Energy Testing, Research and Applications Centre (NEETRAC) is a non-profit, member-supported electric energy research, development and testing centre, housed at the Georgia Institute of Technology.

Utilities	
American Electric Power	FirstEnergy
Ameren	FPL
BC Hydro	Hydro Quebec
CenterPoint Energy	NRECA
Consolidated Edison	Pacific Gas & Electric
Dominion	PacificCorp
Duke Energy	SCE&G
EPRI	Southern California
Exelon	Southern Company

Table 13: Participating members in the NEETRAC research organisation [14]

The authors of the paper “First Practical Utility Implementations of Monitored Withstand Diagnostic in the USA” [14] have pointed out well-known side effects of a conventional withstand test, as per the following chapter:
“Proof or withstand tests have been used for a very long time in the cable industry and find their origins in the well-known routine tests carried out in accessories and cable factories. Although this test continues to serve the industry well, when a simple Withstand is implemented in the field users continue to be concerned by three issues:

- There is no way to estimate the quality of the cable system, and hence the risk of failure, prior to the application of the proof voltage.
- There is no way to adjust the extent of the test (either by decreasing or increasing) according to the quality of the cable system.
- There is no way to judge the quality of the pass, should the cable system support the proof voltage i.e. was the pass a good one or a marginal one.”

It had been suggested that if a diagnostic parameter, such as **dielectric loss, leakage or partial discharge, were monitored during a proof test, then all of the three issues noted above might be addressed**. Consequently, since 2008, the authors have been conducting Monitored Withstand Tests (MWT) on utility systems using very low frequency (VLF) waveforms to assess the practicality of the initial hypothesis. Experience has shown that the Monitored Withstand Test, whether using partial discharge or dielectric loss does provide utility engineers with considerable and useful information.

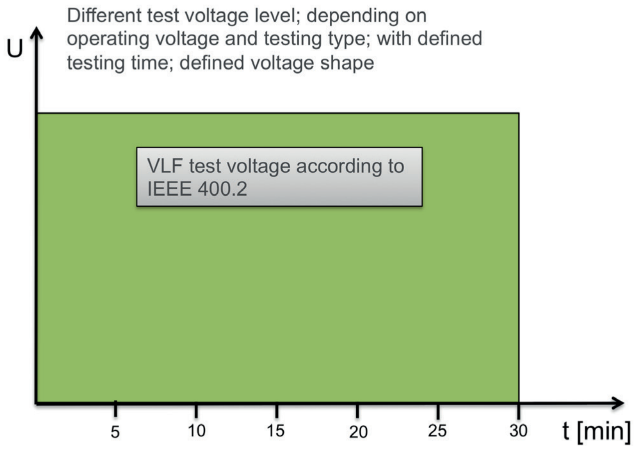


Figure 3: Simple VLF Test according to IEEE 400.2 [11]

One of the drawbacks of Simple Withstand tests is that there is no straightforward way to estimate the "Pass" margin – once a test (say 30 min at 2 U_0) is completed, it is impossible to differentiate among those passing segments. That is, it is impossible to distinguish the segments that would survive 120 min from those that would have only survived 40 min. Thus, it is useful to employ the concept of a Monitored Withstand Test whereby a dielectric property or discharge characteristic is monitored to provide additional data.

There are four ways these data are useful in making decisions during the test.

1. Provide an estimate of the "Pass" margin.
2. Enable a utility to stop a test after a short time if the monitored property appears close to imminent failure on test, thereby allowing the required remediation work to take place at a convenient (lowest cost) time.
3. Enable a utility to stop a test early if the monitored property provided definitive evidence of good performance, thereby increasing the number of tests that could be completed and improving the overall efficiency of the field test.
4. Enable a utility to extend a test if the monitored property provides indications that the "Pass" margin is not sufficient large, thereby focusing test resources on sections that present the most concern.

In a Simple Withstand test, the applied voltage is raised to a prescribed level, usually 1.5 to 2.5 times the nominal circuit operating voltage for a prescribed time. The purpose is to cause weak points in the circuit to fail during the elevated voltage application during which time the circuit is not supplying customers and the available energy (which may be related to the safety risk) is considerably lower. Testing occurs at a time when the impact of a failure (if it occurs) is low and repairs can be made quickly and most effectively.

When performing a Monitored Withstand Test, a dielectric or discharge property is monitored during the withstand period. The data and interpretation are available in real time during the test so that the decisions outlined above might be made. The dielectric or discharge values monitored are similar to those described in earlier sections. However, their implementation and interpretation differ due to the requirement for a fixed voltage and a relatively long period of voltage application. Within these constraints, leakage current, partial discharge (magnitude and repetition rate) and tan delta (stability and magnitude) might readily be used as monitors.

As described in [14] **Figure 4**, the schematic also includes a commonly implemented MWT sequence in the form of a stepped increase in voltage and a hold period.
The critical part of the test is the measurement and interpretation during the Withstand Test. The step/ramp in voltage allows an evaluation before the start of the Withstand Test. This approach is valuable in that it enables the field engineers to assess the condition of the cable system before embarking on the MWT.

Weak cable conditions can be formed at a concentrated point (puncture) or a more widely distributed general ageing.
Accordingly, the only way in which a cable system may "Pass" a MWT is if there is no dielectric puncture and compliant information from the monitored property. Stable data (narrowly varying data) and low magnitude are the main criteria for assessment.
At this stage, it is instructive to examine the differences between the interpretations of Standard Dielectric Loss measurements compared to the assessment of the same property in a MWT.

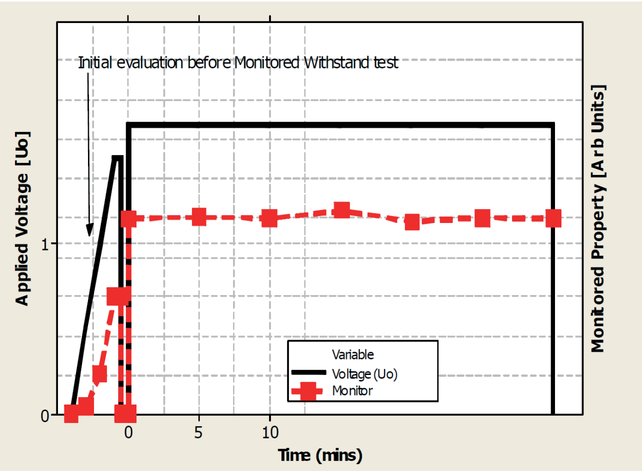


Figure 4: Schematic of a MWT (black) with optional diagnostic measurement (red) [14]

3.1 MWT TD

The interpretation of the dielectric loss measurement shall focus on:

- Stability within a voltage step assessed via the Standard Deviation of the TD measurement
- Tip-up (difference in the mean value of tan delta at two selected voltages) tan delta (mean value at U_0).

When using the monitoring mode, the constant voltage employed does not permit assessment of the tip-up. However, this information can be made available if a voltage ramp is used just before the withstand voltage level is applied. Otherwise, the tip-up cannot form part of the standard hierarchy for Monitored Withstand.

There are similar issues with the mean tan delta. A mean tan delta can be calculated for the entire withstand period of the test. However, since this is a MWT, testing occurs at voltages above U_0, the voltage commonly used for standard tan delta assessments.
The concept of mean tan delta is useful even at this higher voltage, but the critical values for assessment cannot be the same as those used for tan delta at U_0. In fact, these values are likely to be higher than those used for the standard tan delta assessment.
In the approach that is detailed here, the stability has been assessed by considering the difference between initial and 10-minute cases. Ten minutes has been chosen in that it is long enough to determine the underlying trend, yet sufficient time remains for the user to make an active decision on whether they wish to curtail the test at 15 minutes.
Generally the stability is the most useful parameter for assessing the behaviour during the Withstand Test.
Further, it is stated that it is most important to note that the attributes are similar for the Ramp and Hold phases but that the levels will be quite different due to the differences in the voltages and times of application.

	Voltage step **Portion and tan delta assessment**	**Voltage hold** **(Withstand – constant voltage portion**
Stability (Standard Deviation)	Over 6 to 12 measurements at U_0	Extended time at IEEE 400.2 voltage level
Voltage dependence of tan delta (tip-up)	Between 1.5 U_0 and 0.5 U_0	–
Tan delta (Mean)	Over 6 to 12 measurements at U_0	Extended time at IEEE 400.2 voltage level
Change in tan delta over time	–	Between 0 and 10 minutes

↗ Table 14: Comparison of diagnostic features for step and hold portions of MWT [11]

Condition assessment	**Tan δ stability measured @ U_0 [E-3] (dielectric loss mode)**	**Tan δ stability measured @ IEEE Std. 400.2 Withstand levels [E-3] (monitored withstand mode)**
No action required	< 0.3	< 1.4
Further study advised	0.3 to 0.4	1.4 to 2.8
Action required	> 0.4	> 2.8

↗ Table 15: Criteria for condition assessment criteria of PILC insulations for dielectric loss and monitored withstand modes [14]

Test time guidance	Condition assessment	Change in tan delta between 0 and 10 minutes		VLF-TD stability (Standard Deviation) at maintenance level [10^{-3}]		Mean VLF-TD at mainte-nance level [10^{-3}]
PE-based insulations (i.e. PE, XLPE, WTRXLPE)						
Reduced to 15 mins	**No action required**	< 0.25	and	< 0.25	and	< 5
Retain 30 mins	**Further study advised**	> 0.25 and < 17		> 0.25 and < 6		> 5 and < 45
Extended to 60 mins	**Action required**	> 17	or	> 6	or	> 45
Paper insulations (i.e. PILC)						
Reduced to 15 mins	**No action required**	< 1.3	and	< 0.7	and	< 75
Retain 30 mins	**Further study advised**	> 0.13 and < 4		> 0.7 and < 3.5		> 75 and < 135
Extended to 60 mins	**Action required**	> 4	or	> 3.5	or	> 135

↗ Table 16: Test time guidance and condition assessment for Monitored Withstand Tests on MV cable systems [14]

The trend within the monitored period indicates categorical attributes that make it possible to understand the cable condition:

- Flat
- Upward trend
- Downward trend, etc.
- Stability within the monitored period
- Monitored property (mean value at withstand voltage)

No action required	Standard 30 minutes test time may be reduced to 15 minutes
Further study	Retain standard 30 minutes
Action required	Standard 30 minutes test time should be increased to 60 minutes.

↗ Table 17: Recommended testing time depending on action status

In the context of a MWT, the condition assessment (no action required, etc.) may also be used as real-time guidance for deciding whether and for how long to perform the Withstand Test. The current recommended approach by the authors of [14] is to use the condition assessment to suggest how the IEEE 400.2 standard Withstand Test time might be modified by the cable system condition in respect of testing time.

The results of a VLF AC-sinusoidal MWT in which the tan delta was monitored continuously for the whole 30 minutes appears in **Figure 5**.

When the criteria are applied to the example in **Figure 5**, the test results lead to the following assessment:

Tested segment did not have a dielectric puncture		
change between 0 and 10 min:	0	E-3
Stability:	0.79	E-3
Tan delta:	0.90	E-3

The Monitored Withstand assessment of this performance would likely be "No action required" and the **test time may be reduced to 15 minutes.**
On this occasion, the utility chose not to reduce the test time even though it was possible in this case.

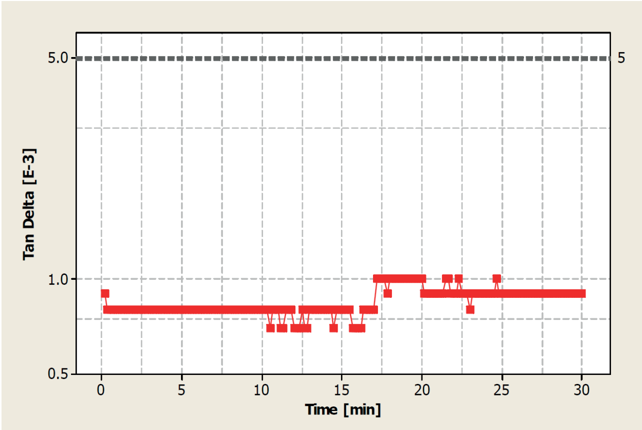


Figure 5: Tan delta MWT on service-aged XLPE cable [14]

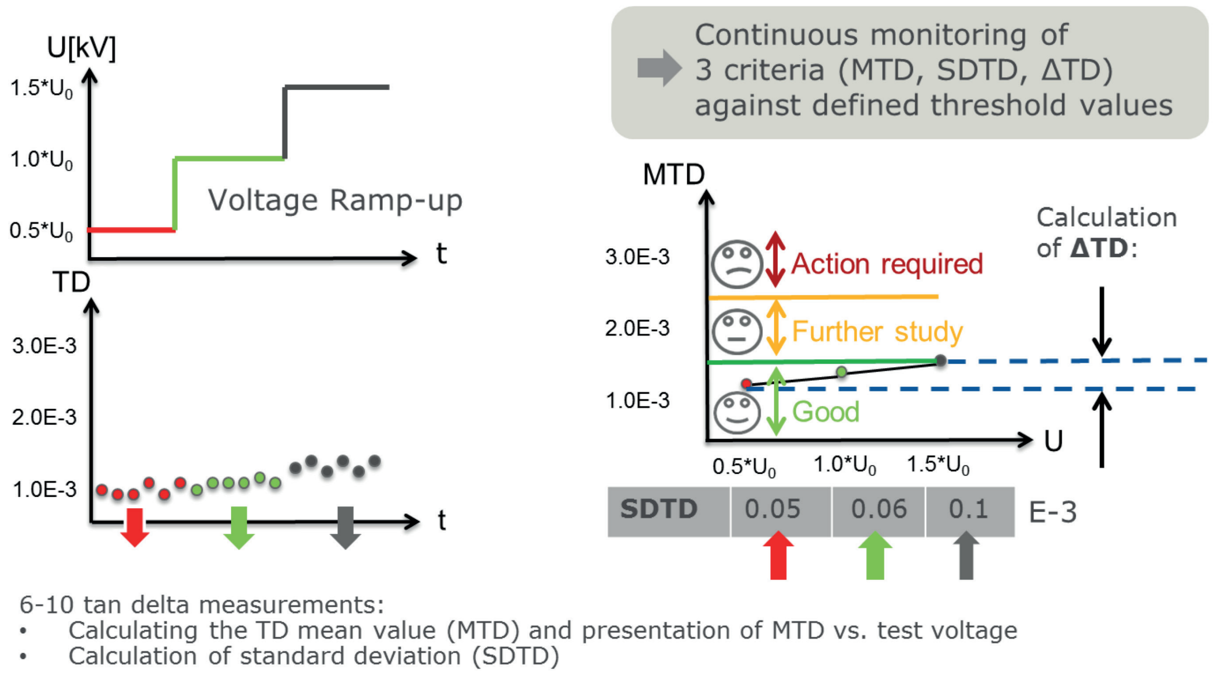
In summary, the challenge for the MWT is to find a way to take the available test data and make them available in a way that covers the wide range of situations that might develop in the field. [14] The paper published at the 8th International Conference of Insulation Power Cables, Jicable 2011, was the first official paper that addressed the critical questions behind the Simple Withstand Test. The paper illustrates a practical approach that can be implemented by utilities.

The last chapter of this work contains several additional practical case studies that illustrate where a MWT would have been helpful in order to recognise the marginal "Pass" of Simple Withstand Test.
The utility mentioned in this case study welcomed the fundamental knowledge input offered by the paper [14]. The difficulties that are faced in the subsequent case studies are caused by the complexity that cable networks can have. In densely populated cities with a highly developed metropolitan district, cable constellations have been developing over the past 50 years. The first generation of XLPE cable was implemented in the early 1980s. Sections of previous PILC cables have been replaced. In the later stage, the late 1980s, the second generation of XLPE began to be implemented. Today, cable networks contain old PILC cable sections, first generation XLPE (later referred to as water-tree-prone cable sections), second generation XLPE, and so on. Due to the mixed constellation, evaluation criteria for mixed cables are very difficult to establish. Sometimes, certain sections of water-tree-prone cables cannot be identified as critical, as they are overshadowed by the overall leakage condition of PILC sections. Water tree ageing cannot be detected by PD measurement. Accordingly, in cases where the TD values exhibit relatively good condition, a potential threat due to a highly service-aged condition in a particular WTPC section would not become visible. With an understanding of these complex situations, the utility still utilises a Simple Withstand Test according to IEEE 400.2. The minimum time of 15 minutes is applied in order not to overstress over an unnecessary range in order to gain time for improvement works.

After implementation of the said maintenance procedure, it was discovered that the strategy of 15 min VLF test at 2 U_0 only guarantees ~60% performance certainties. In other words, 40% of the tested cables have passed the Simple Withstand Test with a marginal "Pass". The extreme cases showed up as cable failures within a few hours after re-energising. The implementation of the Monitored Withstand Test makes it possible to prevent on-load outages soon after re-energising.

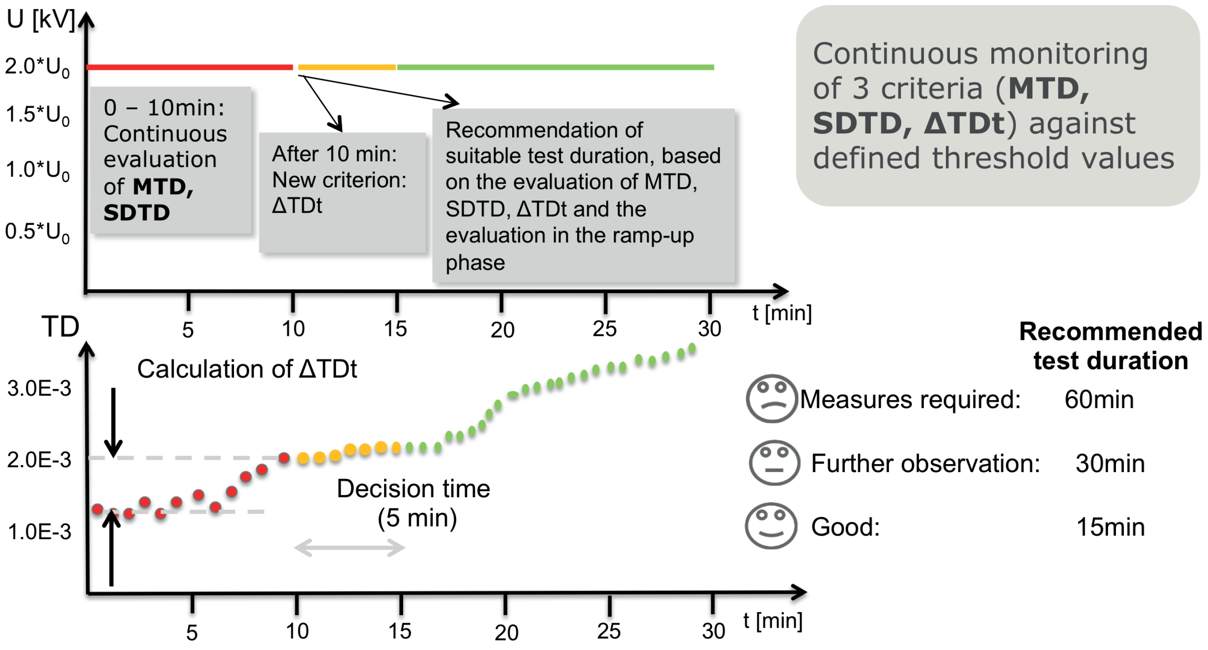
Summary – Monitored Withstand Test MWT

MWT – ramp-up stage



↗ Figure 6: Illustration of MWT ramp-up stage

MWT – hold stage



↗ Figure 7: Illustration of MWT hold stage

Example MWT 1:

XLPE cable in good condition

Ramp-up

- Low MTD
- Low SDTD
- Low ΔTD

MWT hold phase

- Low MTD
- Low tΔTD
- Low SDTD

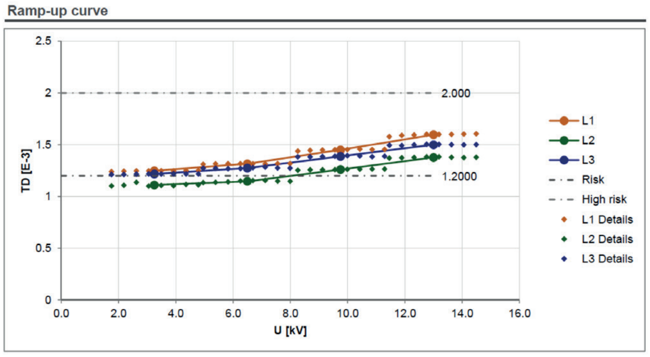


Figure 8: Ref. 8438CM, ramp-up, XLPE stable condition

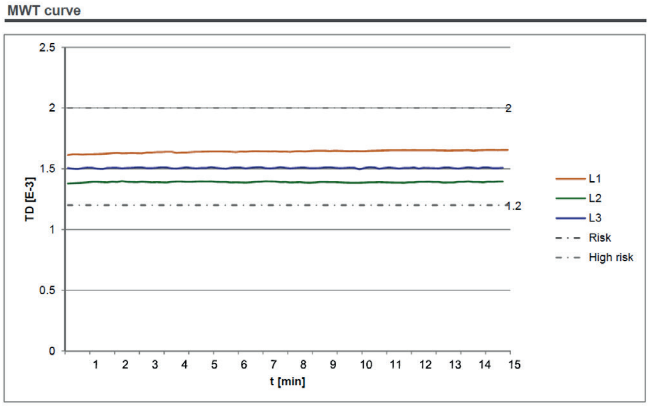


Figure 9: Ref. 8438CM, MWT hold phase, XLPE stable time stability

Example MWT 2:

XLPE cable with influence of humidity

Ramp-up

- Increased MTD
- Increased SDTD
- Decreasing ΔTD

MWT hold phase

- Increased MTD
- High tΔTD
- Increased SDTD

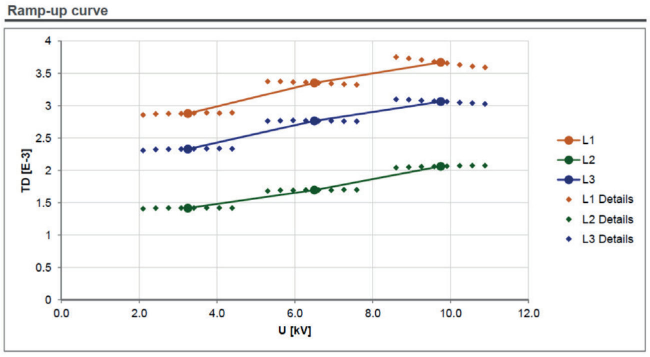


Figure 10: Ref. 12518CM, ramp-up, decreasing trend

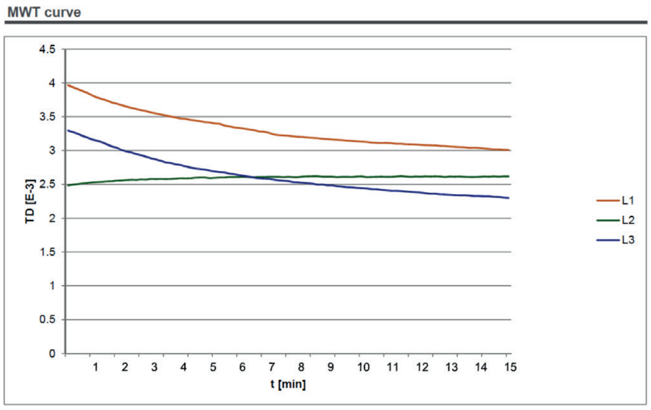


Figure 11: Ref. 12518CM, MWT hold phase, XLPE with decreasing tΔTD

Example MWT 3:

Mixed cable with aged PILC, joint failure during test

Ramp-up

- High MTD value, highly service-aged PILC
- Very high MTD value in L1 at 1.5 U_0
- Increased SDTD
- Decreasing ΔTD in L2, L3; indicates aged PILC

MWT hold phase

- Stable MTD in L2 and L3
- Decreasing tΔTD in L1; indication of moisture in a joint
- Breakdown after 4 minutes

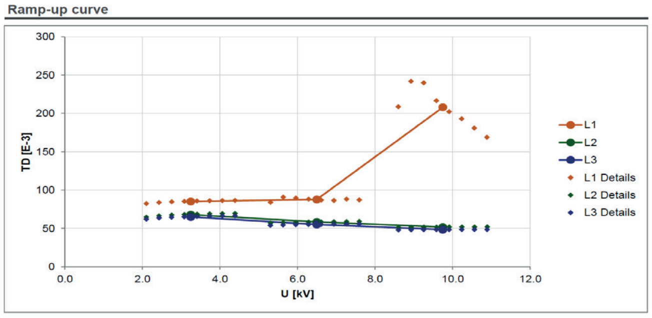


Figure 12: Ref. 3730-31, ramp-up, tracking & moisture in L1, decreasing DTD, aged PILC

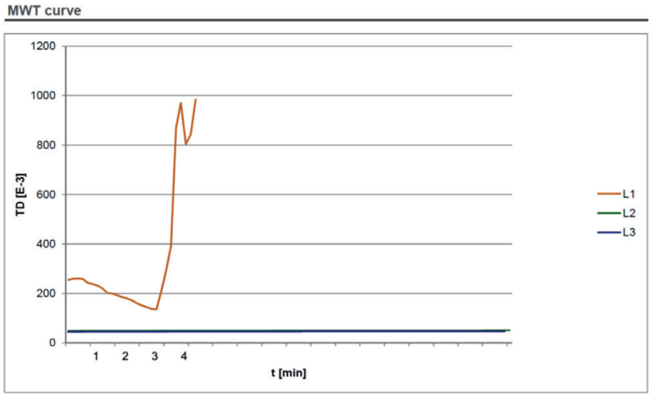


Figure 13: Ref. 3730-31, MWT hold phase, joint breakdown after 4 minutes

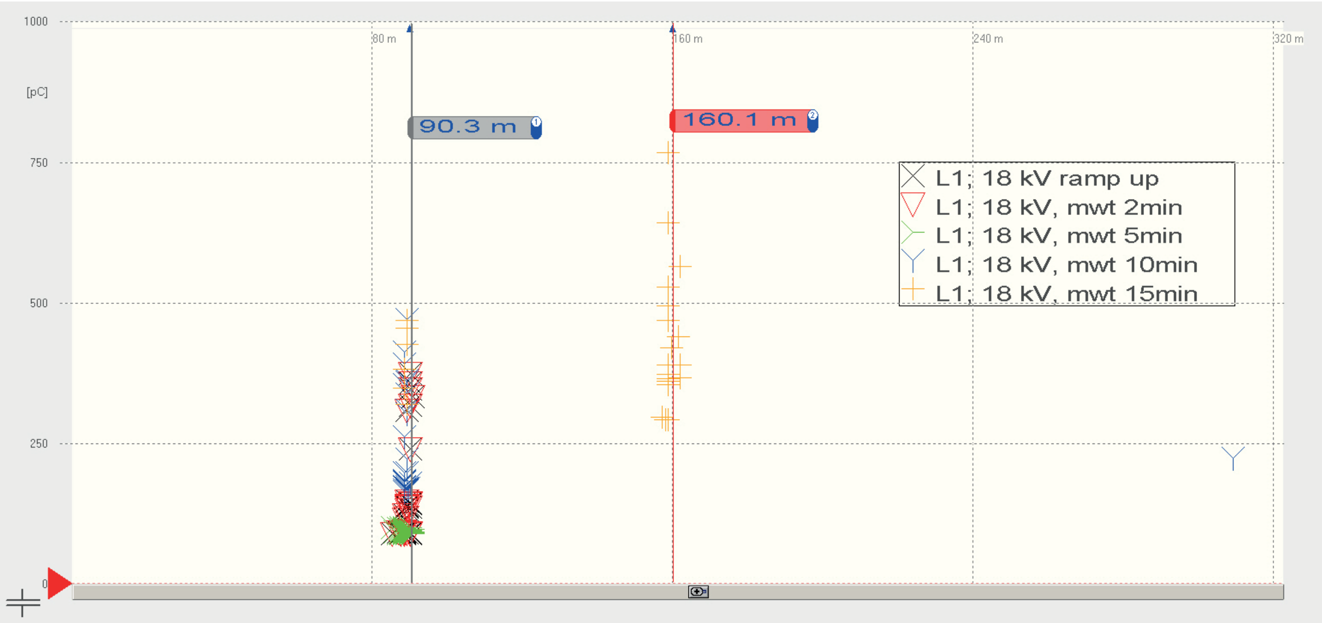
3.2 MWT PD

The Monitored Withstand Test with PD measurement in parallel to the VLF test has become the most meaningful form of commissioning test in recent years. For newly installed cable circuits, the meaning of a Withstand Test has a special focus on installation weaknesses. Mistakes made during the process of joint and termination installation can be identified in the very initial stage, as they are very often visible by the presence of partial discharges.

A common practice with reference to IEC 60502 is to substitute the mandatory after-laying test (Simple Withstand Test) with the Monitored Withstand Test PD. The VLF test voltage according to IEC 60502 is applied and the PD activities are monitored in parallel over the time period. This procedure shows up all potential weak spots with PD activities within the first few minutes. If no PD activities are given, the duration of the monitored after-laying test can be reduced to 15 minutes for each phase.

A common practice implemented by a German utility after gaining several years of experience proves that all weaknesses show up with PD after the first 2 minutes. As a result of this, the utility has implemented that an after-laying test can be completed after 5 minutes if no PD activities appear.

The general key criteria for a new installation of XLPE is that max. 100 pC is acceptable at 3 x U_0 testing voltage.



↗ Figure 14: PD localisation graph: PD activity over time

With this method, it is possible to identify joint mounting faults during the acceptance test. Commonly, these mounting faults are related to

- Poor workmanship
- Poor quality of accessories

		
Grains of sand	Fluff inside the shrinkdown plastic tube	Incision by a knife

↗ Table 18: Examples of joint mounting faults

3.3 Full MWT (TD + PD) – Monitored Withstand Diagnostics

The Full Monitored Withstand Test is described as a VLF Withstand Test with parallel monitoring of TD as well as PD throughout the testing period.

For maintenance tests, many utilities have implemented the rule of applying a VLF test after repair work has been conducted on a cable circuit. Besides the ageing of the cable, this test highlights installation mistakes or defects in the newly installed accessories. The VLF test is also applied with a maintenance test voltage level to accelerate single severe water trees to the surface during this test time instead of them remaining hidden and showing up as an unexpected cable failure soon after the circuit is energised.

Non-destructive cable diagnostics of old cable systems
Old cable systems are valuable assets. Therefore, cautious handling of old cable insulation is the main priority during diagnostic measurements on old cable systems. Accordingly, experienced utilities limit the applied diagnostic voltage to 1.5 U_0. Some of them limit the applied diagnostic voltage further down to 1.0 U_0 and consequently avoid unnecessary electric stress in old cable systems. [15]
The utilities thereby deliberately ignore the extended diagnostic results that could be gained by applying higher test voltages in order to avoid the potential risk of damaging the old insulation material.
The efficiency of cable diagnostics is essentially increased through extended diagnostic options applying dissipation factor measurement TD and partial discharge measurement PD.
The conventional ramp-up of the diagnostic voltage is applied during tan delta and partial discharge measurement and extended by tan delta hysteresis measurement for critical cables.

Most recently, an adaptive trend analysis by means of tan delta and partial discharge measurement has been used for critical cable systems to gain more information on the extent of ongoing cable deterioration and the indicated fault phenomena. The high significance of the acquired information helps to understand the fault phenomena and to subsequently make the right decisions with regard to cable refurbishment. The newly developed diagnostics procedure is called **Monitored Withstand Diagnostics** MWD, and offers adaptive trend analysis (see **Figure 15**)
MWD shows similarities to the Monitored Withstand Testing (MWT) diagnostics procedure. Monitored Withstand Testing [2] was developed by the American Institute NEETRAC and has already been integrated in the American Cable Testing Standard IEEE 400.2 -2013 [11].

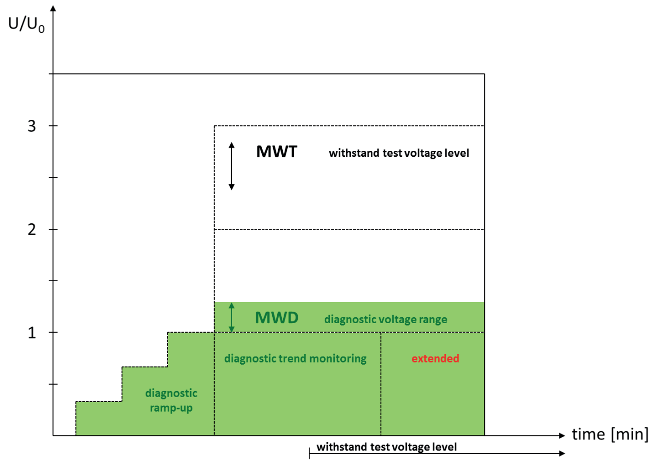


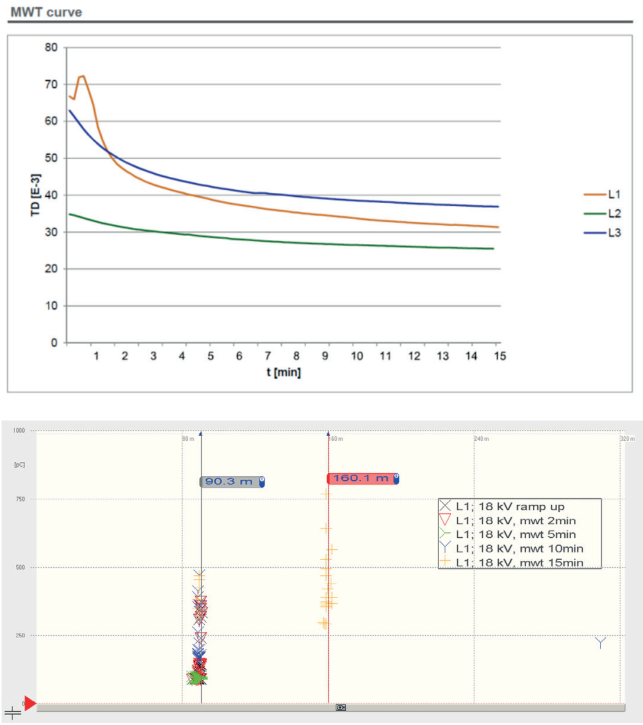
Figure 15: Monitored Withstand Diagnostics [15]

The MWT TD measurement can show the influence of ageing parameters such as:

- Water tree ageing
- Tracking effect in joints
- Water ingress in joints
- Thermal current effect in joint areas

MWT PD measurement shows the time-related PD activities. Only this approach allows the identification and pinpointing of PD activities in accessories that are influenced by moisture ingress. The MWT TD pattern can visualise the drying characteristic of joints with water ingress.
During the drying period, PD may start to occur in the suspect accessory during the “dry” period of the MWT sequence.
Only the parallel PD measurement during the VLF truesinus® test allows the detection of joints affected by the water ingress.

Numerous case studies have been conducted to understand the most effective maintenance programmes that help to pinpoint and renew the weak cable accessories or cable sections while saving time.



↗ Figure 16: MWT TD curve indicating the drying effect, MWT PD indicating PD over time

4. Practical recommendation for implementing testing voltages in respect to the standards

After-laying test			66 kV cable	38 kV U_0	33 kV cable	19 kV U_0	11 kV cable	6.3 kV U_0
CENELEC / VDE HD 620 IEC 60502	3 U_0	60 min	n.a.	3 U_0	57 kVrect. 42.5 kVrms	3.0 U_0 2.2 U_0	19 kVrms	3 U_0
IEEE 400.2-2013	2-3 U_0	15-60 min	n.a. (80 kV)	2.1 U_0	40 kVrms	2.1 U_0	18 kVrms	2.8 U_0
MWT PD	2 U_0	15-60 min	42.5 kV	1.1 U_0	40 kVrms	2.1 U_0 (max. 2.2 U_0)	18 kVrms	2.8 U_0
Maintenance								
VDE	3 U_0	10 min	n.a.	3 U_0	57 kVrect. 42.5 kVrms	3.0 U_0 2.2 U_0	19 kVrms	3 U_0
IEEE 400.2	2-3 U_0	15-60 min	60 kVrect	1.6 U_0	30.4 kVrms	1.6 U_0	14 kVrms	2.2 U_0
MWT TD	Up to 2 U_0 0.5 – 1.0 – 1.5 2.0-2.2 U_0	15-60 min	Max. 42.5 kVrms	Max. 1.1 U_0 0.5 -0.75 – 1.0 – 1.1 U_0	40.4 kV (0.01-0.1 Hz)	2.0 U_0	14 kVrms	2.2 U_0
TD diagnostic	Up to 1.5 U_0	3 steps	Max. 42.5 kVrms 1.0 U_0 = 38 kVrms	Recom-mended 0.5 -0.75 – 1.0 U_0	30.3 kVrms	1.5 U_0	9.5 kVrms	1.5 U_0
PD diagnostics	Up to 1.7 U_0	4 steps	Max. 42.5 kVrms 1.1 U_0 = 42.5 kVrms	Max. 1.1 U_0 0.5 -0.75 – 1.0 – 1.1 U_0	33 kVrms	1.7 U_0	11 kVrms	1.7 U_0

↗ Table 19: Practical implementation of testing voltages in relation to the selected testing instrument, Viola TD PD

Table based on **Viola TD PD** testing system
kVrms … truesinus®
kVrect … peak value, rectangular

5. Discussion on dielectric response in XLPE/PILC cables

Degraded cable insulation shows an increase in losses and decrease in dielectric strength. Dielectric response in general is a tool which can indicate the degradation and hence condition of electrical insulation of any kind. Water trees, for example, initiate and grow under an electric field after water has penetrated into the polymeric insulation. Water trees have long been recognised as the most hazardous factor in the life of XLPE distribution cables and a major cause of insulation failure.
Water trees can be measured with VLF 0.1 Hz tan delta dissipation factor measurement since such points have decreased electric strength compared to the rest of the polymer-insulated cable. In addition, water and water trees effect leakage currents, DC absorption current, polarisation and depolarisation current, as well as discharge voltage decay and return voltage. Field measurements of some of these parameters have proven to be suitable for detecting degradation and recognising the presence of water-tree ageing.
However, many measurement techniques have disadvantages, which have prevented their widespread application. Nowadays, all of the standards only mention the VLF 0.1 Hz tan delta diagnostic as the most efficient and meaningful tool for dielectric response analysis.

The existing methods of existing cable diagnostics, such as the measurement of the tan δ or DC leakage current, are offline methods. For these reasons, in Japan, some on-site on-line diagnostic methods, such as the DC component current method and the DC superposition method are used to detect water tree deterioration. Accuracy of the DC component current method and the DC superposition method are compared. The conclusion is that the on-line diagnostic methods are considered as efficient as the DC leakage current method. However, the method based on the DC superposition may not be applicable to all cables on site. This is because with a low voltage (< 100 V), water trees can be detected in some cable, while in others, superimposed voltage of 10 kV or more is necessary. At these relatively high DC voltages, one must expect breakdown.
Combining the measurement of tan δ and the total harmonic distortion in the loss current is a new method for diagnostics on power cable systems. However, this method is currently only available on a laboratory level. Moreover, the significance of the relative values of tan δ and the total harmonic distortion current in the insulation are not yet understood.
Results of artificially accelerated ageing studies in laboratories show that tan δ and water trees of polymeric cable increase with time and voltage, both of which are important. However, as an example, acceleration at 16 kV for 2,000 h increased tan δ more than acceleration at 20 kV for 1,000 h. Even with 2,000 h acceleration at 12 kV, the water treeing is more pronounced than with 1,000 h at 20 kV. This leads to the conclusion that the time is the relevant factor. Artificial water-tree ageing is understood to be very difficult to realise.

Dielectric response as a diagnostic tool for power cable systems

Many research groups have measured the dielectric response of oil-paper insulation systems either in the time domain or the frequency domain. The dielectric response in both domains provides novel diagnostic methods for the quality control of medium- and high-voltage cables. However, the information obtained in the frequency and time domains is equivalent only if the insulation system is linear. In addition, dielectric response measurements in both domains indicate that the measurement of non-linearity in the dielectric response could become the basis for the diagnosis of water tree degradation in cables. Non-linearity in the dielectric response has been the subject of study in many doctoral theses.

The polarisation (charging) and depolarisation (discharging) currents of oil-paper insulation increase with moisture content. In addition to dielectric response function, the time domain measurement of polarisation and depolarisation currents makes it possible to estimate the conductivity of the test object. An increase in moisture content will increase conductivity. It is important to observe that the conductivity of the oil paper system depends heavily upon the temperature. Without knowledge of the temperature, no simple criterion based upon the conductivity can be used to estimate the moisture content. Dielectric response gives an overview of the average condition of the insulation system under study, but no localisation of the possible deteriorated areas. Predicting the remaining life of the insulation system based on dielectric response and/or other measurements requires additional further research. [16], [17]

6. Combined TD/PD cable diagnostics

The BAUR VLF diagnostics system is the best equipment on the market and has been approved by numerous power utilities during past decades. Together with the BAUR VLF generators, a compact testing and diagnostics system is available which is unbeaten in reliability, performance and effectiveness.

The most important advantages of BAUR equipment can be summarised as follows:

The BAUR tan delta diagnostic equipment is based on truesinus® technology and is therefore **independent of external influences**. The system is well proven with several 100,000 measurements from around the world, which provides an enormous database from which all customers can benefit. More than 600 systems are in operation worldwide. The latest models of test equipment allow the combination of VLF TD and PD diagnostics. The measurement time is only 10 minutes per phase, or approximate 1 hour for a complete system roll on and off. The system is easy to use and operate and the interpretation of results is mostly automated by the system. Clearly defined evaluation criteria allow straight forward identification and localisation of weak components in a cable circuit.

The BAUR VLF TD and PD diagnostics systems are all **integrated systems**, giving a very low additional weight and size of the diagnostic parts in addition to the VLF generator.

truesinus® is a registered trademark of BAUR GmbH and describes the patent of a VLF sinusoidal waveform that is a pure sine wave with a minimum amount of distortion for any kind of load conditions that can be handled by the VLF generators. A pure sinusoidal waveform is the essential basis for highly precise tan delta loss factor measurement.

↗ Figure 17: BAUR VLF TD series: PHG80 TD (57 kVrms); viola TD (42.5 kVrms); frida TD (24 kVrms)

7. TD loss factor measurement – tan delta

7.1 Why use VLF diagnostics for dissipation factor measurement?

VLF versus power frequency 50 Hz

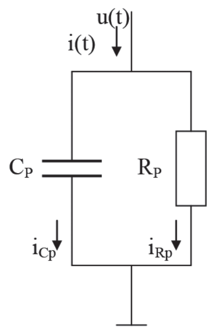
Water trees (WT) in solid dielectrics are more sensitive to the dissipation factor using lower frequencies due to the time effect of depolarisation. The classification of a good, medium or severely WT aged cable condition is more effective using VLF compared to 50 Hz or variable frequencies.

Loss factor simulations using mathematical correlations, e.g. based on the damping factor of an oscillating wave, depend entirely on the length of the measured cable. Furthermore, the tan delta (TD) and delta TD at voltage rise and descent can give a more detailed answer when diagnosing water ingress in joints or terminations [14]. The user has to rely on a consistent database, especially if severe criteria are used that are expensive and need maintenance. Calibration and validation procedures have to be carefully handled; wrong decisions in the field environment may become very costly. [6]

7.2 Basic background of tan δ dissipation factor (TD)

Tan δ is a measure of the degree of real power dissipation in a dielectric material and therefore its losses.
In the case of underground cables, this test measures the bulk losses rather than the losses resulting from a specific defect. Therefore, the tan δ measurement constitutes a cable diagnostic technique that assesses the general condition of the cable system insulation. Tan δ can be employed on all cable types; however, test results must be considered with respect to the specific cable insulation material and accessory type.
For modelling, the cable insulation system is simply represented by an equivalent circuit that consists of two elements; a resistor and a capacitor, see **Figure 19**.

When voltage is applied to the cable, the total current (I) will be the contributions of the capacitor current (IC) and the resistor current (IR). Tan δ is the ratio between the resistor current and the capacitor current. The angle δ is the angle between the total current and the charging current when they are represented as phasors. [13]
The measurement of the tan δ value is often also described as tan delta, TD, loss factor or dissipation factor measurement.



$$\tan \delta_L = \frac{P}{Q} = \frac{1}{\omega C \cdot R} = \frac{\kappa_\infty}{\omega \varepsilon_0 \varepsilon_r}$$

Figure 18: Simplified single-line diagram used to describe DPF at one single frequency [13]

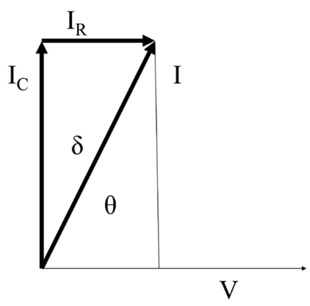


Figure 19: Extract from IEEE 400.2-2001, Fig. 6 – Phasor diagram for high loss dielectric material [13]

Figure 20 shows the different tan δ values for different polymer insulated cables. The values indicate that tan δ at 0.1 Hz is different from tan δ at 50 Hz.

Diagnostic methods, like partial discharge (PD) and dissipation factor (TD) measurements are recommended in order to control the insulation condition under HV stress, based on a voltage waveform which conforms to the IEC 60060-3 standard. Diagnostic tests, starting at a voltage level of 0.5 U_0 and rising to a maximum of 2 U_0, are common in practice and are, therefore, comparable with values between phases and historical data. The maximum diagnostic voltage level should be carefully handled to avoid incipient cable failures, especially on aged cable systems. If the cable condition is unknown or in a critical stage, the applied voltage level should never exceed those recommended by the manufacturer or user.

Avoiding a possible breakdown of the insulation, the operator might limit the voltage level far below the dielectric strength or at least reaching TD tip-up criteria or the partial discharge inception voltage level. [1]
According to **Figure 21**, the dissipation factor should depend heavily on frequency. Due to the resonant frequency of space charge polarisation, the measured vales are nevertheless comparable. For different insulating materials, Tan δ might be higher or lower.

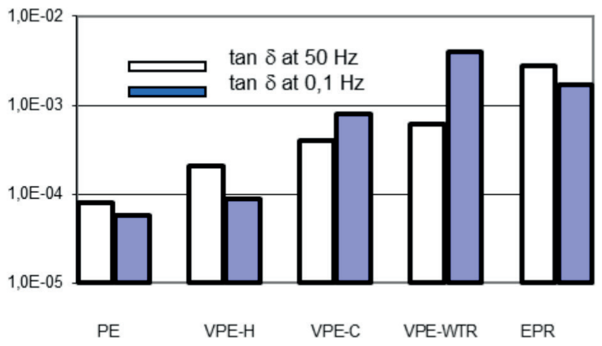
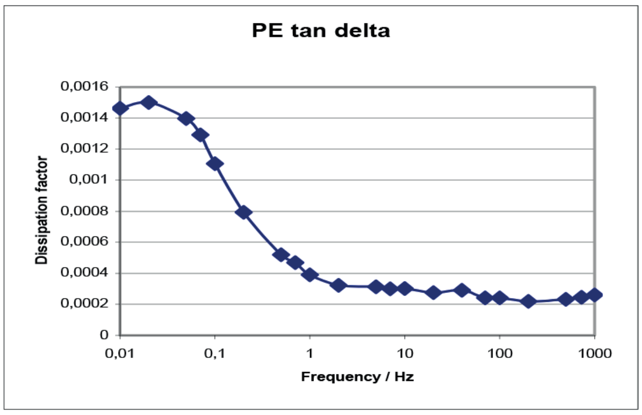


Figure 20: Dissipation factor for new polymer insulated MV cables at 0.1 Hz / 50 Hz, (H: Homopolymer, C: Copolymer, WTR: Water Tree Retardant) [Kus, 1995] Fig. 4 [1]



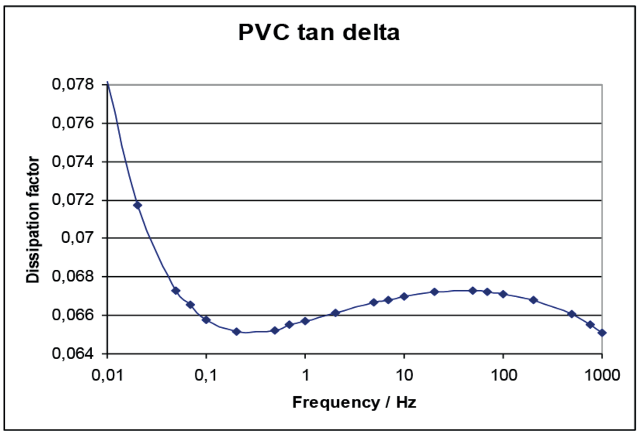


Figure 21: Frequency domain spectroscopy of service-aged PE and PVC cables [1]

Figure 23 shows the high sensitivity of tan δ measurements at 0.1 Hz on water trees compared to 50 Hz measurements. **Figure 22** shows that the tan δ at 0.1 Hz increases significantly with test voltage level. This resulted in the expression of limits for XLPE and PE cables mentioned below. [1]

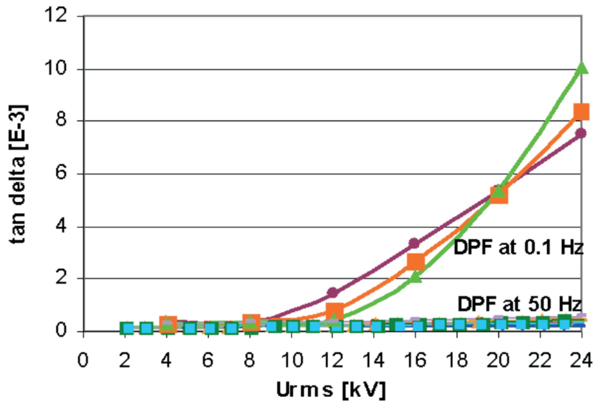


Figure 22: Nonlinearity of DPF on service-aged XLPE cables at 0.1 Hz and at 50 Hz excavated and extracted in 2008 [1]

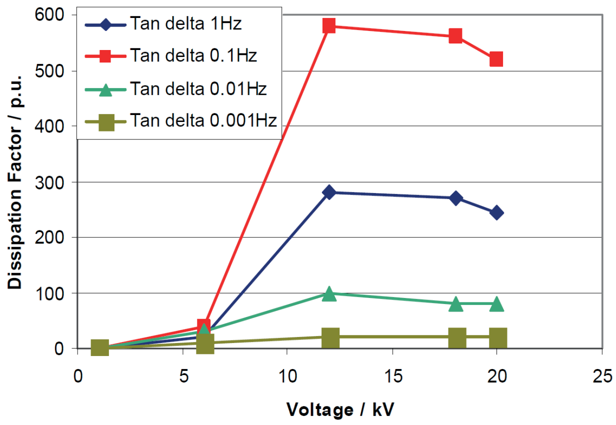
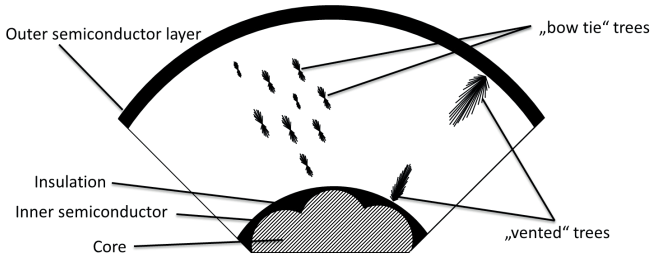


Figure 23: Comparison of non-linearity in the frequency domain of a heavily water-tree-aged XLPE cable [Kus, 1998] [1]

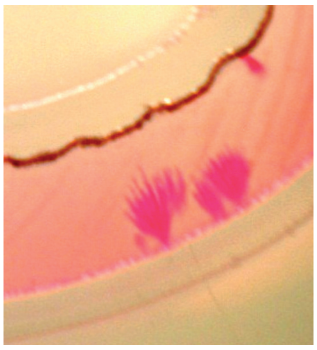
7.3 Water Tree – Electrical Tree

The experience over the past years has shown that water-treeing is the major factor that determines durability, especially of first-generation polymeric cables. While installation and mounting errors tend to be locally repairable, water-treeing occurs in areas where extension of the equipment life can only be achieved through the replacement of sections or through chemical refurbishment. Water-treeing is an effect on the physical background that has not yet been fully explained despite various theories. Basically, water trees are channel-shaped structures that develop in the form of minute trees in the insulating material as a result of moisture and electrical fields emanating from defects. The electrical conditions prevalent in these water-trees, which are mostly invisible to the naked eye, differ from those in the healthy surrounding insulating material and this feature can be utilised for their measurement. The development of water trees is a process that takes several years. Water trees can occur continuously in a cable without reducing its functional capacity, and the critical phase is entered when the PD-inception field strength at the tips of a water tree is exceeded. Water trees can be determined by the tan delta measurement, as they influence the leakage current along the cable. Since they are not accompanied by partial discharges, water trees cannot be located in the same way as partial discharges.

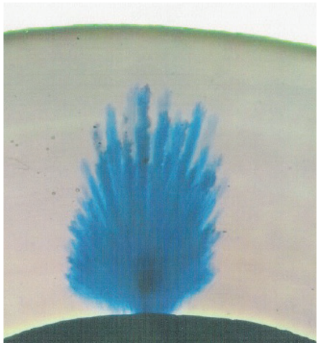
Electrical treeing is a process which, unlike water-treeing, takes place only at spots of high local electrical field strength and is followed by a series of partial discharges. However, the resulting hollow, channel-shaped structures are visible to the naked eye (**Figure 28**). The final breakdown of the insulation path under the influence of electrical trees is sometimes just a question of minutes or hours.



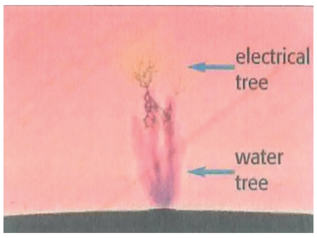
↗ Figure 24: Illustration of "bow-tie" trees and "vented" trees



↗ Figure 25: Water tree, channel shaped structure



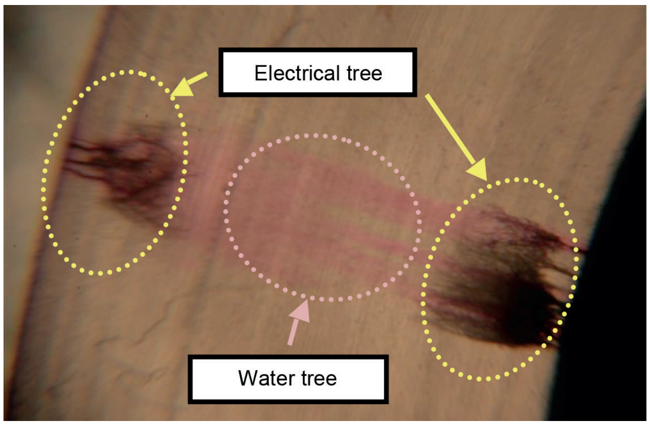
↗ Figure 26: Water tree, channel shaped structure



↗ Figure 27: Water tree with developing level of electrical tree, PD activity

Unlike water-treeing, **electrical treeing can be detected by PD measurement.**

Since long water trees in the insulating material are likely to pave the way for future electrical trees, they can also be used to measure the ageing condition of a plastic insulated cable. A diagnostic method that does not give just a "go/no-go" appraisal, but which also evaluates the overall condition of the cable insulation must produce a measurement value that will correlate very well with the concentration of long water trees. Even though this insight into the cable insulation can only give an integrated result, significant similarities can be detected in most cases between the results of the measurements and the actual state of the cable using appropriate methods of diagnostics.
The higher the dissipation factor of the insulation, the lower the dielectric strength.



↗ Figure 28: Photo of actual water tree and electrical tree after dissection (XLPE cross section)

↗ Figure 29: Incomplete degassing of the cable in the factory after 14 months in operation

↗ Figure 30: Aged XLPE insulation, voids in XLPE, visible without colouring, 115 kV cable

7.4 Tan δ measurements on service-aged cables

In the past few years, most of the industrialised countries beside Europe also started to follow the diagnostics guidelines established in Europe and, due to different design of cables, the test voltage of up to 2 U_0 has been questioned. Based on this, NEETRAC performed numerous field tests and carried out research, and the results and experience are summarised in the following chapter.

This section considers tan δ measurements carried out in the field, with the testing having been performed at one of the utilities participating in the CDFI project. Its name is not revealed here because of the confidential nature of the data. The utility decided to conduct tan δ measurements on a 25 kV XLPE direct buried cable system that initially operated at 15 kV and was upgraded to 25 kV operations in 2006. A considerable number of failures occurred after the system was upgraded and the utility seriously considered the total replacement of affected subdivisions.
Tan δ measurements were conducted at 0.5, 1.0, 1.5 and 2.0 x U_0. **Figure 31** shows the cumulative distribution functions of the tan δ field data for all test voltages.

The results show that if the values given by the IEEE Std. 400 (section 8.4) [13] are considered for assessment, 64% of the cables are considered highly degraded, 16% aged, and only 20% in good condition.
These proportions seem to be extreme in the sense that a follow-up record of onsite failures after testing has been kept and, to date, no more failures have occurred. This test was conducted in July 2006. Similar results are obtained when evaluating the data using the tip-up criteria. This could be an indication that the values as given for the standard are probably too conservative or that more features for evaluation are needed.

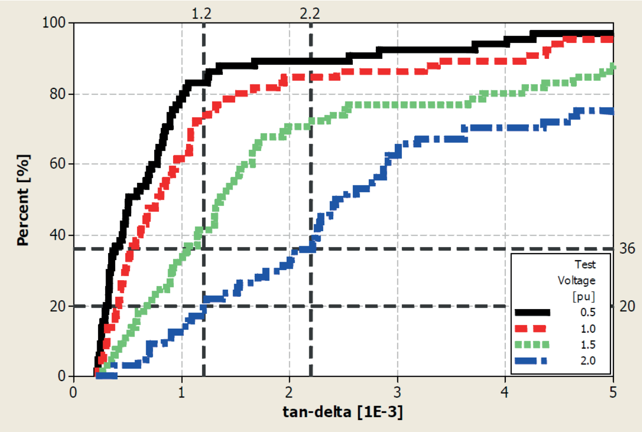


Figure 31: Cumulative distribution functions of tan delta field data for > 10,360 m of cable measured [18]

Influence of some field condition issues on the interpretation using the standard equivalent circuit
Tan δ measurements are most often interpreted in terms of a simple circuit within a parallel connected resistance and capacitance. This equivalent circuit lumps all of the contributions along the length into single circuit elements. Thus it should be clear that to achieve the correct interpretation, the correct equivalent circuit needs to be used. In the course of the work reported here, it has been determined that there are at least three important cases where the assumption of the simple equivalent circuit may not be completely appropriate:

- The presence of partial discharge (PD)
- Corroded neutral wires
- Non-uniform water tree degradation

It has been seen in the laboratory measurements that PD has an effect on the measurements of tan δ.

The effect can be explained by means of 2 case scenarios:

- Corona at the terminations and PD from large voids within the cable insulation. This first case may perturb the measurement in that the corona discharge current adds to the measured leakage current. Thus this may not really be considered as adding to the cable loss. Nevertheless, it does indicate the importance of ensuring discharge-free terminations when conducting any sort of measurement in the field.
- In the second case of a large void discharge within a cable, the presence of internal PD can increase the measured tan δ value for XLPE cables by almost an order of magnitude. If tested lengths of cable contain PD, which often comes from accessories, then this effect can complicate diagnostics.

There is no question that the simple equivalent circuit does not account for this situation. A more elaborate model should be used. At present, there is no indication regarding which model to use; thus, research efforts are required in this area. When there is significant corrosion of the neutral wires, the tan δ value will also contain a contribution from the equivalent model series resistance. The simple model approach assumes that the series resistance, comprised of the shield resistance, the neutral wire resistance and any contact resistance, are small. When there is significant corrosion of the neutral wires, the previous assumption is incorrect. In this case, the tan δ will contain a contribution from the length-dependent series resistance. Therefore, it is expected that there will be an increment in the tan δ value that is a function of length when the neutral wires are corroded. In other words, the total power losses will be the result of the contribution of the bulk insulation losses and the length-dependent series resistance losses. This leads to a situation similar to the one for partial discharge but with different diagnostic features. This situation has been observed in other field tan δ measurements conducted by the CDFI project. [18]

If higher density regions of water trees exist only in part of the cable segment length, their effect on tan δ would not be reflected in the measurement. In other words, the overall tan δ value may be lower than the value that corresponds to the high-density regions of water trees. **Figure 32** shows two cases for a cable section with non-uniform water tree degradation; the situation can be modelled by making the proper modifications to the equivalent circuit in order to identify useful diagnostic indicators for the tan δ values and tip-up. [18]

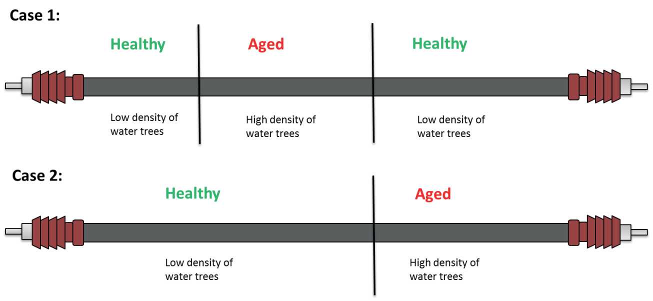


Figure 32: Cable section with non-uniform water tree degradation

7.5 Tan δ – Measurement at lower test voltages

The field data has revealed a way in which tan δ values may be collected and compared to data at lower stresses or testing voltages. The conditioning and comparison methods enable existing success criteria used at the higher stresses to be mapped to lower levels of stress, thereby providing the same level of discrimination, but delivering this at lower stresses. This significantly reduces the risk of failure when under test.
The level of risk reduction may conveniently be estimated from an appropriately parameterised version of the well-known Weibull Equation as mentioned before.

Figure 33 shows the correlation between tan δ measurements from field testing at 2.0 U_0 and 1.5 U_0 for modified diagnostic criteria. The voltage of 1.5 U_0 represents a lower risk of failure during testing to the cable system.
The plot shows a relationship between the data collected at the different voltages. The clarity of the plot is improved by adopting logarithmic scales which further facilitate the identification of the relationship. In this case, the relationship is linear in logarithmic terms, but this need not be so. It is sufficient that the relationship is clear.
The vertical lines represent the already established success criteria from IEEE Std. 400. In the absence of the relationship it is clear that an engineer wishing to utilise the experience set out in IEEE Std. 400 is constrained to test at 2.0 U_0. This forces the engineer to accept a higher level of risk than he may be comfortable with.
With the relationship, it is a straightforward procedure for the engineer to translate the success criteria from the higher stress (1.2, 2.2 and 4 values on the upper X axis for 2.0 U_0) to a lower stress (0.7, 1.3 and 2.3 on the left-hand Y axis for 1.5 U_0) thus reducing the risk. Therefore, such a relationship demonstrates that it is possible to develop criteria for different voltages in a very convenient way.

New evaluation criteria for TD measurement on aged cables are also discussed in the new recommendation mentioned in the IEEE 400.2 D12 draft 2012 [19].

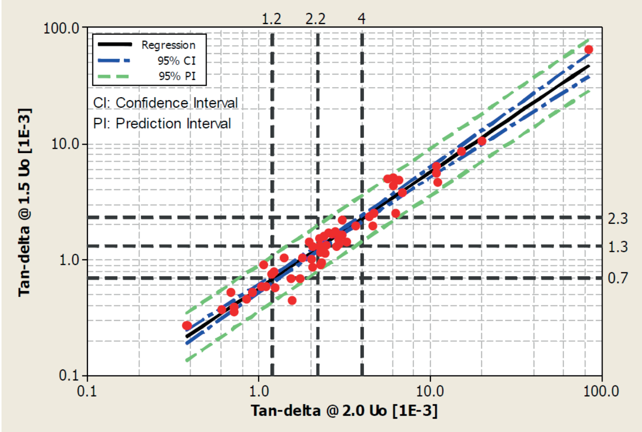


Figure 33: Correlation between tan delta measurements from field testing at 2.0 U0 and 1.5 U_0 for modified diagnostic criteria [18]

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7.6 TD evaluation – important parameters/influences

7.6.1 Important parameters for TD interpretation

1. Stability – Standard Deviation

```
#   Time       Voltage    Current    Tan delta
               kV         mA         E-3
---------------------------------------------
1   12:26:14  18.9       6.4        1.60
2   12:26:24  18.9       6.4        1.61
3   12:26:34  18.9       6.4        1.63
4   12:26:44  18.9       6.4        1.64
5   12:26:55  18.9       6.4        1.64
6   12:27:05  18.9       6.4        1.65
7   12:27:15  18.9       6.4        1.66
8   12:27:25  18.9       6.4        1.67

Phase ....................... : L3
Date/Time ................... : 04-08-2017 12:27:26
Step ........................ : 2
Avg. Value tan delta ........ : 1.636 E-3
Standard deviation .......... : 0.021 E-3
No. of tests ................ : 8
Load ........................ : 541.5 nF
Test sample VSE current ..... : 106.0 µA
Generator VSE current ....... : 10.0 µA
```

Definition of standard deviation
The standard deviation is defined as the average amount by which scores in a distribution differ from the mean, ignoring the sign of the difference.

$$STD = \sqrt{var} = \sqrt{\frac{\sum (x - \bar{x})^2}{N}}$$

The TD Standard Deviation was established to be a very useful figure in analyses of the reason for degradation.

Furthermore, the trend direction is very important!

TD stability as an indicator of weakness in the cable

Standard deviation / stability	Indication	Required measurement	Required action	Comment
< 0.010	▪ Cable in good condition ▪ Water trees ▪ Only few PDs	TD PD	No immediate action, cable in good condition	DTD usually low No PD or no intensive PD
0.010 to 0.100	Water trees & PD Only concentrat-ed PD	TD PD	Moderate water-tree ageing if no PD; PD concentration to be analysed	Moderate water-tree ageing => no immediate action Replacement of joint if PD concentrated
0.100 to 0.500	Water ingress in joints	TD PD may not show high PD values	Only TD can indicat-ed this effect PD results to be considered as damped due to the presence of water. PD value criteria cannot be applied!	Sheath fault location might indicate the location of the joint with water ingress. Water in – leakage current out; joints indicating low PD have to be investigated even if the PD value is low. PD calibration graph might deliver information on the location of the joint with water ingress

> 0.500	Very high water ingress in joint	TD PDs are widely eliminated in affected joints	Only TD shows this effect PD does not show any weak point; immediate replacement of joint Investigation of PD calibration graph	Sheath fault location might indicate the location of the joint with water ingress. Water in – leakage current out PD calibration graph might deliver information on the location of the joint with water ingress

↗ Table 20: TD stability interpretation; suitable as general guideline [20]

2. Delta tan delta DTD

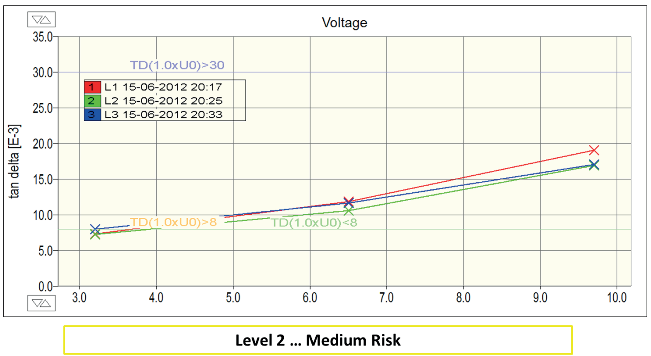
DTD (Delta TD)
[2 U_0] – [U_0] … for new cables
[1.5 U_0] – [0.5 U_0] … for aged cables

Indication of

- ⇨ **PD activity**
- ⇨ **Water trees**

Cables are actually still **in good condition:**
[tan d (2 U_0) – tan d (U_0)] < 0.6 ‰
Cables **with high operating risk:**
[tan d (2 U_0) – tan d (U_0)] > 1.0 ‰

Reference: EWE, acc. to IEEE 400.2



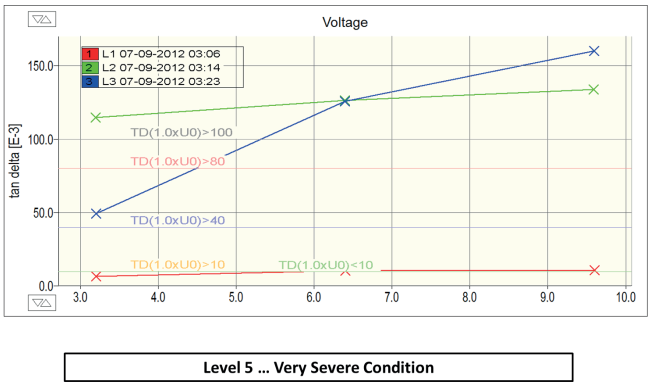
↗ Figure 34: Evaluation of TD results, DTD [20]

3. Absolute TD value

According to to IEEE 400.2-2001 … up to 2 U_0

According to to IEEE 400.2-2013
for service-aged cables … up to 1.5 U_0

Cables are actually still **in good condition**
and do not have to be replaced:
tan d (2 U_0) < 1.2 ‰
Cables **with high operating risk:**
tan d (2 U_0) > 2.2 ‰



↗ Figure 35: Evaluation of TD results, phase comparison [20]

4. Phase comparison

Comparison of L1, L2, L3
Same condition in all phases
=> same TD graph

Especially useful for mixed cable circuits where the MTD value is unknown. One lower phase can give a good indication that other phases have ageing issues.

5. Information on TD details – TD stability over time

#	Time	Voltage kV	Current mA	Tan Delta E-3
1	11:47:14	1.4	0.0	0.40
2	11:47:24	1.4	0.0	0.41
3	11:47:33	1.4	0.0	0.42
4	11:47:44	1.4	0.0	0.42
5	11:47:54	1.4	0.0	0.42
6	11:48:04	1.4	0.0	0.42
7	11:48:14	1.4	0.0	0.43
8	11:48:24	1.4	0.0	0.43

Upward trend

```
Phase ....................... : L1
Date/Time ................... : 04-11-2010 11:48:25
Step ........................ : 1

Avg. Value Tan Delta ........ : 0.419 E-3
Standard Deviation .......... : 0.009 E-3
No. of Tests ................ : 8
Load ........................ : 41.4 nF
Test sample VSE current ..... : 8.0 uA
Generator VSE current ....... : 0.0 uA
```

#	Time	Voltage kV	Current mA	Tan Delta E-3
1	11:49:45	2.9	0.1	2.55
2	11:49:55	2.9	0.1	2.65
3	11:50:05	2.9	0.1	2.73
4	11:50:15	2.9	0.1	2.81
5	11:50:25	2.9	0.1	2.80
6	11:50:35	2.9	0.1	2.86
7	11:50:45	2.9	0.1	2.90
8	11:50:55	2.9	0.1	2.94

Upward trend

```
Phase ....................... : L1
Date/Time ................... : 04-11-2010 11:50:56
Step ........................ : 2
Avg. Value Tan Delta ........ : 2.781 E-3
Standard Deviation .......... : 0.124 E-3
No. of Tests ................ : 8
Load ........................ : 41.0 nF
Test sample VSE current ..... : 16.0 uA
Generator VSE current ....... : 0.3 uA
```

Upward trend 0.40 to 0.43 E-3 //2.55 to 2.94
Losses are developing, tracking
PD track development
Water tree presence

#	Time	Voltage kV	Current mA	Tan Delta E-3
1	11:52:16	4.3	0.1	5.27
2	11:52:26	4.3	0.1	4.90
3	11:52:36	4.3	0.1	4.65
4	11:52:46	4.3	0.1	4.46
5	11:52:56	4.3	0.1	4.46
6	11:53:06	4.3	0.1	4.26
7	11:53:16	4.3	0.1	4.08
8	11:53:26	4.3	0.1	3.92

Downward trend

```
Phase ....................... : L1
Date/Time ................... : 04-11-2010 11:53:27
Step ........................ : 3
Avg. Value Tan Delta ........ : 4.500 E-3
Standard Deviation .......... : 0.412 E-3
No. of Tests ................ : 8
Load ........................ : 40.8 nF
Test sample VSE current ..... : 24.0 uA
Generator VSE current ....... : 2.0 uA
```

#	Time	Voltage kV	Current mA	Tan Delta E-3
1	11:54:47	5.8	0.2	4.26
2	11:54:57	5.8	0.2	4.13
3	11:55:07	5.8	0.2	4.02
4	11:55:18	5.8	0.2	3.86
5	11:55:27	5.8	0.2	3.87
6	11:55:37	5.8	0.2	3.73
7	11:55:47	5.8	0.2	3.61
8	11:55:58	5.8	0.2	3.50

Downward trend

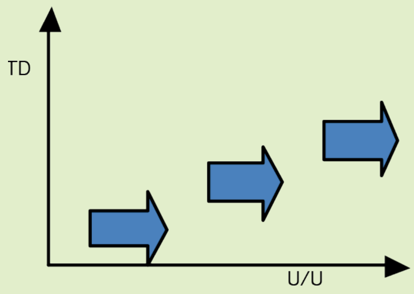
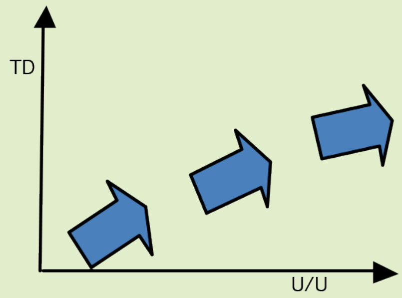
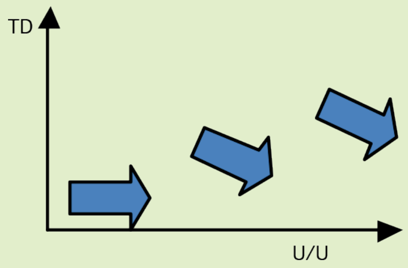
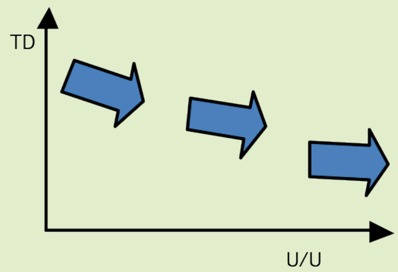
```
Phase ....................... : L1
Date/Time ................... : 04-11-2010 11:55:58
Step ........................ : 4
Avg. Value Tan Delta ........ : 3.872 E-3
Standard Deviation .......... : 0.240 E-3
No. of Tests ................ : 8
Load ........................ : 41.1 nF
Test sample VSE current ..... : 34.0 uA
Generator VSE current ....... : 2.0 uA
```

Downward trend
5.27 to 3.92 E-3 // 4.26 to 3.50 E-3
Humidity vaporising during appl. of high voltage
⇨ TD measurement shall be repeated. Value will stabilise when water is vaporised.

Figure 36: TD stability trend interpretation [20]

7.6.2 TD stability trend analysis

TD stability trend as an indication of leakage behaviour
⇨ Possible indications for TD trend behaviour in XLPE cables

▪ Stable values throughout the voltage stages ▪ Low standard deviation ⇨ Stable condition ⇨ Indication of PD activity, moderate water tree presence	
▪ Increasing TD throughout the voltage stages ▪ Moderate level of standard deviation ⇨ Development of leakage, tracking, thermal current ⇨ Development of water tree to advance stage, electrical tree ⇨ Indication of increase of leakage during appl. of voltage	
▪ Decreasing TD throughout the voltage stages ▪ Higher decreasing rate at higher voltages ▪ Moderate standard deviation ⇨ Indication of humidity presence ⇨ Indication of PD, TD is increasing with the voltage ⇨ Water/humidity will vaporise after the voltage is applied for a certain time ⇨ Indication of water/humidity presence at terminations or joints ⇨ Repeating measurement is recommended ⇨ Water/humidity will vaporise and values will become more stable when repeating the TD measurement	
▪ Negative DTD, dropping TD value over the voltage ▪ Decreasing TD throughout the voltage stages ▪ Higher decreasing rate at higher voltages ▪ High standard deviation ⇨ Indication of humidity/water presence ⇨ Water will start to vaporise as soon as the voltage is applied ⇨ Indication of water presence at terminations or joints ⇨ Repeating measurement is recommended ⇨ Water will vaporise and values will become more stable	

↗ Table 21: Overview of TD trend pattern

To get a better overview of the stability trend during each of the voltage steps, the arrow indication tool is used. Arrows pointing upward indicate a positive trend in the TD value during one voltage step. A horizontal arrow indicates a stable condition. An arrow pointing downwards indicates a decreasing TD value over one voltage level. The visualisation of the stability trend enables a better understanding when comparing the individual behaviour for each phase. Three arrows are used for three voltage steps. The vertical position of the arrow enables the absolute value of the TD average value to be drawn at each voltage level.

7.6.3 Basic pattern of TD trend analysis based on cable elements

The TD trend patterns indicated below are based on practical field examples. The project was carried out in cooperation with an Asian power utility that covered several hundreds of medium-voltage cables (11 kV). Detailed cable information was available for each circuit. Combined TD/PD diagnostics were combined with VLF test results and a detailed case investigation was carried out. Finally, the database in which the individual TD trend patterns were recorded was evaluated with respect to the outcome of the case investigation. The TD trend patterns below show the behaviour of the TD time stability during each voltage step in correlation with the TD absolute values in respect to the applied voltage.

The key patterns allow an understanding of the TD trend pattern for each of the possible elements that can be involved in medium-voltage cable networks.

- XLPE cable in good condition, no water-tree ageing, no PD activity in joint(s)
- XLPE cable with water-tree ageing, no PD activity in joint(s)
- XLPE cable in good condition, PD activity in joint(s)
- XLPE cable in good condition, with joint(s) with minor water ingress, tracking in joint
- PILC cable in good condition, no PD activity
- PILC cable in aged condition, with PD activities
- PILC cable with tracking in a joint, minor PD activities
- PILC cable, highly service-aged, with minor PD activities

Indicator	Calculation	Information
Tan δ stability (SDTD)	Standard deviation of 6 – 10 measurements at U_0	▪ Partial discharges ▪ Wet joints
Delta tan δ (ΔTD)	Difference between the average values at 1.5 U_0 and 0.5 U_0	▪ Water trees ▪ Partial discharges ▪ Vaporisation effects
Mean tan δ (MTD)	Average value of 6 – 10 measurements at U_0	▪ Water trees ▪ Ageing effects (thermal, chemical)

↗ Table 22: Information content of SDTD, DTD, MTD

7.6.3.1 TD trend pattern – XLPE cable in good condition

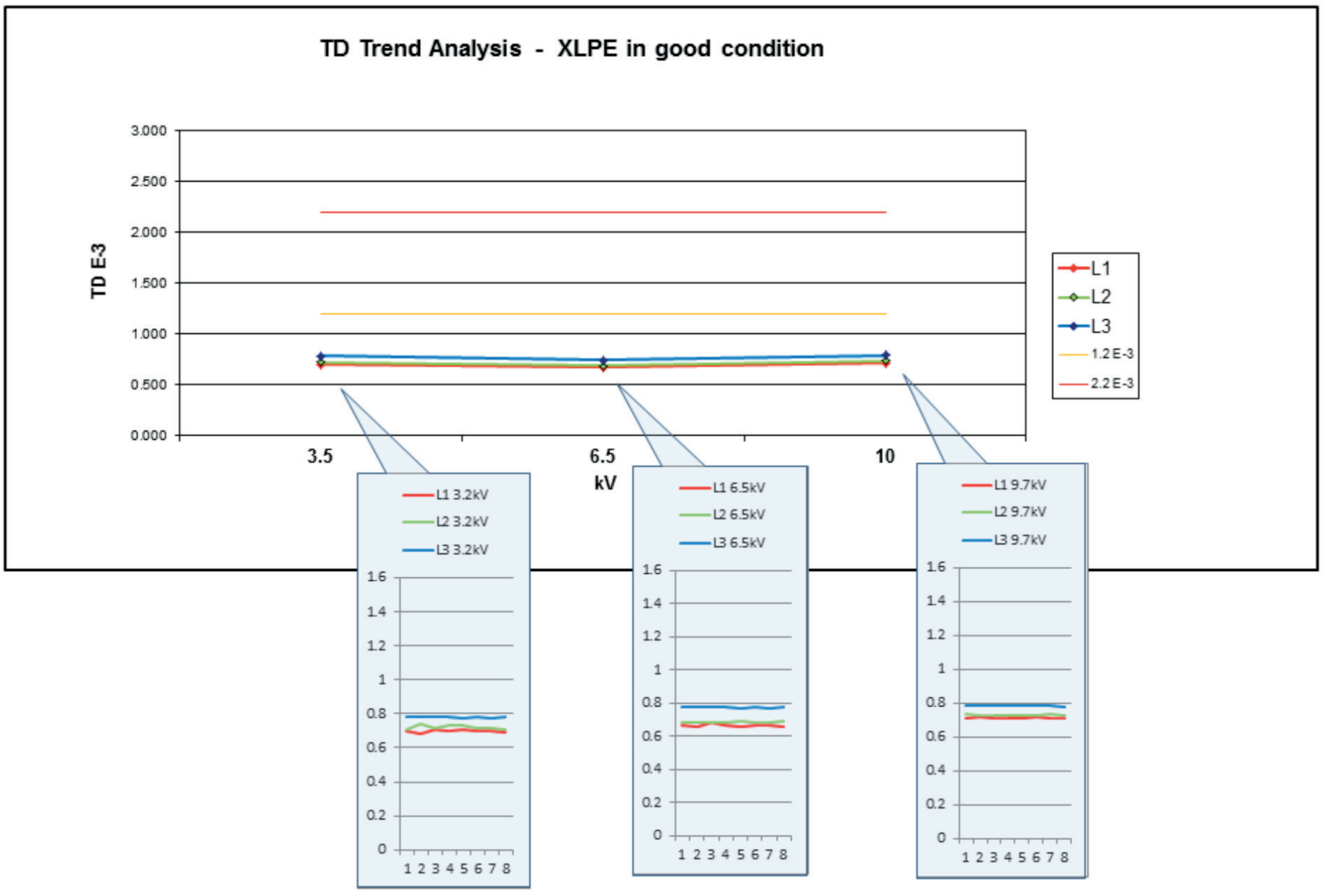


Figure 37: TD trend pattern – XLPE in good condition [20]

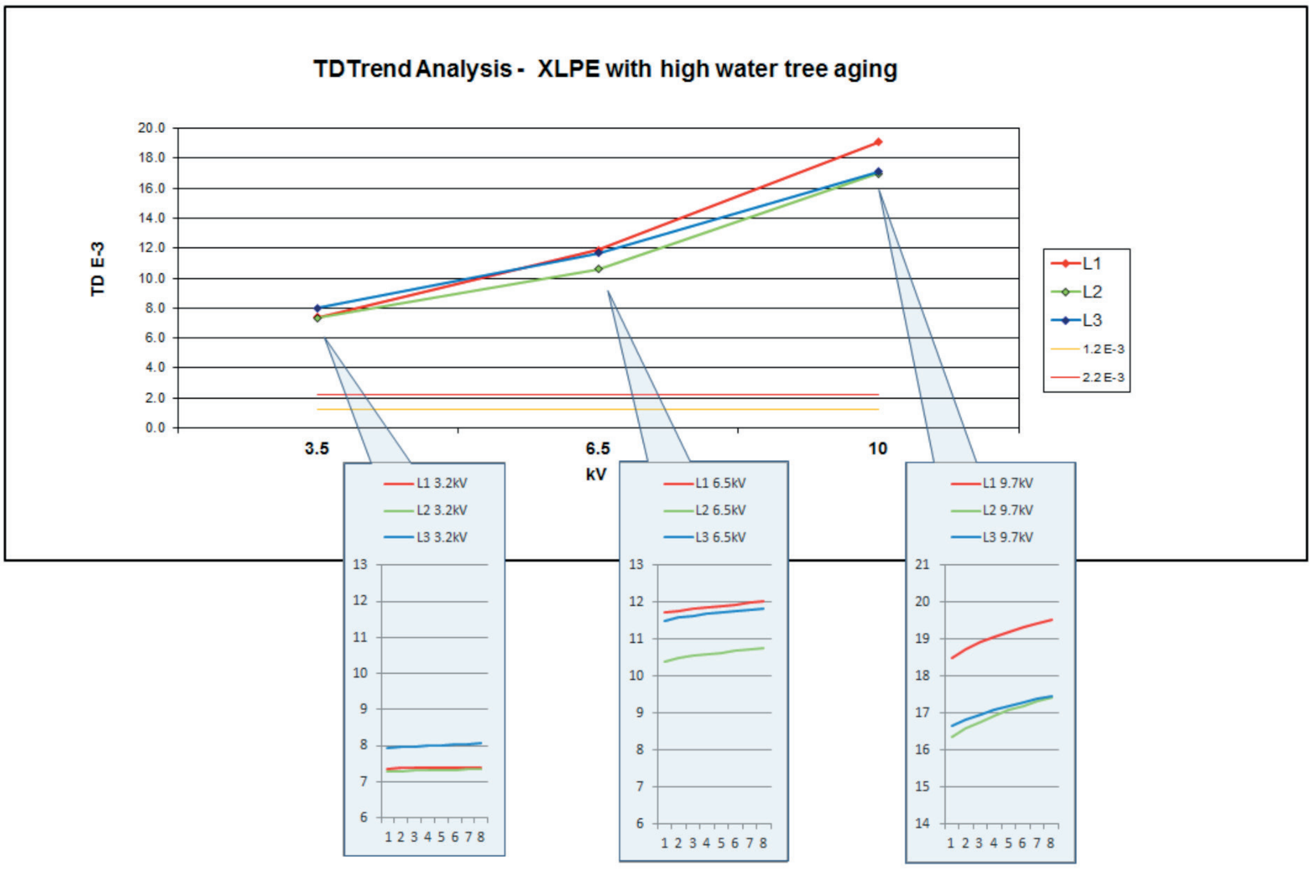
XLPE in good condition:

- Low TD values
- Low DTD
- Low standard dev. < 0.010 E-3
- Stable trend behaviour in all 3 voltage levels

Additional information:

- No PD activities
- Total cable length 1.688 m
- 14 joints
- (7943S10)

7.6.3.2 TD trend pattern – XLPE with high water-tree ageing



↗ Figure 38: TD trend pattern – XLPE with high water-tree ageing [20]

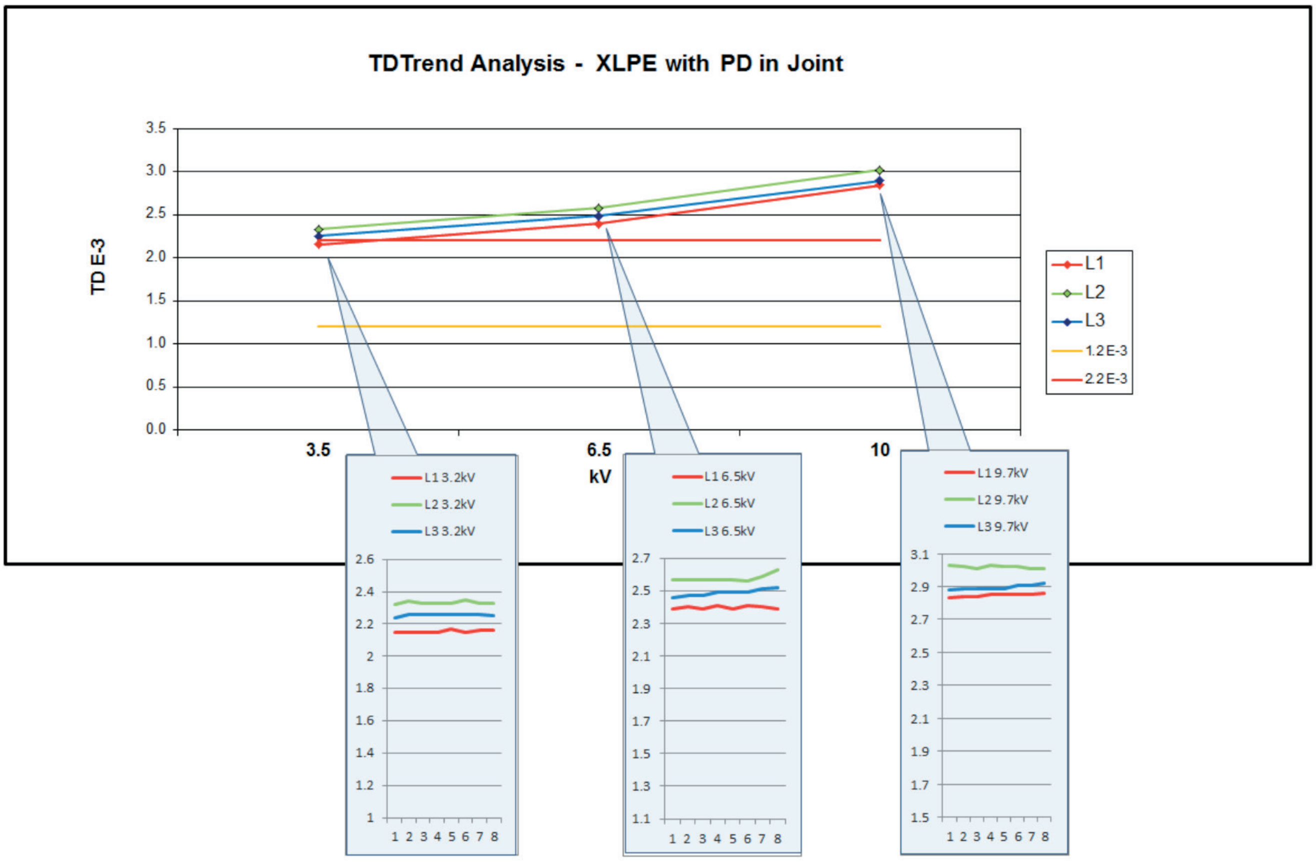
XLPE with high water-tree ageing

- Increasing TD values
- High DTD
- Increased std. dev. < 0.500 E-3
- Increasing trend behaviour with higher voltage

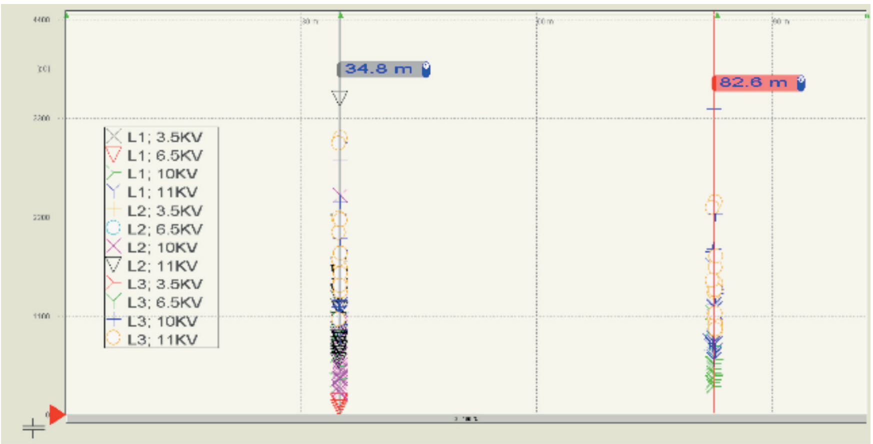
Additional information:

- No PD activities
- Total cable length 933 m
- 15 joints
- Water-tree-prone cable section (90%)
- (3814S03)

7.6.3.3 TD trend pattern – XLPE cable with PD activities in joint(s)



↗ Figure 39: TD trend pattern – XLPE with PD activities in joints [20]



↗ Figure 40: PD localisation graph – XLPE with PD activities in joints [20]

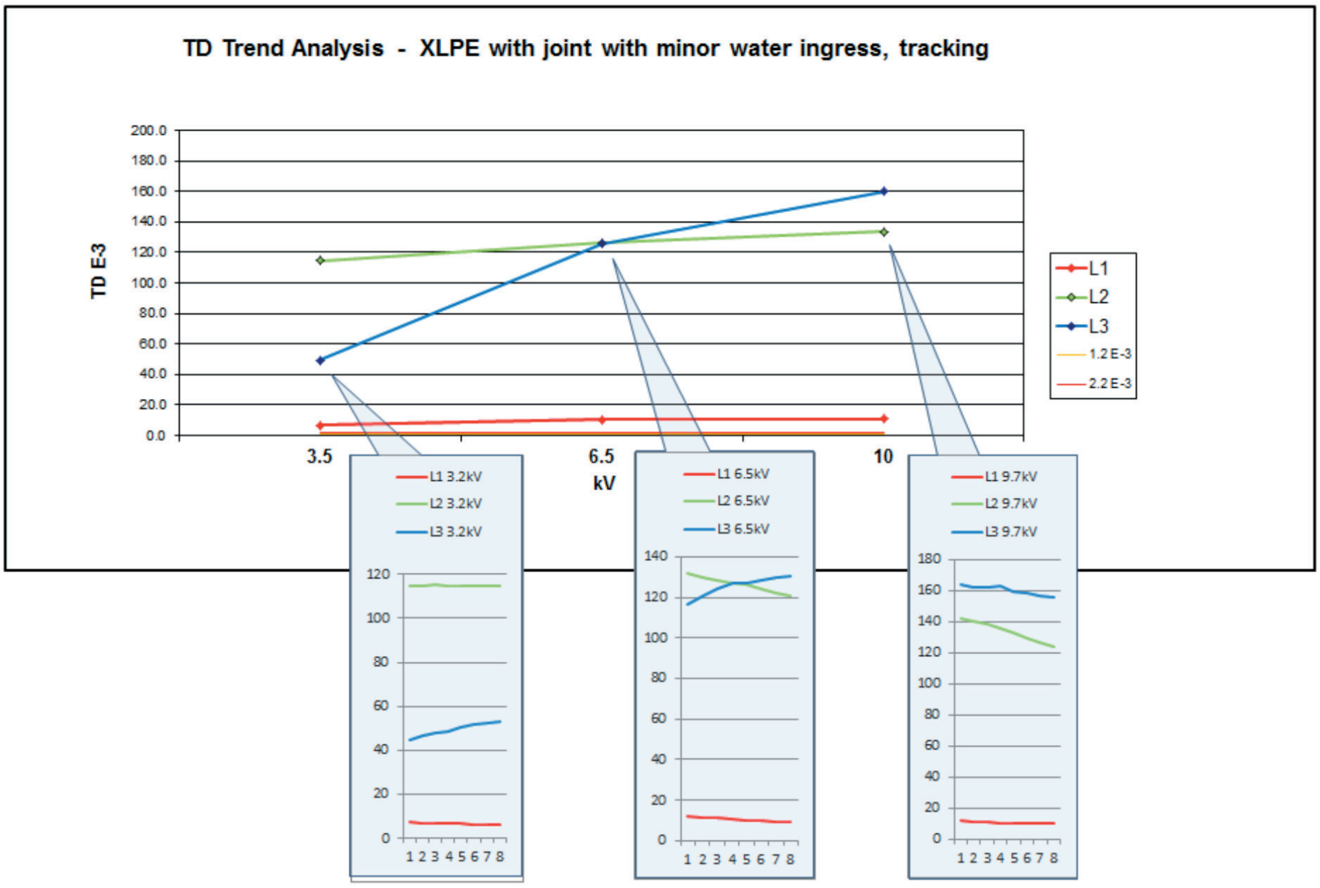
XLPE with PD in joint

- Increasing TD values
- Slightly elevated DTD
- Stable std. dev. < 0.100 E-3
- Rather stable trend behaviour with higher voltage

Additional information:

- PD activities up to 3,000 pC
- Total cable length 102 m
- 2 joints
- New XLPE
- (4579S11)

7.6.3.4 TD trend pattern – XLPE cable with joint(s) with minor water ingress, tracking in joint



↗ Figure 41: TD trend pattern – XLPE with joint with minor water ingress, tracking [20]

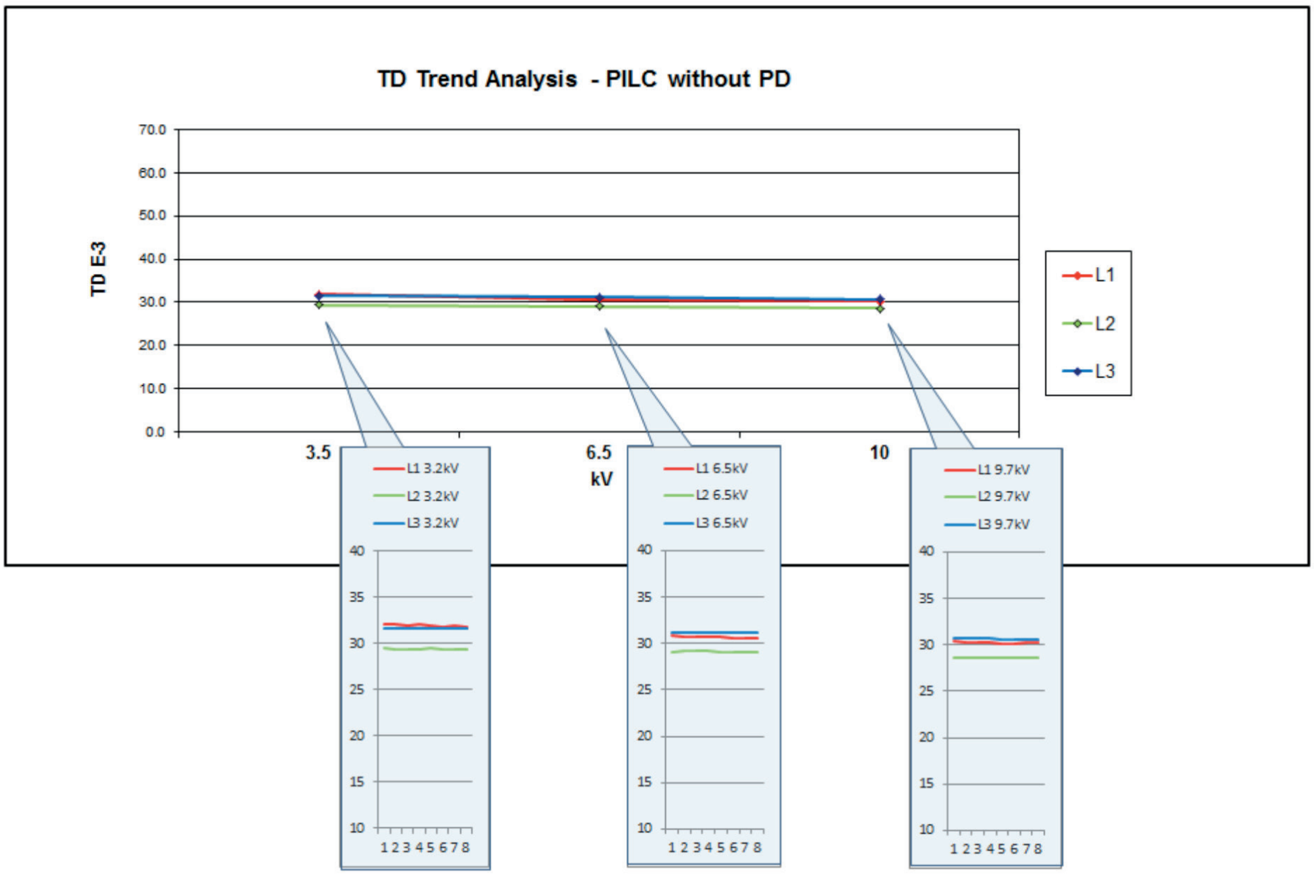
XLPE with joint with minor water ingress, tracking

- L1 … stable, reference phase, joint OK
- L2 … very high TD value, slightly increasing MTD, positive DTD
  Strongly decreasing trend
  High STD > 0.500 E-3
  ⇨ Joint with water ingress
- L3 … very high TD, strongly increasing MTD, positive DTD
  Strongly increasing trend
  High STD > 0.500 E-3
  ⇨ Tracking in one of the joints

Additional information:

- PD activities up to 300 pC only
- Total cable length 186 m
- 2 joints
- (12070S07)

7.6.3.5 TD trend pattern – PILC cable without PD activities



↗ Figure 42: TD trend pattern – PILC without PD activities [20]

PILC cable without PD

- Low TD values (~30 E-3)
- Very low DTD
- Low standard dev. < 0.120 E-3
- Stable trend behaviour in all voltage levels

Additional information:

- PD activities up to 1,000 pC in one joint
- Total cable length 1,681 m
- 12 joints
- (SS10850)

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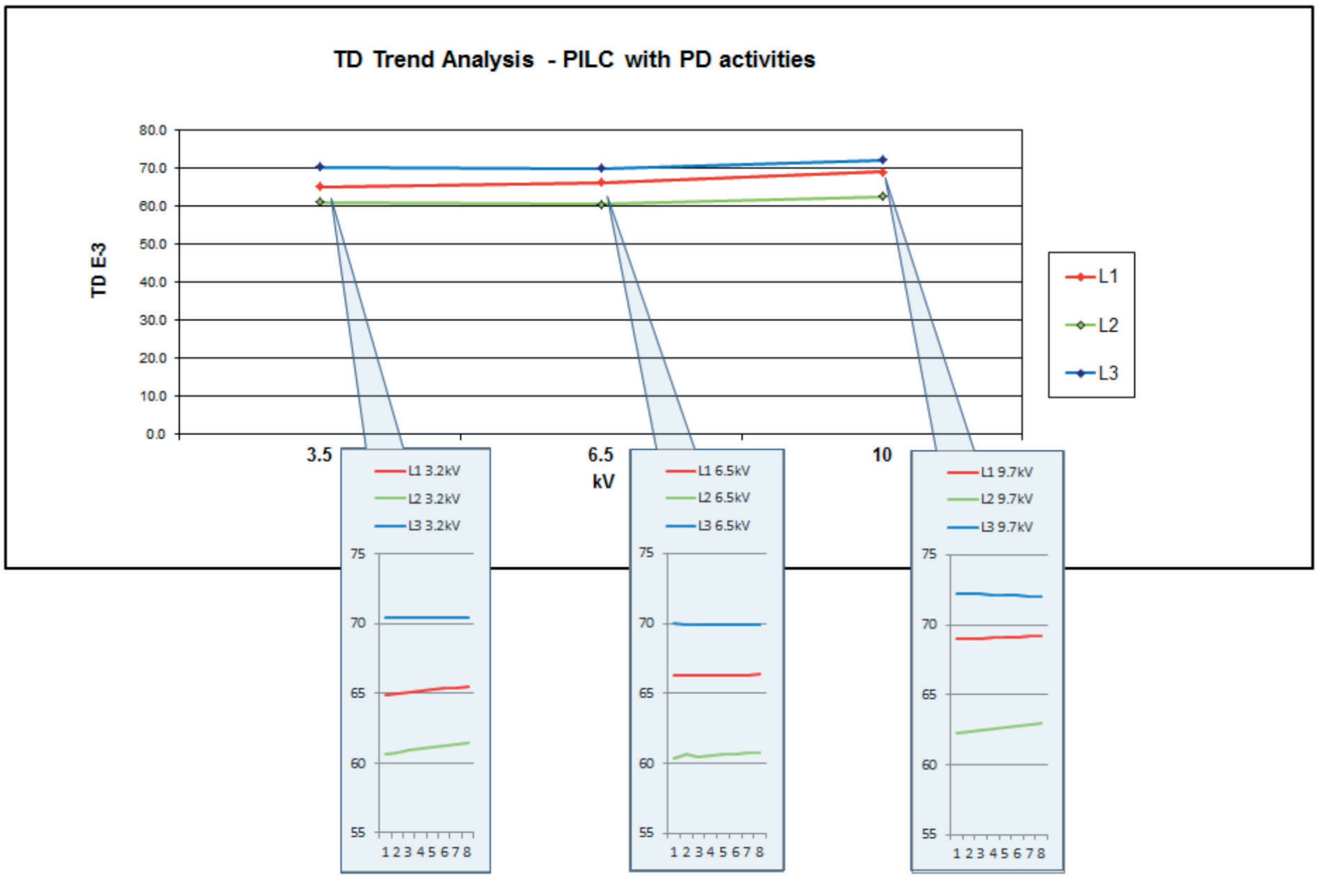
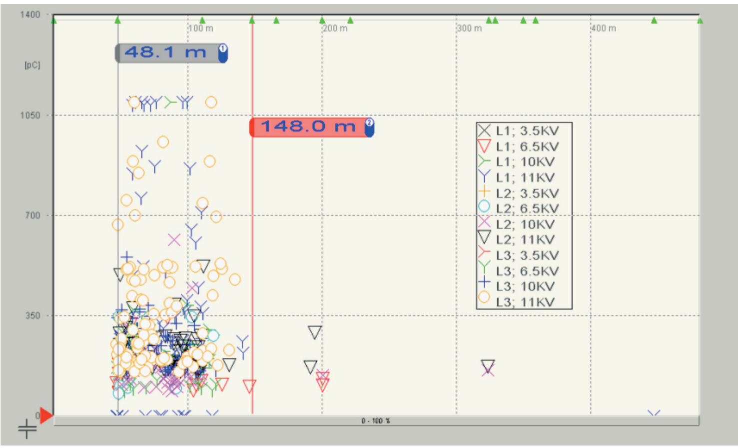
7.6.3.6 TD trend pattern – PILC cable with PD activities



↗ Figure 43: TD trend pattern – PICL cable with PD activities [20]



↗ Figure 44: PD localisation graph – PILC cable with PD activities [20]

PILC cable with PD activities

- TD values (~30 E-3)
- Very low DTD
- Low standard dev. < 0.120 E-3
- Rather stable trend behaviour in all voltage levels
- Only slight tip-up at 1.5 U_0

Additional information:

- PD activities in PILC section up to 1,000 pC
- Total cable length 481 m
- 11 joints
- (1426S08)

7.6.3.7 TD Trend pattern – PILC cable with tracking in a joint, minor PD activities

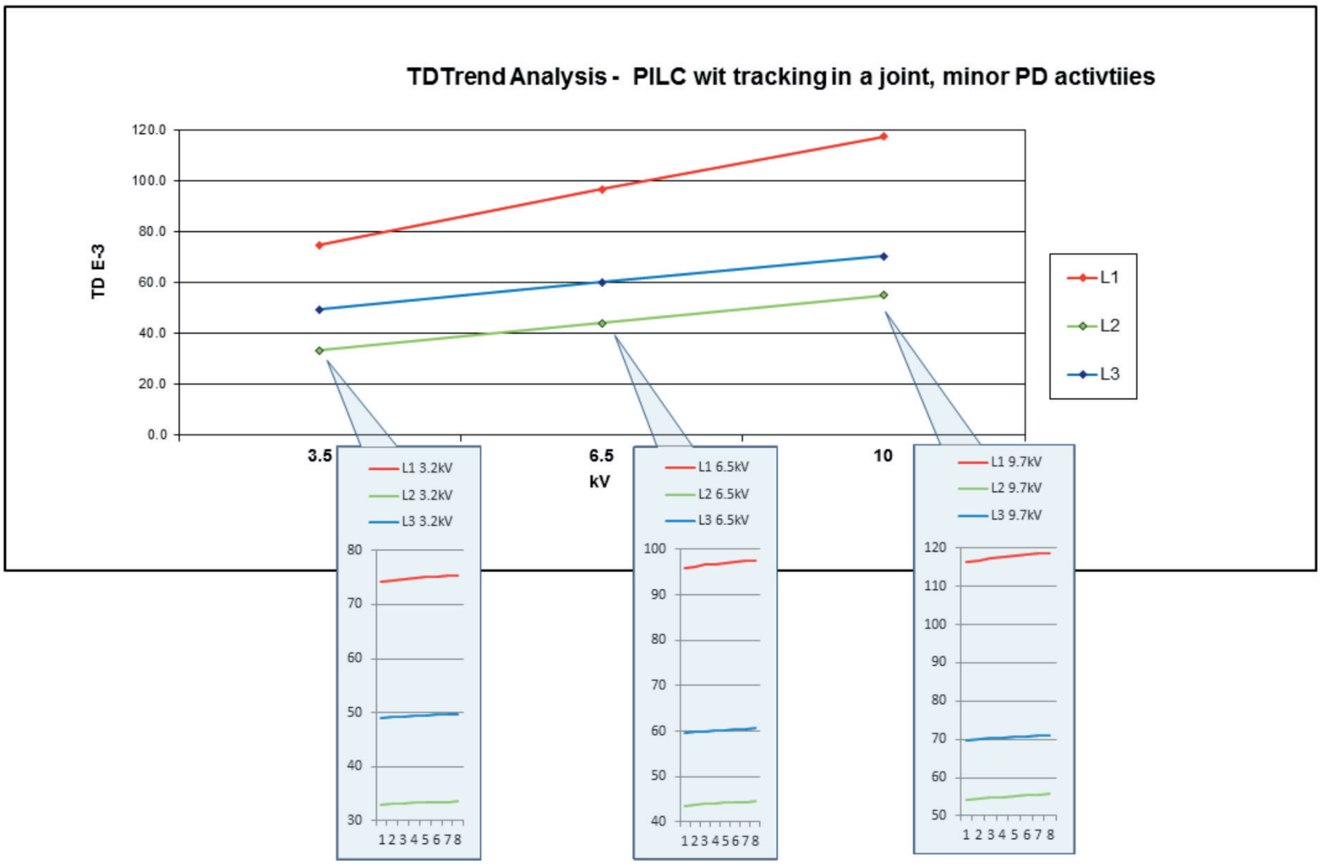


Figure 45: TD trend pattern – PILC cable with tracking in a joint, minor PD activities [20]

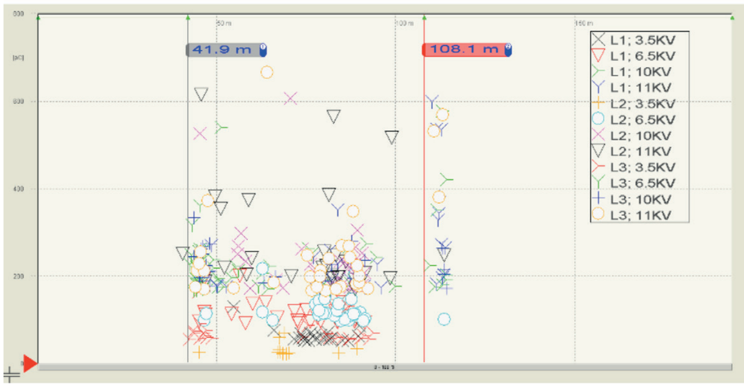


Figure 46: PD localisation graph – PILC cable with tracking in a joint, minor PD activities [20]

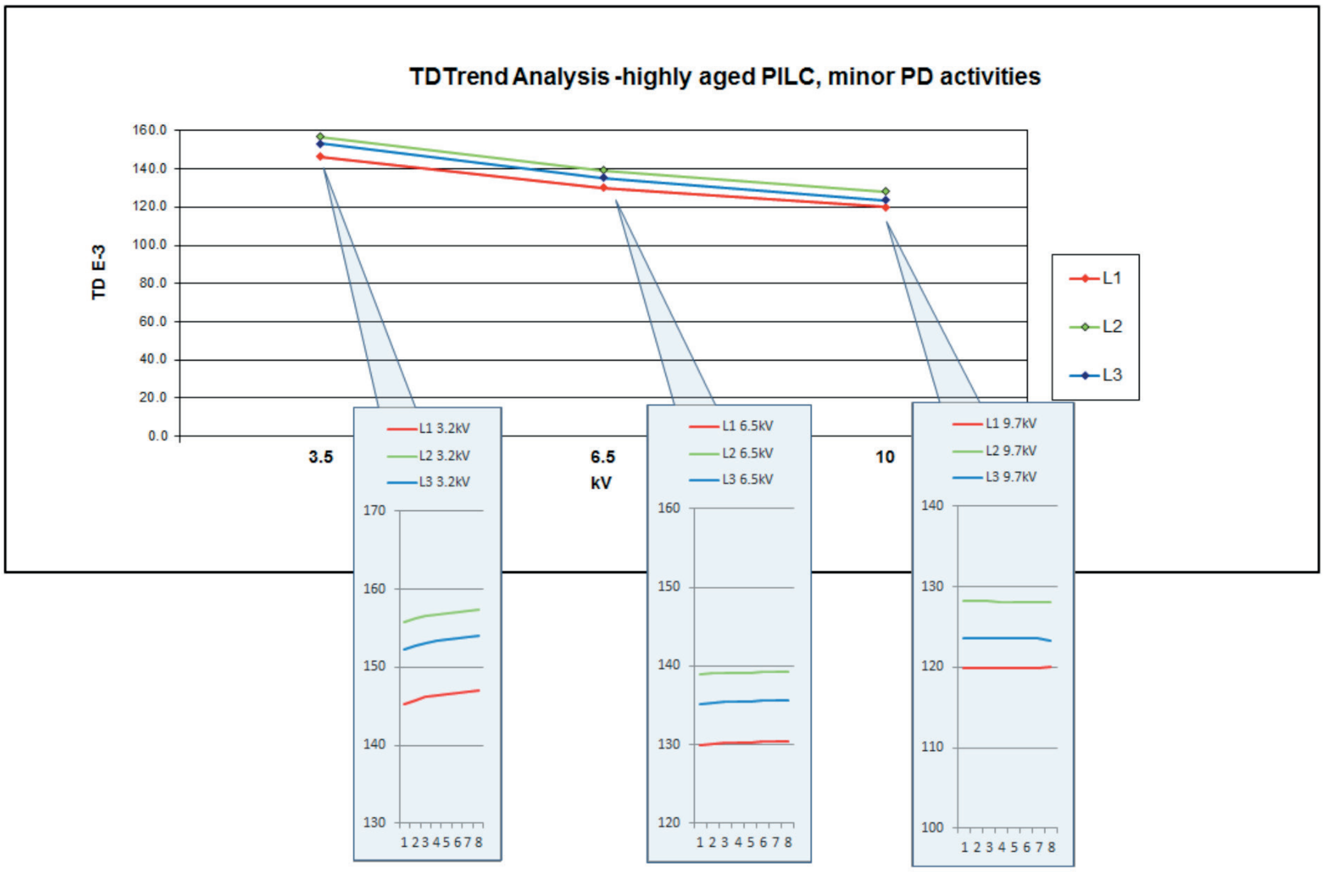
PILC cable with tracking in a joint, with minor PD activities

- Increasing TD values > 70 E-3
- Very high DTD
- High standard dev. > 0.500 E-3
- Increasing trend behaviour in the higher voltage levels

Additional information:

- PD activities in PILC section up to 400 pC
- Total cable length 195 m (mixed cable, 30% PILC AP)
- 2 joints
- (4892S12)

7.6.3.8 TD Trend pattern – highly service-aged PILC cable, with minor PD activities



↗ Figure 47: TD Trend pattern – PILC cable, highly service-aged, minor PD activities [20]

Highly aged PILC cable with minor PD activities

- Moderate to high TD values > 70 E-3
- Decreasing DTD
- High standard dev. > 0.500 E-3
- Increasing trend at low voltage level, stable or decreasing trend at higher voltage level

Additional information:

- PD activities in PILC section up to 300 pC
- Total cable length 557 m (mixed cable, 30% PILC AP)
- 2 joints
- (5525S04)

7.6.3.9 Summary of TD result analysis

TD analysis is a complex topic. Analysis is needed to combine different points of view:

1. Analysis of TD standard deviation STD
2. Analysis of stability at each voltage level
3. Analysis of trend behaviour at each voltage level
4. Delta tan delta DTD
5. Absolute TD value
6. Phase comparison

Combinations of components with difference influences are very common. TD patterns represent the sum of all influencing components.

Like any other diagnostic technique for power cables, tan δ is not free of issues. The issues are important because they can influence the outcome of the diagnostic assessment, thus leading to an incorrect evaluation. Therefore, a clear understanding of how the issues could influence the measurements and therefore the diagnostics is of paramount importance.

This section addresses some of the major issues of tan δ measurements in field testing applications. As mentioned previously, the tan δ can be considered a measure of the integral condition of a cable.

A progressive increase of tan δ value over time indicates the presence of gradually growing water trees and therefore degradation. Thus, in order to recognise this trend, records must be maintained over a period of time, typically several years.
In this case, when the tan δ measurements exceed historically established thresholds of its value and changes with voltage (tip-up) for a particular insulation type, cable design and voltage level; the cable may be evaluated as degraded and could therefore be scheduled for replacement.

Cable accessories such as splices and terminations could have a significant effect on the measured tan δ values. In fact, the accessories themselves could dominate the measurement since the losses for certain types of accessory are much higher than the cable insulation losses.
Therefore, when performing tan δ measurements, the number of accessories and types must be considered in order to evaluate their effects on the measurement.

7.6.4 Examples of TD measurement – trend of stability

Example 1:

L2, L3 stable condition

L1 water ingress in a joint, decreasing trend

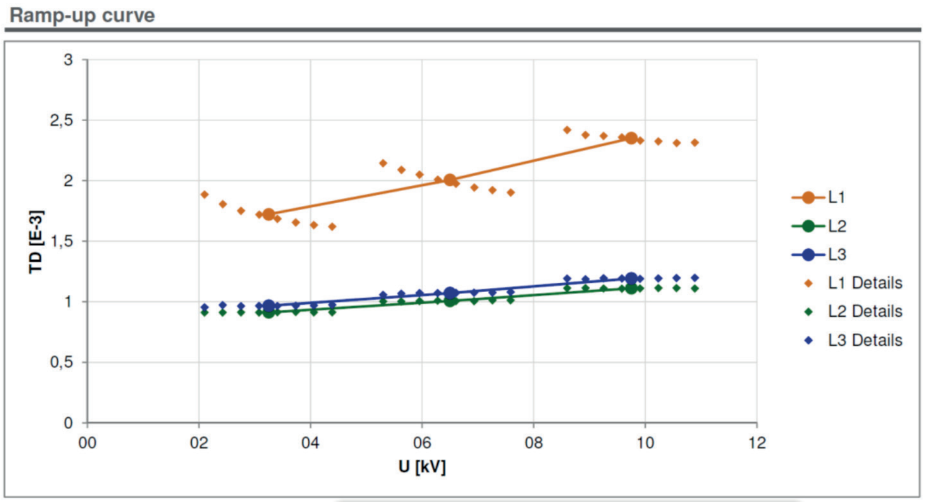


Figure 48: Ref. 2215CM, example L2, L3 stable condition, L1 water ingress in a joint

Example 2:

L2, L3 indication of tracking in at least one of the joints

L1 stable condition

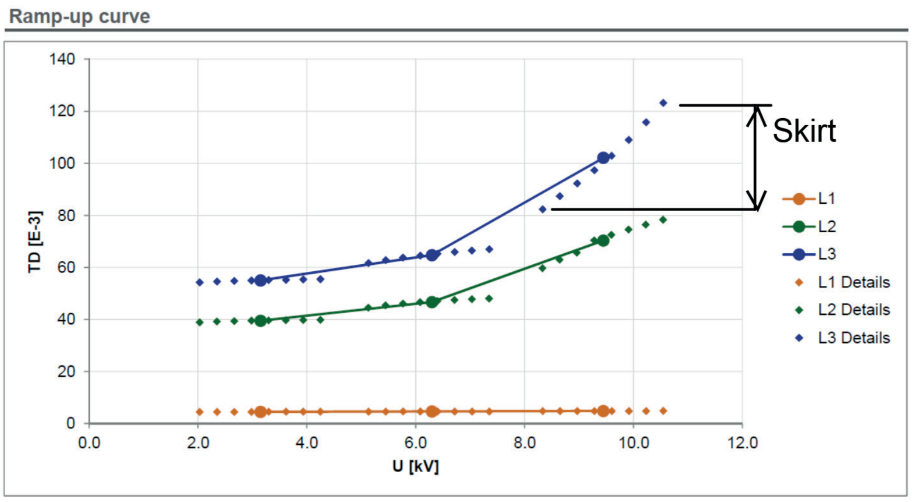
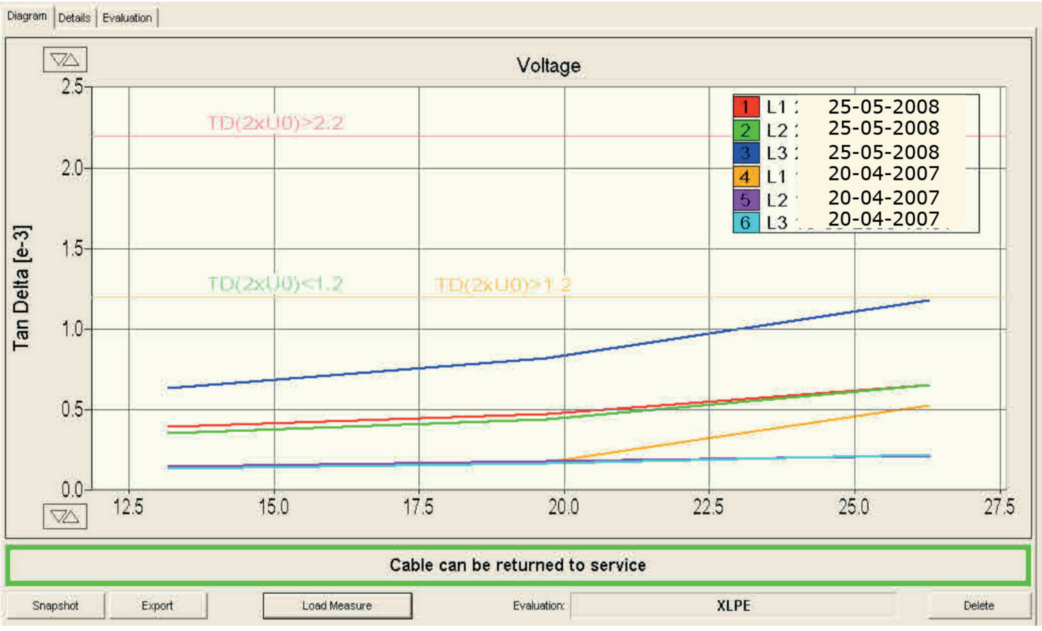


Figure 49: Ref. 8444CM, example L2, L3 tracking in joint, L1 stable condition

7.6.5 TD measurement – result comparison over time

Tan delta measurement as an integral insulation performance measurement can be used as an excellent tool to monitor the ageing behaviour of cable circuits. The development of the dielectric losses over time can be used as a method to recognise the changing characteristic over time.
Very often, TD values are categorised as "further studies advised". If no clear assessment of the source of degradation is possible, retesting after 6 months, 1 year or 3 years is recommended.
Comparing the values at different points in time allows an understanding of the reason for the degradation and the urgency for further action can be more easily defined.



↗ Figure 50: TD comparison of the same XLPE cable after 1 year; visible ageing effect

7.6.6 Influence of surface currents in open terminations

Open terminations are subject to pollution, humidity and mechanical damage. These influences are the main reasons for high surface currents that may appear as high leakage current during the TD measurement and may therefore considerably influence the result.
Proper cleaning may help to reduce the surface conductivity of the termination in many cases, but only to a certain extent. In some environments, a high relative humidity does not completely eliminate this influence.
The complete and definite elimination of the influence of surface currents is most important. The connection technique using guard rings and a VSE-box (Virtual Safety Earth connection arrangement) is used.
Furthermore, depending on the applied voltage level, the electric field at the termination lugs have to be homogenised by means of corona hoods.

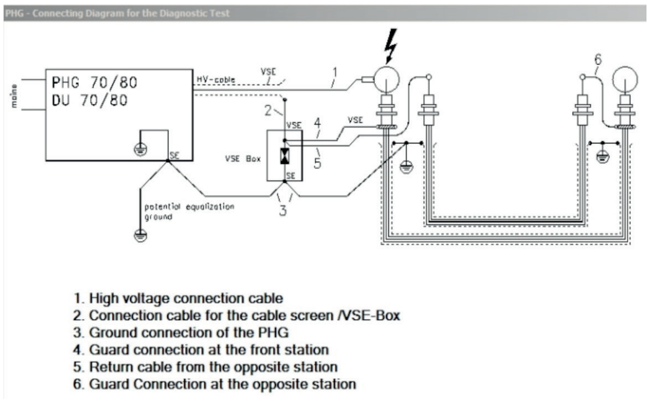
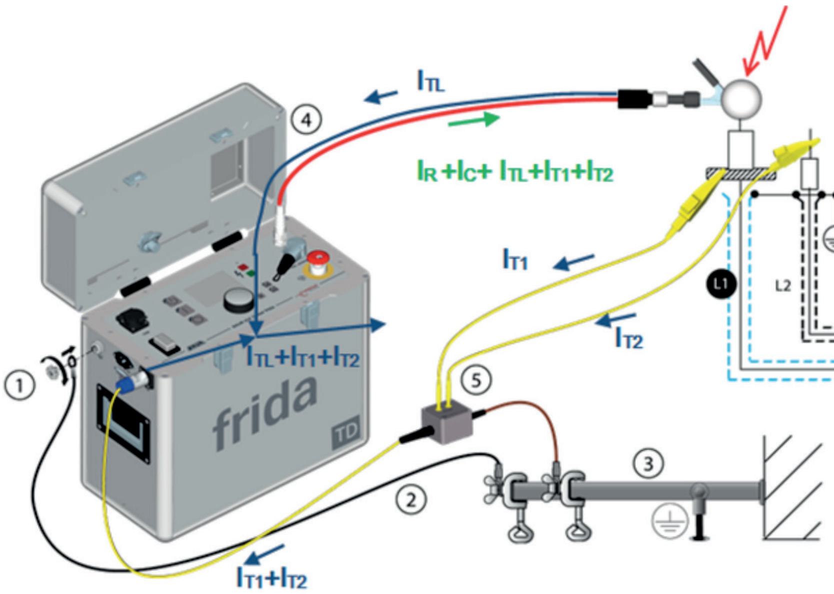


Figure 51: Programmable high-voltage generator (PHG) connection diagram for TD with guard ring application



TD Current: $I_{TD} = I_R + I_C + I_{TL} + I_{T1} + I_{T2} - I_{TL} + I_{T1} + I_{T2} = I_R + I_C$

I_{TL} … test lead leakage

I_{T1} … surface leakage current termination 1 (near end)

I_{T2} … surface leakage current termination 2 (far end)

Figure 52: Guard ring connection technique with VSE box

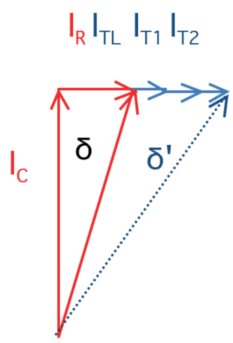
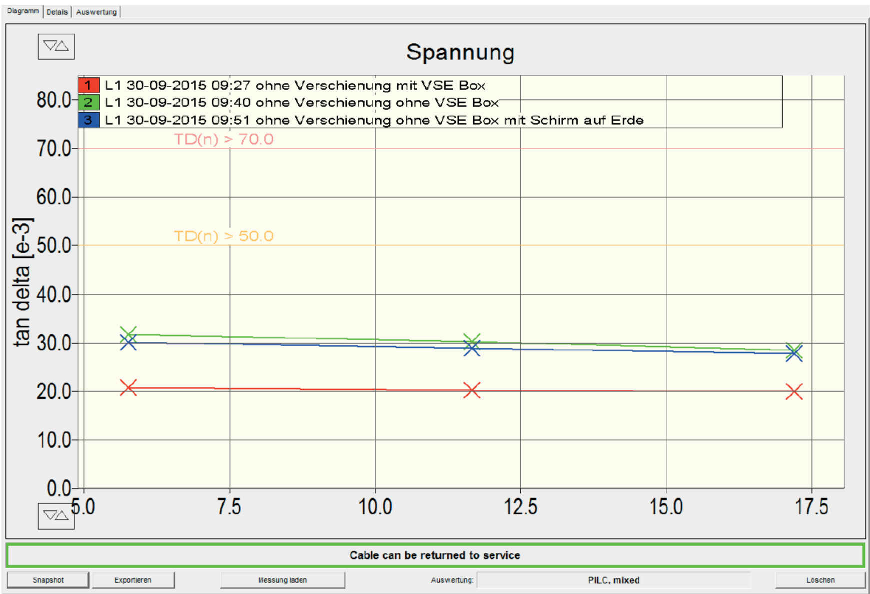


Figure 53: Phasor diagram for visualising the influence of test lead and termination surface leakage current

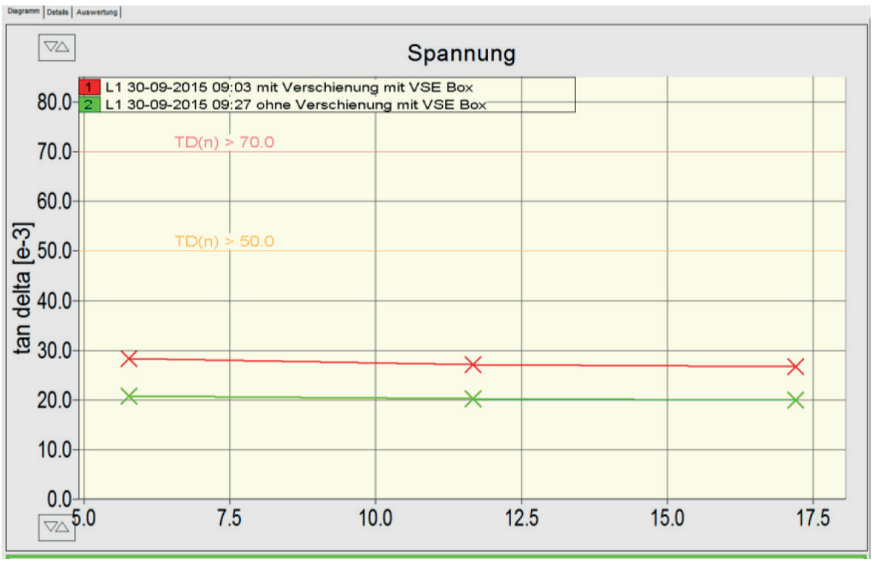
The TD graph is an example of where the termination had been cleaned properly, but the relative humidity was very high. The real loss factor of the cable could only be measured by means of the guard ring application.

↗ Figure 54: TD measurement on open termination, PILC, oil filled termination, with and without VSE box – guard ring application, incl. busbar



↗ Figure 55: TD result: 1. Connection with guard ring application, 2. Without guard ring application, 3. Without guard ring application, cable sheath additionally earthed => influence of surface leakage current visible

↗ Figure 56: TD measurement on open termination, connection with guard ring application, corona hood, disconnected busbar



↗ Figure 57: TD result: 1. Including connected busbar, 2. With disconnected busbar

7.7 Recommended approach for TD evaluation

7.7.1 Loss factor measurement on XLPE cables

The evaluation criteria are defined in IEEE 400.2-2013 [11]. The new guide differentiates between "service-aged" cables and newly installed cables.
For **service-aged** PE-based insulated cables, the applied voltage levels are defined with 3 voltage steps from 0.5 U_0 up to 1.5 U_0 only. The VLF-TD criteria are defined at the middle value at 1.0 U_0.

- If tan δ measured at 1.0 U_0 is < 4 x 10^{-3} and the difference of tan δ measured at 1.5 U_0 and 0.5 U_0 is < 5 x 10^{-3}, the cable is in **good condition and there is "No action required".**
- If tan δ measured at 1.0 U_0 is > 50 x 10^{-3} or the difference of tan δ measured at 1.5 U_0 and 0.5 U_0 is > 80 x 10^{-3}, the cable is in **bad condition and there is "Action required".**

7.7.2 Loss factor measurement on PILC

Unlike for XLPE cables, no single evaluation criterion exists for PILC cables because different types of cable construction and insulation liquids are used. What is known from experience is that all three cores of a PILC cable should behave similarly and the increase of the tan δ value of aged cables measured at 0.5 U_0 and 1.5 U_0 should be small.
Experience in European countries that have been using a lot of paper cables, such as France, Spain and Portugal, show that absolute TD values up to 70 x 10^{-3} and differences of 10 to max. 20% between measurements at U_0 and 2 U_0 are considered to be acceptable. Some of the utilities limit the max. value to 50 x 10^{-3} or even less. For highly aged circuits, the applied voltage for TD loss factor measurement is limited to 0.5 U_0 to 1.5 U_0 which is similar to XLPE cables.

7.7.3 Loss factor measurement on mixed cable circuits

Loss factor measurement results of mixed cable traces have to be evaluated taking into consideration the length (capacity) relation between the XLPE part and PILC part. In a mixed cable circuit, the loss factor of the PILC section is the highest contribution factor, being much higher than the loss factor of the XLPE section.
For a rough calculation, the capacity/km of XLPE and PILC can be considered the same. As an example, the loss factor measured for a cable circuit consisting of 50% XLPE and 50% PILC is half the value of the PILC part ($\tan\delta = 1/(\omega * C * R)$). If the XLPE section is twice the PILC section, the loss factor measured is 1/3 of the loss factor of the paper section and vice versa.

7.7.4 Viewing points / definitions used for evaluation:

▪ "1.5 U_0 mixed cable evaluation"	Evaluation criteria applied for **mixed cables**
▪ "1.5 U_0 XLPE cable evaluation"	Evaluation criteria applied for **XLPE and WTP-XLPE cables (water-tree-prone cables)**
▪ Standard deviation / stability	… Following IEEE 400.2-2013 [11] and BAUR TD Diagnostic Guidelines V4 03.2013 [20]
▪ TD trend analysis	BAUR TD Diagnostic Guidelines V4 03.2013 [20]
▪ Delta tan delta DTD	… Following IEEE 400.2-2013 [11]
▪ Mean TD value MTD	… Following IEEE 400.2-2013 [11]

Standard deviation / stability is handled according to BAUR's internal "Tan Delta Diagnostic Guidelines V4 03.2013". The mentioned values closely correlate to IEEE 400.2-draft 12 (Jan. 2012) and the new field guide IEEE 400.2-2013.

7.8 Evaluation criteria according to IEEE 400.2-2013 and other experience values

7.8.1 Evaluation criteria for XLPE cables

Extract from IEEE 400.2-2013, Table I.1 for XLPE (outside North America) or new cables from 1.0 U_0 to 2.0 U_0

Condition assessment	TD stability (measured by standard deviation) at U_0 $[10^{-3}]$		Differential TD (difference in mean TD) between 2.0 U_0 and U_0 $[10^{-3}]$		Mean TD at 2 U_0 $[10^{-3}]$
No action required	< 0.1	and	< 0.6	and	< 1.2
Further study advised	0.1 to 0.5	or	0.6 to 1	or	1.2 to 2
Action required	> 0.5		> 1		> 2

↗ Table 23: IEEE 400.2-2013 for XLPE cables 1.0 – 2.0 U_0 [11, p. 48]

The mentioned values stated in IEEE 400.2-2013 (Table I.1) are for TD measurement from 1.0 U_0 to 2.0 U_0. As the main studies of practical results focused on power utilities in North America, IEEE summarises the above criteria as "outside North America".
The wide experience of BAUR supports the fact that the IEEE 400.2-2013 values defined for America can also be applied worldwide very well.

Adapted evaluation criteria for XLPE for TD measurements from 0.5 U_0 to 1.5 U_0 – new cables:

Condition assessment	TD stability (measured by standard deviation) at U_0 $[10^{-3}]$		Differential TD (difference in mean TD) between 1.5 U_0 and 0.5 U_0 $[10^{-3}]$		Mean TD at 1.5 U_0 $[10^{-3}]$
No action required	< 0.1	and	< 0.6	and	< 1.2 to < 2.2
Further study advised	0.1 to 0.5	or	0.6 to 1	or	1.2 to 2
Action required	> 0.5		> 1		> 2.2

↗ Table 24: Table I.1 of IEEE 400.2-2013 adjusted according to BAUR experience for 0.5 U_0 to 1.5 U_0 XLPE cables

The values from IEEE 400.2-2013 for new XLPE are directly applied to measurement values from 0.5 U_0 to 1.5 U_0. Marginal differences are not considered.

Applied evaluation criteria:

Name of evaluation:	XLPE 1.5 U_0
Criterion	Comment
TD(1.0xU_0) > 2.2	Cable with high operating risk
TD(1.5xU_0) – (0.5U_0) > 1.0	Cable with high operating risk
TD(1.0xU_0) > 1.2	Highly service-aged cable
TD(1.0xU_0) < 1.2	Cable can be returned to service
TD(1.5xU_0) – (0.5U_0) < 0.6	Cable can be returned to service

Adapted evaluation criteria for XLPE for TD measurements from 0.5 U_0 to 1.5 U_0 – aged cables:

Table 4: Historical figures of merit for condition assessment of service-aged PE-based insulations (i.e. PE, XLPE and TRXLPE) using 0.1 Hz – TD measurement up to 1.5 U_0

Condition assessment	VLF-TD time stability (VLF-TDTS measured by standard deviation at U_0 [10^{-3}]		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 [10^{-3}]		Mean VLF-TD at U_0 [10^{-3}]
No action required	< 0.1	and	< 5	and	< 4
Further study advised	0.1 to 0.5	or	5 to 80	or	4 to 50
Action required	> 0.5		> 80		> 50

↗ Table 25: Table 4, IEEE 400.2-2013 [11, p. 19] – Evaluation criteria for service-aged PE-based insulation

Extract from IEEE 400.2-2013, Table I.4 for paper insulations PILC, also applicable for mixed cables

Condition assessment	TD stability (measured by standard deviation) at U_0 [10^{-3}]		Differential TD (difference in mean TD) between 2.0 U_0 and U_0 [10^{-3}]		Mean TD at 2 U_0 [10^{-3}]
No action required	< 0.5	and	-20 to 20	and	< 50
Further study advised	0.5 to 1	or	-20 to -50 or 20 to 50	or	50 to 100
Action required	> 1		< -20 or > 50		> 100

↗ Table 26: IEEE 400.2-2013, International figures for PILC cables (1.0 U_0 to 2.0 U_0) [11, p. 49]

Condition assessment	TD stability (measured by standard deviation) at U_0 [10^{-3}]		Differential TD (difference in mean TD) between 1.5 U_0 and 0.5 U_0 [10^{-3}]		Mean TD at 1.5 U_0 [10^{-3}]
No action required	< 0.5	and	-10 to 10	and	< 50
Further study advised	0.5 to 1	or	-10 to -20 or 10 to 20	or	50 to 70
Action required	> 1		< -20 or > 20		> 70

↗ Table 27: Adjusted table I.4 of IEEE 400.2-2013 according to BAUR experience for 0.5 U_0 to 1.5 U_0 PILC & mixed cables

Applied evaluation criteria:

Name of evaluation:	PILC, mixed 1.5 U_0
Criterion	Comment
TD(1.0xU_0) > 70.0	Cable with high operating risk
TD(1.5xU_0) – (0.5xU_0) > 20.0	Cable with high operating risk
TD(1.0xU_0) > 50.0	Cable highly service-aged
TD(1.5xU_0) – TD(0.5xU_0) > 10.0	Cable highly service-aged
TD(1.0xU_0) < 50.0	Cable can be returned to service
TD(1.5xU_0) – TD(0.5xU_0) < 10.0	Cable can be returned to service

7.8.2 Newly implemented evaluation criteria for tan delta loss factor measurement acc. to IEEE 400.2-2013

Annex I: Tan delta criteria used outside North America [11, p. 48]

Tables 4 to 6 in this guide are based on data obtained on North American cable designs and installations. Tables I.1, I.2, I.3 and I.4 list the ranges in the TD assessment criteria for different cable insulations used in different countries outside North America by industry and utilities. Lower and upper TD and differential TD limits are individually applied. The number of utilities or countries is not known and no information is available about failure occurrences or service conditions.

Table I1: Alternate figures of merit for the condition assessment of PE-based insulations (i.e. PE, XLPE) TD measurement up to 2 U_0

Condition assessment	TD stability (measured by standard deviation) at U_0 [10^{-3}]		Differential TD (difference in mean TD) between 2 U_0 and U_0 [10^{-3}]		Mean TD at 2 U_0 [10^{-3}]
No action required	< 0.1	and	< 0.6	and	< 1.2
Further study advised	0.1 to 0.5	or	0.6 to 1	or	1.2 to 2
Action required	> 0.5		> 1		> 2

Table I2: Alternate figures of merit for condition assessment for PE with additives based insulations (i.e. TRXLPE, co-polymers) 1) TD measurement up to 2 U_0

Condition assessment	TD stability (measured by standard deviation) at U_0 [10^{-3}]		Differential TD (difference in mean TD) between 2 U_0 and U_0 [10^{-3}]		Mean TD at 2 U_0 [10^{-3}]
No action required	< 0.5	and	< 1.5	and	< 8
Further study advised	0.5 to 1	or	1.5 to 3	or	8 to 10
Action required	> 1		> 3		> 10

1) Note: Due to a long-term polymerisation effect, the mean TD results measured at 2 U_0, immediately after production of co-polymer insulations may be significantly higher. After one or two years, the absolute TD values may decrease close to levels similar to XLPE or PE insulations.

↗ Table 28: Table I1/I2 IEEE 400.2-2013, [11, pp. 48-49], ANNEX I, Evaluation criteria for outside North America

Table I3: International figures of insulations (i.e. EPR) – TD measurement up to 2 U_0

Condition assessment	TD stability (measured by standard deviation) at U_0 [10^{-3}]		Differential TD (difference in mean TD) between 2 U_0 and U_0 [10^{-3}]		Mean TD at 2 U_0 [10^{-3}]
No action required	< 0.5	and	< 4	and	< 10
Further study advised	0.5 to 1	or	4 to 10	or	10 to 80
Action required	> 1		> 10		> 80

Table I4: International figures for the condition of paper insulations (i.e. PILC) – TD measurement up to 2 U_0

Condition assessment	TD temporal stability (measured by standard deviation) at U_0 [10^{-3}]		Differential TD – (difference in mean TD) between 2 U_0 and U_0 [10^{-3}]		Mean TD at 2 U_0 [10^{-3}]
No action required	< 0.5	and	-20 to 20	and	< 50
Further study advised	0.5 to 1	or	-20 to -50 or 20 to 50	or	50 to 100
Action required	> 1		< -50 or > 50		> 100

↗ Table 29: Table I3/ I4, IEEE 400.2-2013, [11, pp. 48-49], ANNEX I, Evaluation criteria for outside North America

Furthermore, IEEE 400.2-2013 states different criteria that shall apply for a cable network according to the special experience based on mainly NEERTRAC for the cable types used in North America. As the research focused mainly on the North American market, these values might not fully adapt for other countries.

Table 5: Historical figures of merit for the condition assessment of service-aged filled insulations (i.e. EPR & Vulkene)1 using 0.1 Hz – TD measurement up to 1.5 U_0

Condition assess-ment	Filled insulation system	VLF-TD time stability (VLF-TDTS meas-ured by standard deviation at U_0 [10^{-3}]		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 [10^{-3}]		Mean VLF-TD at U_0 [10^{-3}]
No action required	*** If it is not possible to definitively identify a filled insulation**	**< 0.1**		**< 5**		**< 35**
	Carbon-filled (black) EPR	< 0.1	**and**	< 2	**and**	<20
	Mineral-filled (pink) EPR	< 0.1		< 4		<20
	** Discharge-resistant EPR	< 0.1		< 6		< 100
	** Mineral-filled XLPE	-		-		< 100
Further study advised	*** If it is not possible to definitively identify a filled insulation**	**0.1 to 1.3**		**5 to 100**		**35 to 120**
	Carbon-filled (black) EPR	0.1 to 2.7	**or**	2 to 120	**or**	20 to 100
	Mineral-filled (pink) EPR	0.1 to 1		4 to 120		20 to 100
	** Discharge-resistant EPR	0.1 to 1		6 to 10		100 to 350
	** Mineral-filled XLPE	-		-		100 to 350
Action required	*** If it is not possible to definitively identify a filled insulation**	**> 1.3**		**> 100**		**> 120**
	Carbon-filled (black) EPR	> 2.7	**or**	> 120	**or**	> 100
	Mineral-filled (pink) EPR	> 1		> 120		> 100
	** Discharge-resistant EPR	> 1		> 10		> 350
	** Mineral-filled XLPE	-		-		> 350

* Experience has shown that it is quite difficult to precisely identify the type of filled insulation of field-installed cable. The issues encountered include: incorrect or missing records, obliterated or obscured markings on the cable jacket, indistinct colouring, etc. In these cases, using the criteria for the collated data sets is recommended.

** Insufficient data have been collected to make precise estimates of criteria, consequently the criteria are likely to contain considerable errors, see Appendix G. However, they are included here to provide some guidance to engineers encountering these insulation systems in the field.

↗ Table 30: Table 5, IEEE 400.2-2013 [11, p. 20] – Evaluation criteria for service-aged filled cables (EPRs)

Very similar values in a simplified version can be found in "Aging Management Program Guidance for Medium Voltage Cable Systems for Nuclear Power Plants" prepared by the Electric Power Research Institute through an interactive Technical Advisory Group review process. [21]

Table 5-1:
Preliminary tan δ assessment criteria for butyl rubber (in terms of x 10^{-3}; 0.1 Hz test frequency) (Note 1)

Condition	Tan δ		Absolute value of the difference in tan δ between 0.5 U_0 and 1.5 U_0 (Notes 2 and 3)
Good	≤ 12	and	≤ 3
Further study required	12 < tan δ ≤ 50	or	3+ to 10
Action required	> 50		> 10+

Notes:
1. This is based on Figure C-13 in EPRI report "Plant Support Engineering: Medium-Voltage Cable Aging Management Guide (1016689)" [15] and in-plant test results and consultation with tan δ testers.
2. Differentials may be taken at 1 U_0 at the user's discretion. See the text contained in this table.
3. The difference in tan δ is normally positive. Negative differences should be treated as very significant and may indicate a problem with a test or be an indication of the presence of a significant defect.

↗ Table 31: Table 5-1 – EPRI tan delta assessment criteria for EPR butyl rubber cables [21]

Table 5-2:
Preliminary tan δ assessment criteria for black EPR (in terms of x 10^{-3}; 0.1 Hz test frequency) (Note 1)

Condition	Tan δ		Absolute value of the difference in tan δ between 0.5 U_0 and 1.5 U_0 (Notes 2 and 3)
Good	≤ 12	and	≤ 3
Further study required	12 < tan δ ≤ 50	or	3+ to 10
Action required	> 50		> 10+

Notes:
1. This is based on Figure C-1 in EPRI Report 1016689 [15] and associated in-plant results and consultation with tan δ testers.
2. Differentials may be taken at 1 U_0 and 2 U_0 at the user's discretion. See text preceding these tables.
3. The difference in tan δ is normally positive. Negative differences should be treated as very significant and may indicate a problem with a test or be an indication of the presence of a significant defect.

↗ Table 32: EPRI tan delta assessment criteria for black EPR cables [21]

Table 5-3:
Preliminary tan δ assessment criteria for EPR (Note 1) (in terms of x 10^{-3}; 0.1 Hz test frequency) (Note 2)

Condition	Tan δ		Absolute value of the difference in tan δ between 0.5 U_0 and 1.5 U_0 (Notes 3 and 4)
Good	≤ 15	and	≤ 3
Further study required	15 < tan δ ≤ 30	or	3+ to 8
Action required	> 30		> 8+

Notes:
1. This may also be used for "Gray" UniBlend® EPR (approximate time of manufacture from the late 1970s on).
2. This is based on Figures C-3 and C-4 in EPRI Report 1016689 [15] and consultation with tan δ testers.
3. Differentials may be taken at 1 U_0 and 2 U_0 at the user's discretion. See text preceding these tables.
4. The difference in tan δ is normally positive. Negative differences should be treated as very significant and may indicate a problem with a test or be an indication of the presence of a significant defect.

↗ Table 33: EPRI tan delta assessment criteria for pink EPR cables [21]

Table 5-4:
Preliminary tan δ assessment criteria for brown EPR (in terms of x 10^{-3}; 0.1 Hz test frequency) (Note 1)

Condition	Tan δ		Absolute value of the difference in tan δ between 0.5 U_0 and 1.5 U_0 (Notes 2 and 3)
Good	≤ 50	and	≤ 5
Further study required	50 < tan δ ≤60	or	5+ to 15
Action required	> 60		> 15+

Notes:
1. This is based on Figures C-3 and C-4 in EPRI Report 1016689 [15] and consultation with tan δ testers.
2. Differentials may be taken at 1 U_0 and 2 U_0 at the user's discretion. See text preceding these tables.
3. The difference in tan δ is normally positive. Negative differences should be treated as very significant and may indicate a problem with a test or be an indication of the presence of a significant defect.

↗ Table 34: EPRI tan delta assessment criteria for brown EPR cables [21]

Further information on tan delta evaluation criteria could be found IEEE 400.2/D11 but was removed in the later stage of D12 due to insufficient data.

Table 7:
Historical figures of merit for the condition assessment of service-aged paper insulations (i.e. PILC) using 0.1 Hz – TD measurement up to 1.5 U_0

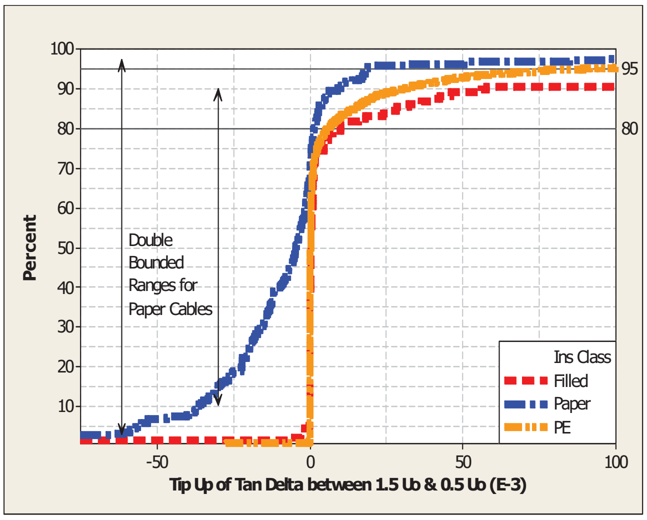
Condition assessment	VLF-TD time stability (VLF-TDTS measured by standard deviation at U_0 [10^{-3}]		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 [10^{-3}]		Mean VLF-TD at U_0 [10^{-3}]
No action required	< 0.1	and	-35 to 10	and	< 85
Further study advised	0.1 to 0.4	or	-35 to -50 or 10 to 100	or	85 to 200
Action required	> 0.4		< -50 or > 100		> 200

The condition assessment for the cable system may be undertaken by considering the VLF-TD characteristics in the sequence VLF-TD Temporal Stability, then Differential VLF-TD, and finally Mean VLF-TD. The condition assessment is determined by the most serious condition of any of the features. Any prioritisation or extra differentiation between tested cable system portions may be accomplished by looking at the assessments for different features. Examples of the condition assessment of cable systems are shown in Table 7 of [11]

↗ Table 35: page 21, IEEE 400.2-2013 [11, p. 21] – Evaluation criteria for service-aged PILC cables

Note: For DTD in PILC cables

Figure 58 of [22] shows the distribution of tip-up data for different ranges of tip-up where tip-up is the difference in tan delta measured at 1.5 U_0 and 0.5 U_0. As many users have noted, it is quite common for PILC cables to show a negative tip-up, however excessive negative values have been considered atypical in the same manner as unusually large



↗ Figure 58: TD tip-up distribution in filled, PILC and PE cables [22]

7.8.3 Tan delta as a measuring tool for humidity in cable accessories

VLF TD hysteresis at voltage rise and voltage decay

A new TD effect was found in 1999, using VLF delta TD at increasing voltage over time to locate poorly installed accessories. Brincourt et al. EDF, France and NEETRAC were clearly able prove water or humidity ingress in accessories using a delta TD method.

Decreasing TD values at rising voltage is usually caused by humidity, which can evaporate in a short time. As a consequence, the drying out effect becomes measureable within a short time – usually within one or two minutes. If the TD measurement is used with increased and with decreased voltage levels, a TD hysteresis can be correlated with higher moisture content in the insulation.

The probability of poorly installed joints and water ingress can be assumed. In many practical cases a TD measurement before and after replacement of joints can solve the problem.

Internally, moisture defects embedded in the cable insulation show very small or no hysteresis effects. Because long-term HV stress to insulation that has already degraded is not good practice, a new methodology of TD hysteresis was introduced by BAUR.

The hysteresis of the dissipation factor is evaluated by using a VLF voltage rise and decay in a single process **Figure 59** and **Figure 60**. [6]

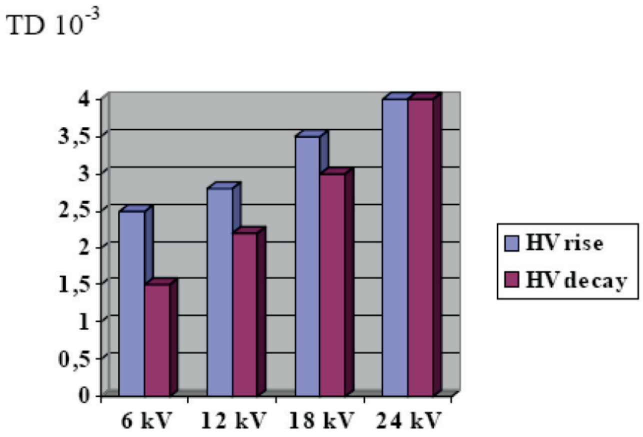


Figure 59: Hysteresis of dissipation factor TD at VLF voltage rise and voltage decay [6]

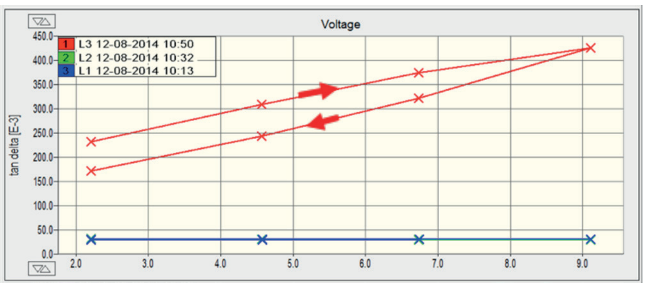


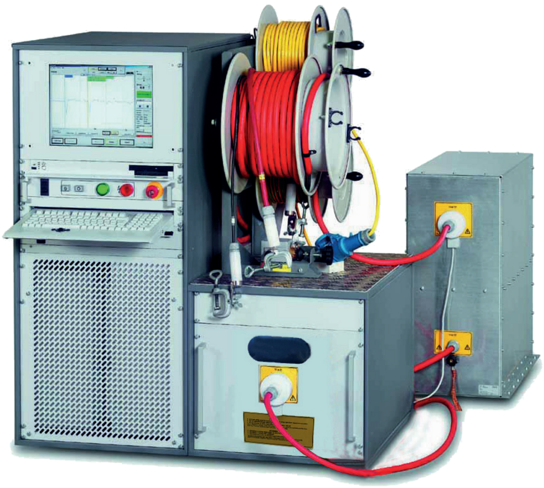
Figure 60: VLF tan delta hysteresis measurement on a PILC cable

TD values on alternative types of insulation, such as PILC, EPR, TR-XLPE, Co-Polymers, exhibit different TD levels from new, and they develop in respect of ageing. Individual criteria levels for each type of insulation, and TD comparison between phases are very helpful tools for qualification.

The evaluation of TD stability delivers further very informative indications. A negative stability trend indicates a small amount of water ingress in joints or humidity influence at terminations. Additionally, negative DTD (delta tan delta) behaviour indicates less leakage influence over time. A high amount of water ingress in joints may not necessarily be influenced by the applied voltage during the TD measurement. High fluctuations of the TD value throughout each of the voltage steps are the only significant indicator.

8. PD partial discharge localisation and level measurement

8.1 Background



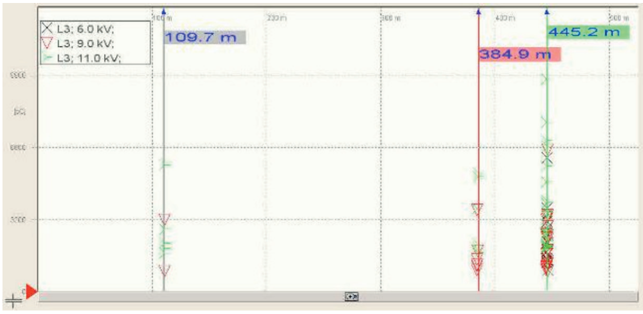
↗ Figure 61: BAUR PHG 70/80 TD PD

↗ Figure 62: BAUR Frida TD + PD TaD 62

Using partial discharge measurement with source localisation, the direct allocation of partial discharge activity on cable segments, joints or cable terminations is possible. Partial discharge measurement is based on a VLF truesinus® voltage waveform.

The travelling partial discharge pulses are subject to the damping effect of the cable. Therefore, the level to be measured is dependent on the distance from the end to the partial discharge source. For partial discharge source location only, the time delay between the first and the reflected pulse is important.

In XLPE cables, the partial discharge source is not located in the cable insulation itself, but in the accessories. If the partial discharge source were located within the cable insulation, this would lead to a breakdown within a very short time (stage of electrical tree) during normal operation. Practical measurements have proved that most of the partial discharge sources are located in the joints. Partial discharge sources outside the joints are rare and in those cases most defects are to be found in the sheath.
This leads to the fact that for on-site partial discharge diagnostics, for XLPE cable, partial discharge levels in the range of only 100 pC are relevant. Most important is knowledge of the location of the partial discharge source.



↗ Figure 63: PD localisation graph of a XLPE cable with 3 joints with PD activity

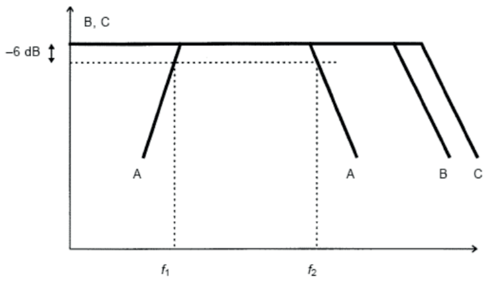
8.2 Partial discharge measurement according to IEC 60270

Partial discharges (PD) are local electrical discharges that occur at faults, inhomogeneities, minor defects or voids in the insulation, e.g. at joints and terminations. In many cases, partial discharges are the preliminary stage for a breakdown of the insulation. Therefore, the occurrence of partial discharges is an essential criterion for assessing the insulation quality. Partial discharge testing is performed after laying a new cable, making repairs and to verify the operational reliability of aged cables as it is capable of identifying the following faults:

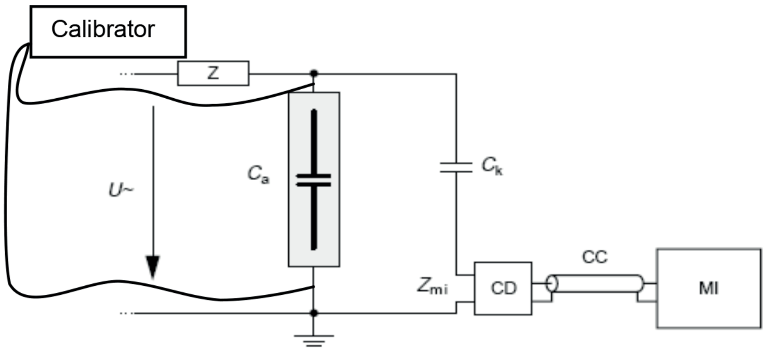
- Faults in new and old cable accessories (e.g. poorly assembled joints)
- Faults in the insulation of plastic-insulated cables (e.g. electrical trees)
- Insufficient mass-impregnated paper insulation due to drying
- Mechanical damage to the cable sheath

The conventional measurement of partial discharges according to IEC 60270 (High-voltage test techniques – Partial discharge measurement) is for partial discharge measurement to be performed at the cable end.

Partial discharges inside the cables cause a short term breakdown of the cable insulation. The pulse-shaped recharging current caused is detected at the coupling capacitor of the measurement unit (quadripole) in parallel to the cable, and is converted into an equivalent voltage signal. This voltage signal is then recorded by the partial discharge detection system and monitored as an impulse on the monitor.
The system measures the PD level based on the low frequency range defined by the band-pass "A" in the range of 30 kHz to 500 kHz. The practical measurement band width is defined from 100 kHz and 400kHz. The measurement of the PD location and the creation of the localisation graph are based on the PDSL channel from 30 kHz to 11 MHz.



↗ Figure 64: Definition of measurement band width acc. to IEC 60270 [36]



↗ Figure 65: PD measurement circuit acc. to IEC 60270 [36]

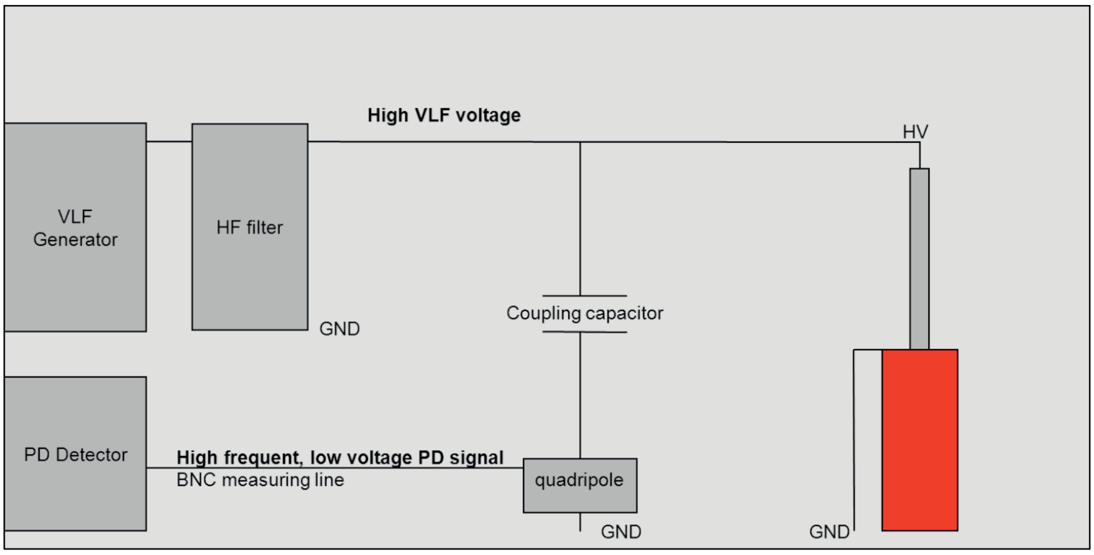


Figure 66: Test setup of BAUR VLF PD system

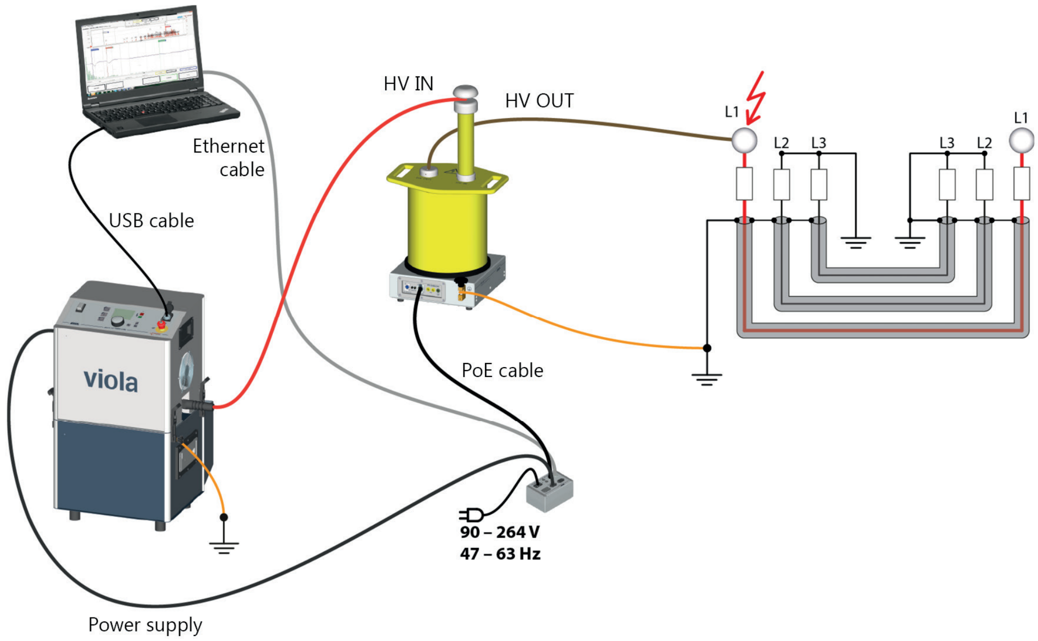


Figure 67: Connection diagram viola TD + PD TaD 62

Test setup

- VLF Generator — Generation of symmetrical sine-wave voltage (truesinus®), frequency 0.1Hz
- HF Filter — Filtering of generator-caused HF disturbance (e.g. from power electronic components)
- Coupling capacitor & quadripole — Detection of recharging current and conversion into equivalent voltage signal
- PD detector — Recording of PD discharge events and signal processing for graphical display

Theory of PD detection

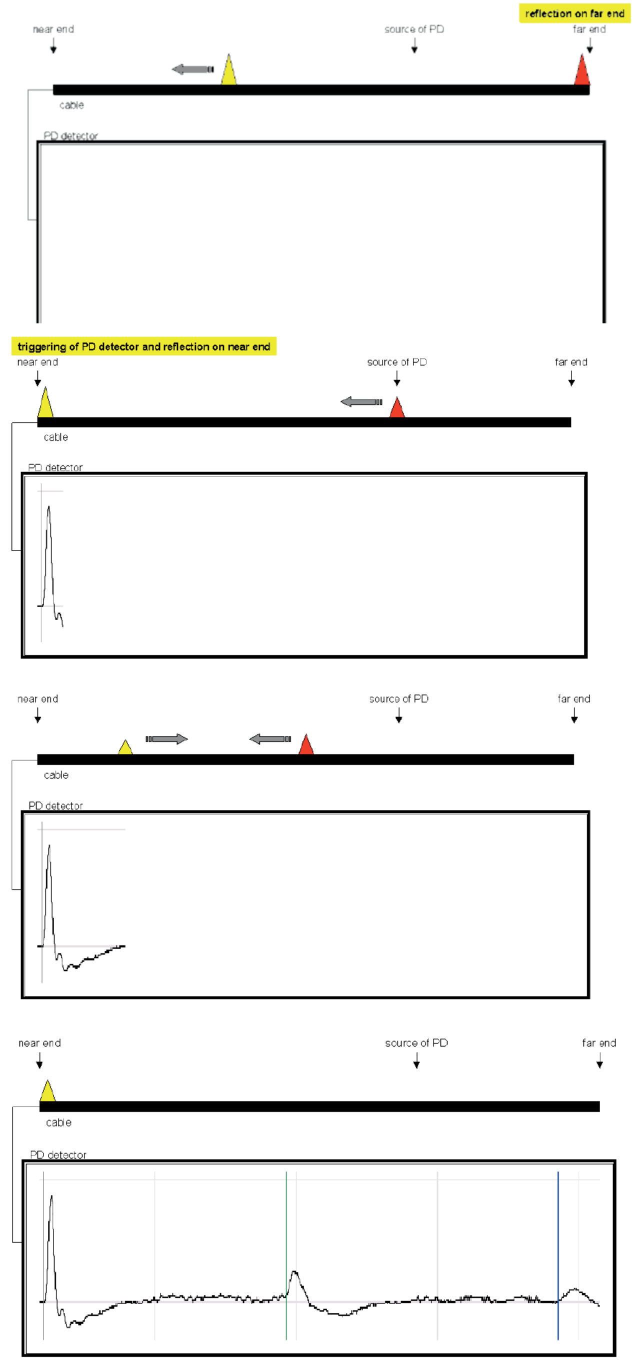
Diagnostics on PE/XLPE and PILC cables

VLF test and ageing diagnosis of PE/XLPE cables by means of dissipation factor measurement are criteria, on which the assessment of energy cables can be based. Partial discharge measurement with localisation of the partial discharge source closes the gap in the insulation diagnostics of PILC and assures the assessment of plastic cables.

The VLF Voltage Withstand Test is a pure "go/no-go" statement about the dielectric strength of the weakest point within a cable system. It is carried out after laying, after repairs, or on service-aged cables to prove operational safety.

Diagnostics via VLF dissipation factor measurement delivers information about the overall ageing of plastic cables.
The partial discharge measuring method provides reliable information on whether there are installation errors or electrical trees on plastic cables that have not yet caused a breakdown.
It can be estimated whether a dissipation factor measurement was possibly influenced by intensive partial discharges (for example in joints).
And using partial discharge measurement with source localisation enables direct allocation of partial discharge activity on cable segments, joints or cable terminations. The person responsible is thus in the position to take preventive measures and avoid local faults in the plant.

Beside the application on cables, partial discharge level measurements of other samples are also possible.
Partial discharge level measurement can be implemented into the PHG TD system, which then forms the PHG TD/PD cable test and diagnostics system. All of the important cable data can be stored in the program, so that step-by-step, a cable database is created which allows the operational evaluation of the diagnostic results on the basis of the historical evolution of a cable system.

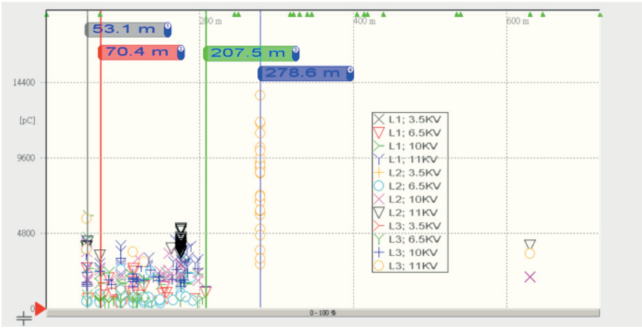


↗ Figure 68: Sequence of graphical PD pulse localisation

Experience on paper mass impregnated cables PILC

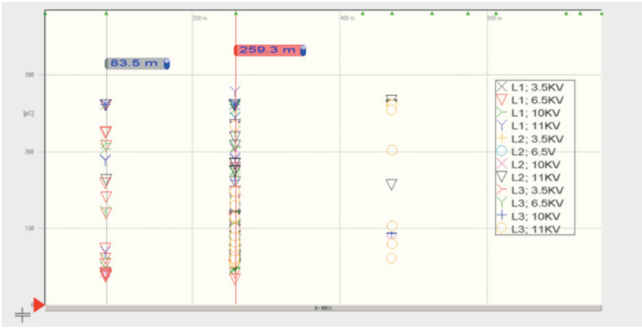
PD measurement on paper mass cables with respect to the measuring technique is the same as that on XLPE cables. The most important difference exists in the interpretation of the results. Inherent in its design, paper mass impregnated cable has a lot of PD activities within its insulation. In comparison to an XLPE cable, this is not harmful to the insulation.

The voids in the insulation open and close frequently due to the thermal expansion and viscosity of the insulation mass. The harmlessness of this characteristic is proven by paper mass cables showing nano-Coulomb (nC) values of PD (**Figure 69** shows up to 5,000 pC) but with them being in operation for more than 80 years. This background PD level of the cable itself depends on type, manufacturer, manufacturing year and condition of the cable, and ranges between some 10 pC and some 1,000 pC without risking the cable's service reliability.



↗ Figure 69: Typical example of scattered PD activity along a PILC section (Ref. 11225)

As already described for the XLPE cables, the PD of paper mass cables is measured in order to locate defects in joints and terminations as well as the cable itself. In some cases, defects of the sheath (corrosion of the lead sheath) are detected. In comparison to XLPE cables, the paper mass cables were never routinely PD tested by the manufacturer, and therefore the interpretation of the results and the operational risk are much more difficult compared to XLPE cables.



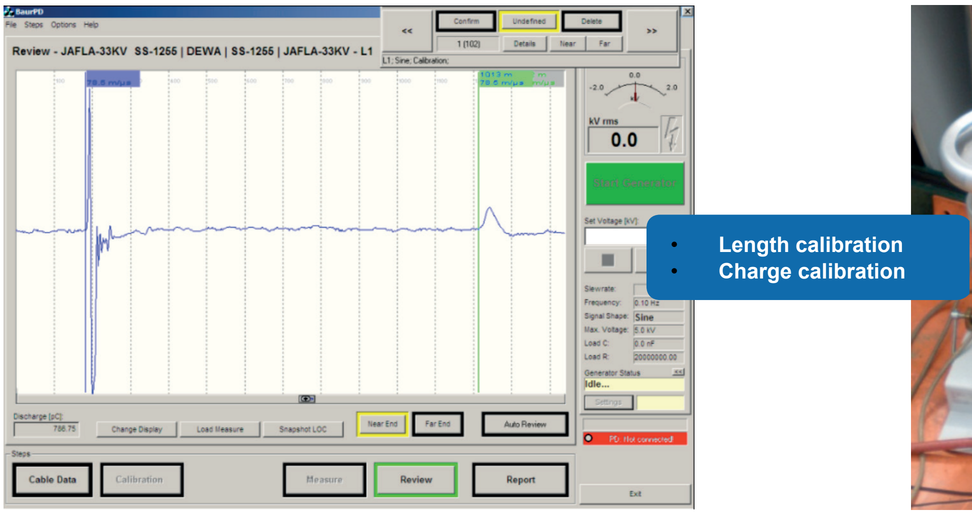
↗ Figure 70: Typical example of multiple joints showing PD activity (Ref. 6467)

Only comparison between the cables of different phases and of same type and manufacturing year enable clear interpretation. Additionally, the measurement itself is more difficult for paper insulated cables. Many discharges in the cable may be recorded by the measurement system; each impulse shows the equivalent position of the source and this leads to a distribution of many pulses along the entire cable length. In order to locate a defect that shows up with a PD level higher than this scattered activity, many recordings are required. Measurement systems with automatic position recognition are to be favoured. Practical experience of utilities in Germany, Austria, Italy, Russia, Ukraine and other countries have shown that despite the difficulties described above, reliable identification of PD sources in PILC as well as mixed cables is possible. Even sheath defects can be identified.
In addition, frequent lead corrosion at railway crossings and river crossings areas has been detected.

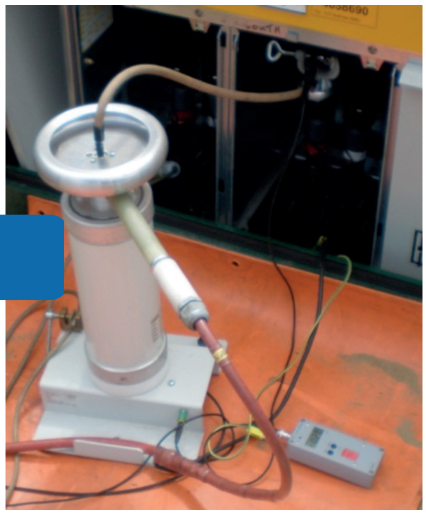
Therefore, PD location and measurement on PILC cables is even more highly recommended in order to increase the reliability of the grid.

8.3 Calibration

IEC 60270 specifies the performance of an onsite calibration for each test. As the measured partial discharge charge is damped in amplitude as a result of travelling along the length of the cable, it needs to be corrected by a damping factor to detect the apparent charge Qa. A known charge (calibration charge in pC) is thereby sent to the test-setup. The cable length and charge can be measured from the recorded graph.



↗ Figure 71: Screenshot of BAUR PD software – calibration graph



↗ Figure 72: CU60 PD coupler with calibrator

8.4 TDR measurement for joint characteristic identification

8.4.1 The background to TDR interpretation

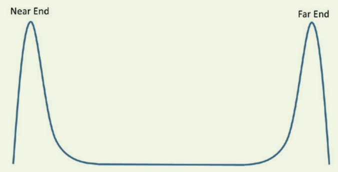
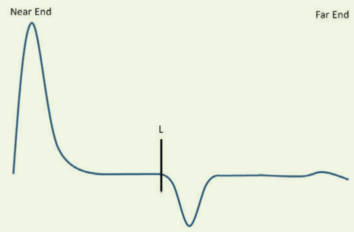
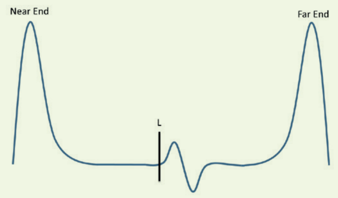
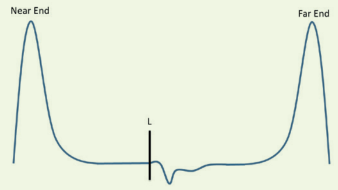
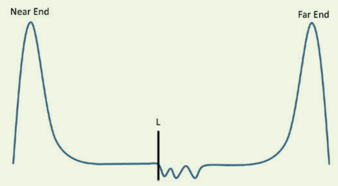
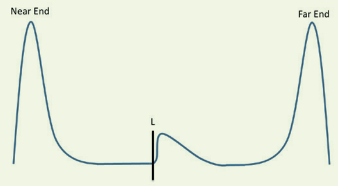
TDR analysis is a widely accepted method for fault location. The equipment is light-weight and the test time is short. The PD diagnostics procedure includes the calibration stage and a calibration pulse is comparable to a TDR impulse. However, there are unresolved issues with this method. Historical TDR data analysis is to be studied further in order to confidently assess, e.g. joint positions and cable end. The TDR pulse is a low-voltage pulse, which is influenced by cable length and high number of joints, as well as high noise environment. Operators' skills are required to differentiate between regular impedance changes caused by a transition joint and irregular impedance changes caused by water ingress. Careful evaluation and interpretation is essential to prevent incorrect assessments.

Detailed Time Domain Reflectometry (TDR) graph characteristics have been elaborated in detail by NEETRAC. [23] According to these findings, calibration graphs that are basically TDR graphs can be used to identify the characteristic of a joint depending on the TDR pulse reflection pattern. [23]

3.2.4 Success Criteria

Typical waveforms and their meaning appear in Table 11. The actual appearance of the waveforms varies and will not exactly match those shown in the reference example. Therefore, there are no unified success criteria for TDR testing.

Table 11: Cable conditions distinguishable using TDR [64]

Case	TDR
Uniform cable segment with no joints.	
Uniform cable segment with no joints and shorted conductor at distance L from Near End.	
Cable segment with a joint at a distance L from Near End.	
Cable segment with a wet joint at a distance L from Near End.	
Uniform cable segment with water ingress at distance L from Near End.	
Uniform cable segment with localised corroded neutrals at a distance L from Near End.	

Prepared by NEETRAC under GITC Project #E21-FJT (incl. DE – FC02-04HH11237), page 59 of 323

↗ Figure 73: Table 11 of NEETRAC report, TDR graph interpretation for identifying cable conditions [23]

8.4.2 TDR / PD calibration graph as a tool for identifying joint positions:

Application of calibrator impulse as TDR source:

- Limitation from 10 nC to 50 nC (depending on the calibrator used)

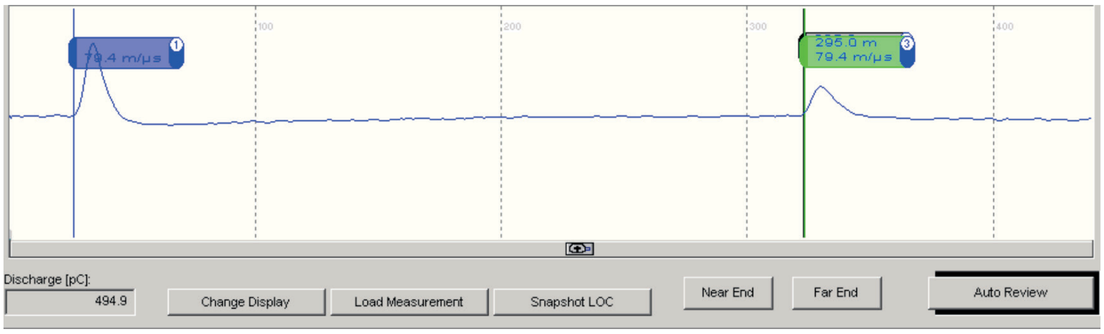


Figure 74: TDR / calibration graph of a cable with 295 m without any joint

The calibration sequence is part of every PD measurement on site. The calibration graph is a very helpful tool for identifying joint positions.

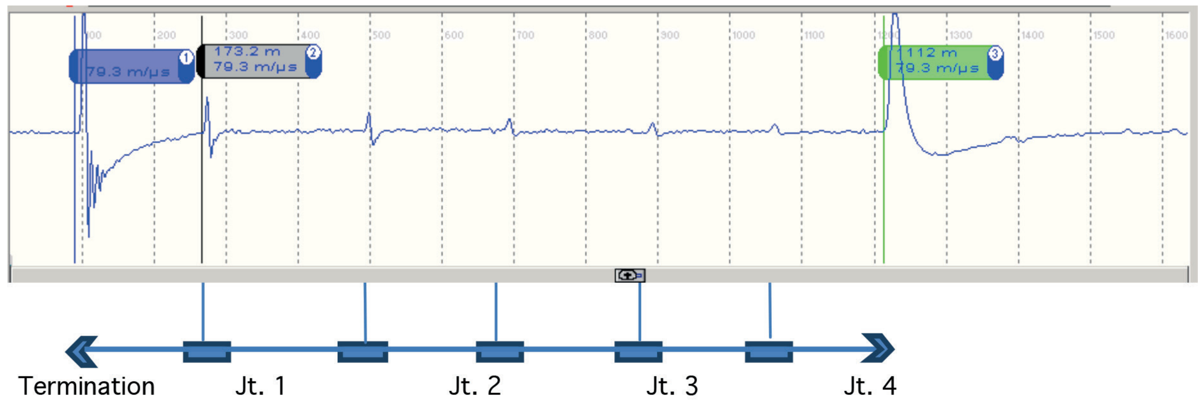


Figure 75: TDR / calibration graph of a new XLPE cable with 6 equal sections and 5 joints

Examples for detection of joints with irregular characteristic

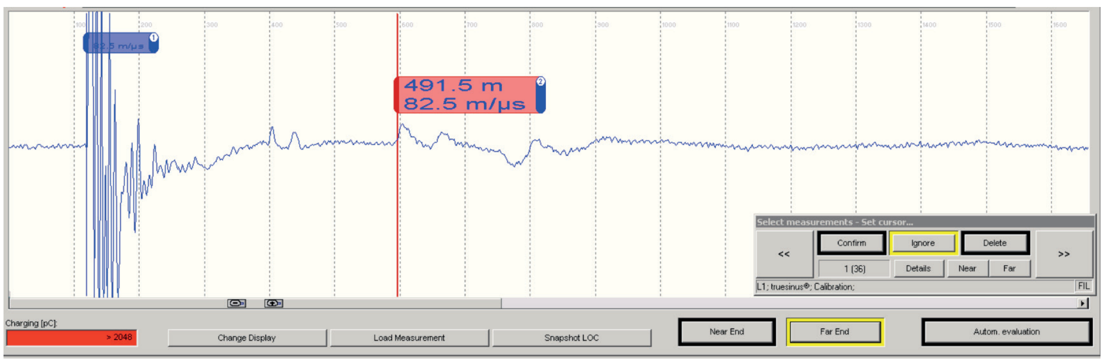
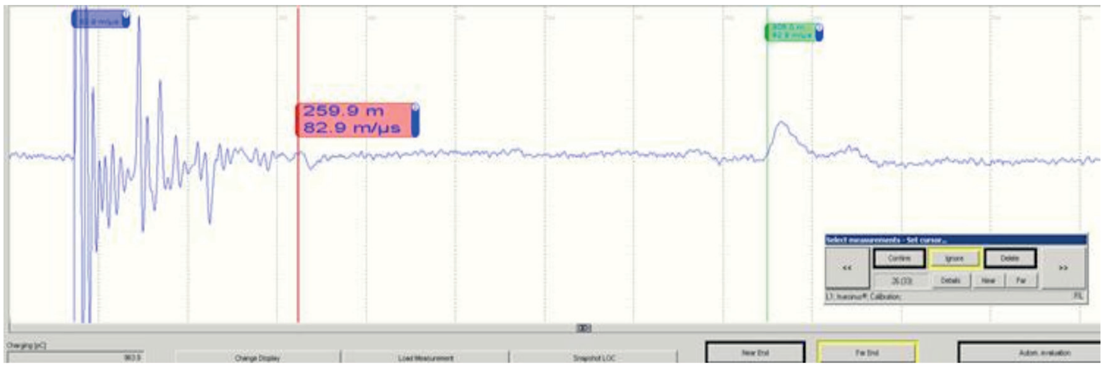
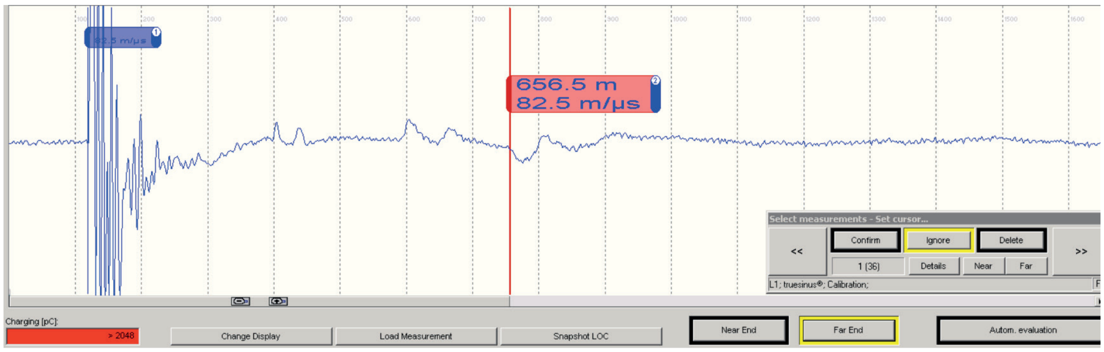


Figure 76: TDR / calibration graph with identification of several joints, e.g. 491.5 m



↗ Figure 77: TDR / calibration graph with identification of a joint with water ingress at 260 m



↗ Figure 78: TDR / calibration graph with identification of joint with water ingress at 656.5 m

8.5 Advanced TDR – approach IRG 4000

Similar to the PD calibration / TDR approach, the application of a high-end TDR device has several advantages and additional abilities to read joint characteristics in underground cables.

- Pulse width 20 ns – 1.3 ms
- Pulse voltage 20 V – 200 V

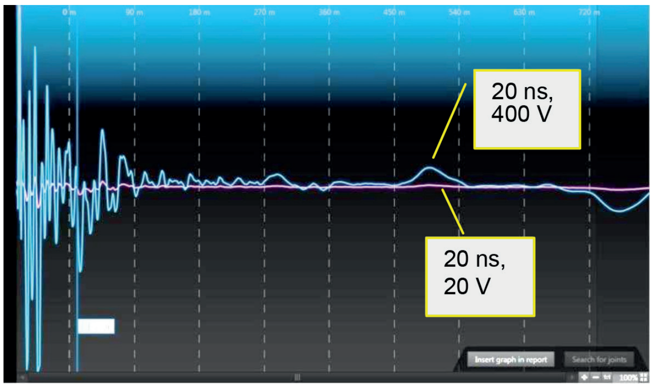


Figure 79: TDR IRG 4000, 20 ns / 20 V – 200 V, sensitive TDR graph

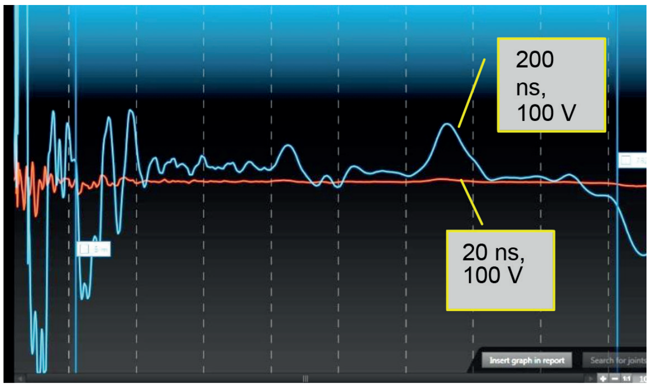


Figure 80: TDR IRG 4000, 20 ns-200 ns / 100 V, significant TDR graph

8.6 PD Phase Resolving Pattern – PRPD

Knowledge of the phasing makes it possible to pinpoint the type of fault. The measured PD level is indeed proportional to the actual charge.
However, it can only be used for evaluating a possible cause. The PD measured value depends on the dielectric at the fault position, is inversely proportional to the thickness of the insulation medium and is weaker the farther the fault is from the location of the measuring device. Thus, the absolute PD value is less significant. On the other hand, with the help of phasing, the inner and outer partial discharge can be differentiated quite reliably, irrespective of the level.

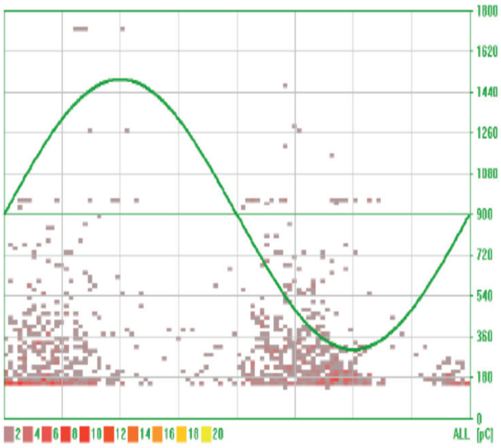


Figure 81: Example for VLF 0.1 Hz, PRPD pattern, inner PD

Inner partial discharges
Inner partial discharges arise during field changes in the insulation and can be described approximately with capacitive equivalent circuit diagrams. Causes for inner partial discharges can include:

- Gas or liquid filled inclusions in the XLPE insulation
- Cracks in the insulation
- Electrical trees
- Loose end caps
- Metal parts enclosed in the insulation, e.g. due to improper assembly of joints

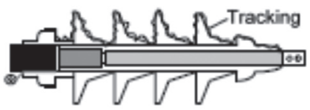
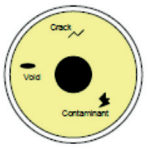
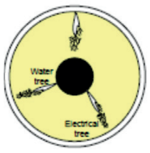
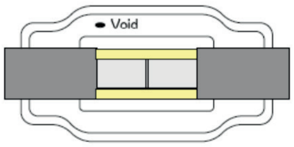
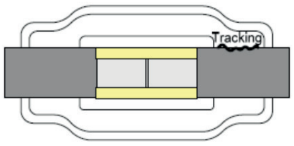
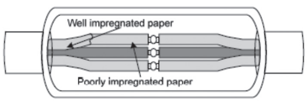
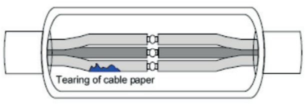
Outer partial discharges
Outer partial discharges can be described by peak-plate-equivalent circuit diagrams. They typically develop on:

- Surfaces where high electric field strengths occur
- An inhomogeneous field of a phase-over-earth arrangement

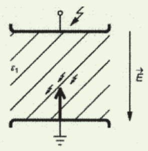
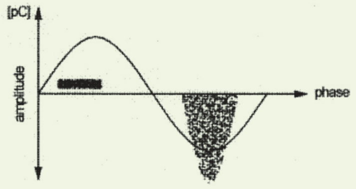
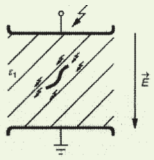
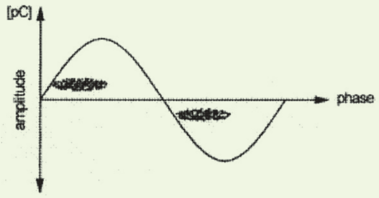
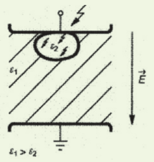
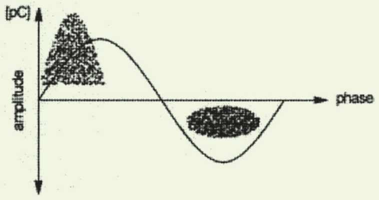
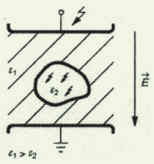
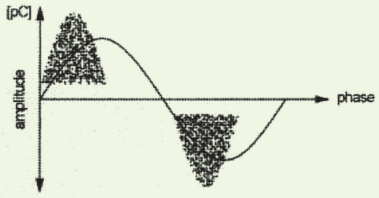
The difference between inner and outer partial discharges is achieved when one refers to the phase information because:

- Inner PDs mostly occur on the voltage rise of the sine half-wave (in addition, during inner PDs, the extinction voltage is lower than the inception voltage)
- Outer PDs are mostly found in the maximum of the sine half-waves, i.e. close to the peak

8.6.1 Typical sources of partial discharge

Accessories	Cause	Effect	Phase pattern
Termination 	Dirt accumulation, oxidation	Sliding discharges on the surface	Outer PD
	Installation faults, manufacturing faults	Partial discharges inside the insulation	Inner PD
Cable 	Cracks, air pockets, dirt	Partial discharges, slow damage to the insulation	Inner PD
	Water trees, electrical trees	Partial discharges, quick bridging of insulation	Inner PD
XLPE joints 	Installation faults, manufacturing faults, ageing	Partial discharges, slow damage to the insulation	Inner PD
	Humidity	Sliding discharges between conductor and shielding	Outer PD
PILC joints 	Defective impregnation	Partial discharges, local dielectric stress	Inner PD
	Installation faults, manufacturing faults	Partial discharges, change in insulation properties	Inner PD

↗ Table 36: Typical sources of PD causes, effects and pattern

Conducting material (tip electrode) with direct contact with the metal electrode			Difference in amplitudes of semi-waves: > Factor 3
Conducting material without contact with the metal electrode			Increasing frequency with rising voltage, at constant amplitude
Non-conducting material with direct contact with the metal electrode			Difference in amplitudes of semi-waves: > Factor 3
Non-conducting material without contact with the metal electrode			Difference in amplitudes of semi-waves: < Factor 3

↗ Table 37: Sources: J. Fuhr: Procedure for identification and localisation of dangerous PD sources in power transformers; A. Küchler: Hochspannungstechnik, Grundlagen – Technologie – Anwendung, 3rd

8.6.2 PD-level / PDIV: VLF 0.1 Hz vs. 50 Hz Power Frequency

The comparative characteristics of partial discharge behaviour at 0.1 Hz and 50 Hz is shown in **Figure 83**. They show that VLF at 0.1 Hz has the highest coincidence in relation to 50 Hz, whereas Cos-Rect. VLF waveform or oscillating wave OWTS differ highly in PD level and rate.

Results based on sinusoidal waveform are shown in **Figure 82**. Quite similar results can be found in respect of PDIV. The ratio varies in all cases with less than 10%. As we can see, the VLF also shows comparative results at higher voltage levels up to 80 kV. Very similar PD patterns at higher sinusoidal voltage levels on different artificial joint faults on a 110 kV XLPE cable have been identified. [24]

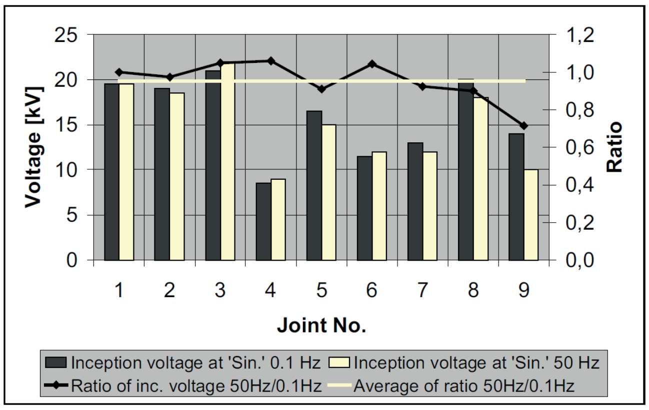


Figure 82: Partial discharge inception voltage in comparison with HV source [24]

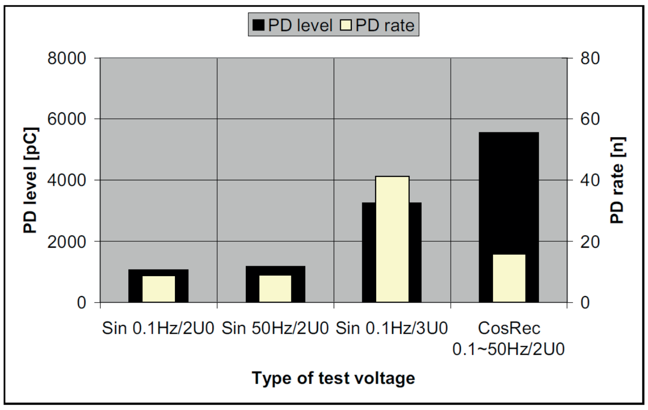


Figure 83: PD levels with 0.1 Hz sinusoidal wave shape, 50 Hz power frequency and Cos-Rectangular 0.1 Hz [24]

8.6.3 Comparability of PRPD at 0.1Hz VLF vs. 50 Hz

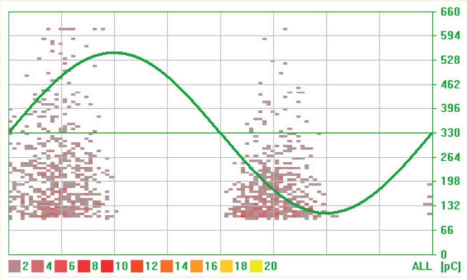
Comparison measurements have been conducted in laboratories and different examples of jointing failures were prepared. Comparative tests of partial discharge measurement with PRPD pattern with 0.1 Hz VLF test voltage and 50 Hz power frequency voltage have been performed. The examples below show, that

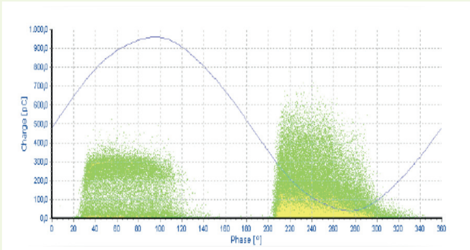
- The measurements showed that the prepared fault locations could be detected by both measuring systems
- The PRPD patterns are comparable
- The inception and extinction voltages are partially different, but no clear advantages can be drawn for either of the two systems
- The measured PD levels are in the same range and can be compared with each other

⇨ Measured values are comparable
⇨ Assessment of joint weaknesses is possible with the 0.1 Hz phase resolved PD test (PRPD)

Example 1: Field control hoses were not shrunk onto the detached core insulations of the cable ends.

	VLF 0.1 Hz	50 Hz
PDIV	12.0 kV	26 kV
PDEV	12.0 kV	24.5 kV
Max. PD level	600 pC (24 kV)	700 pC (30 kV)
PD pattern	PD pattern: 24 kV (2.0 U_0)	PD pattern: 30 kV (2.5 U_0)

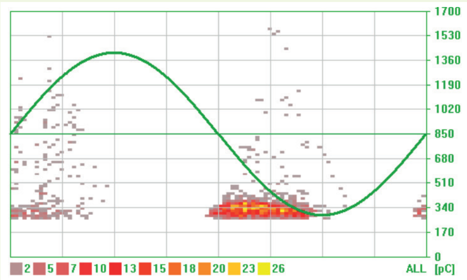


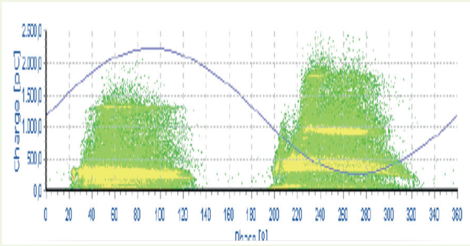


↗ Table 38: PRPD comp. 0.1 Hz – 50 Hz, example 1

Example 2: Yellow filling strip was not wound over the screw connector and the screw projections were not removed

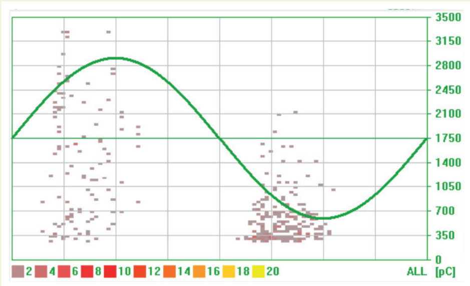
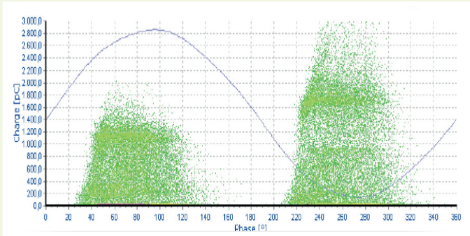
	VLF 0.1 Hz	50 Hz
PDIV	7.0 kV	5.5 kV
PDEV	6.0 kV	4.8 kV
Max. PD level	1,700 pC (12 kV)	2,500 pC (12 kV)
PD pattern	PD pattern: 12 kV (1.0 U_0)	PD pattern: 12 kV (1.0 U_0)





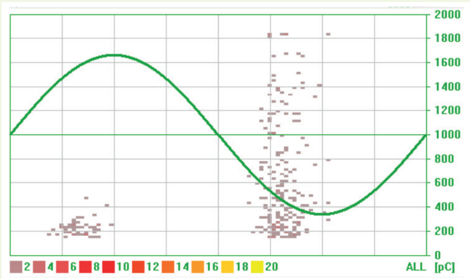
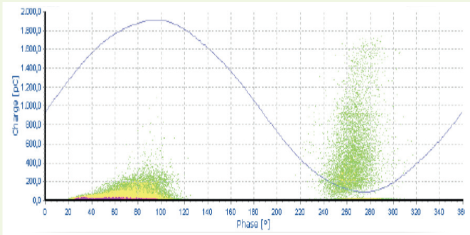
↗ Table 39: PRPD Comp. 0.1 Hz – 50 Hz, example 2

Example 3: The field control hoses, the shielded isolating body and the outer hose were not shrunk sufficiently and were without folds.

	VLF 0.1 Hz	50 Hz
PDIV	8.0 kV	8.6 kV
PDEV	7.0 kV	8.6 kV
Max. PD level	3,500 pC (12 kV)	3,000 pC (12 kV)
PD pattern	PD pattern: 12 kV (1.0 U_0) 	PD pattern: 12 kV (1.0 U_0) 

↗ Table 40: PRPD comp. 0.1 Hz – 50 Hz, example 3

Example 4: The yellow filling strips were not mounted over the stripped edges of the outer duct of the cable ends.

	VLF 0.1 Hz	50 Hz
PDIV	13.0 kV	11.2 kV
PDEV	12.0 kV	11.5 kV
Max. PD level	1,900 pC (15 kV)	1,600 pC (15 kV)
PD pattern	PD pattern: 15 kV (1.25 U_0) 	PD pattern: 15 kV (1.25 U_0) 

↗ Table 41: PRPD comp. 0.1 Hz – 50 Hz, example 4

8.6.4 Locally resolved PD phase pattern

For PRPD pattern recognition in underground cables, it is most important to differentiate the PD events based on their origin. In a PRPD pattern, only the PD activities of a single location should be combined in a PRPD pattern. The BAUR software can support this feature and provide individual, locally resolved PR phase patterns.

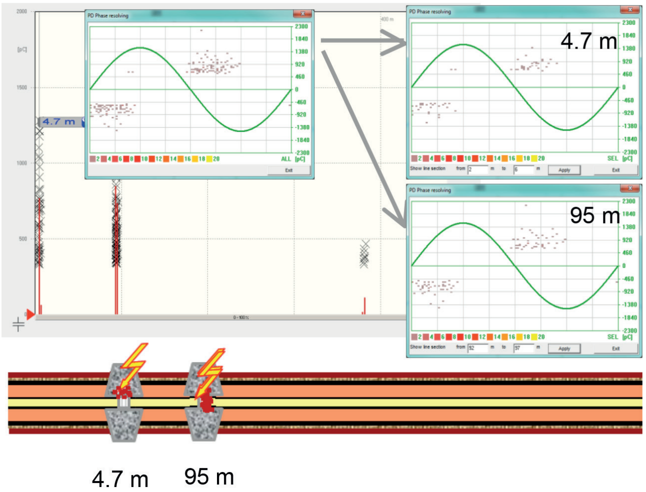


Figure 84: Locally resolved PD phase pattern

8.6.5 Practical examples of PRPD pattern recognition

Example 1:
Non-conducting material without direct contact with the metal electrode

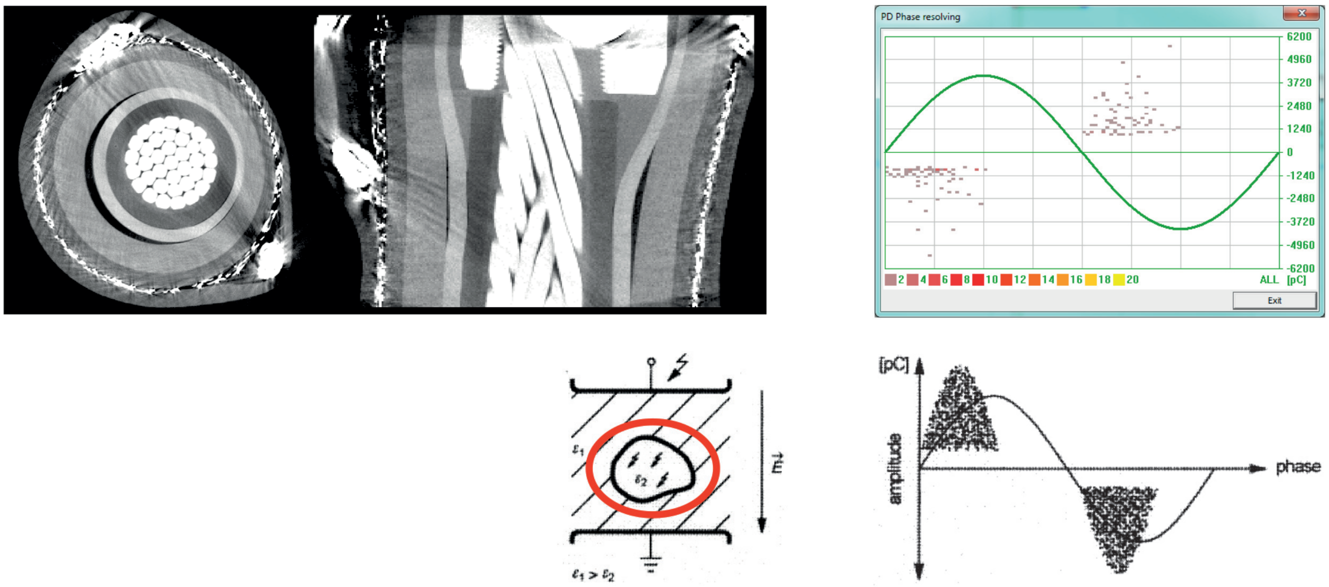
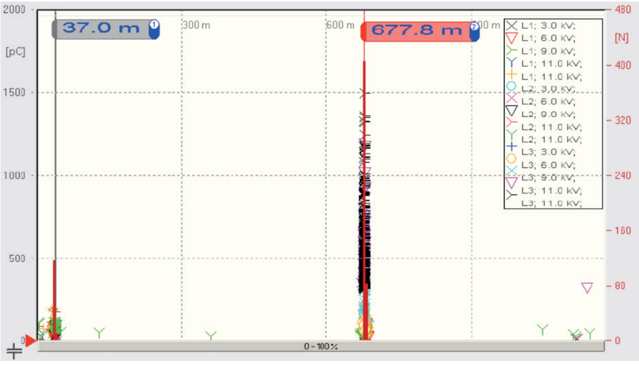
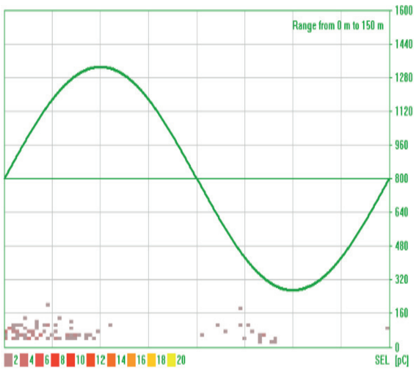


Figure 85: Inner partial discharge source, incomplete shrinking in heat shrink joint, PRPD pattern

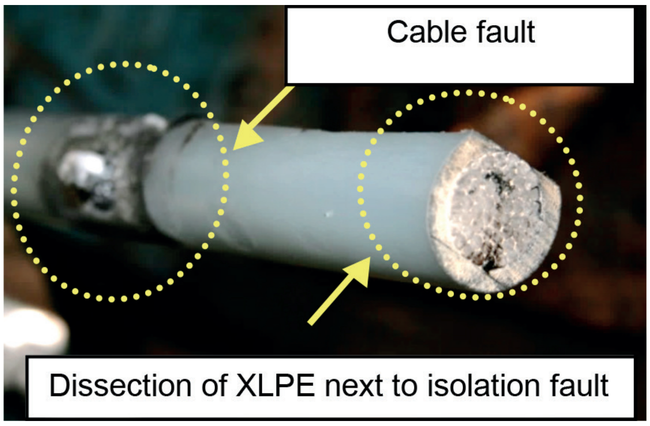
Example 2:



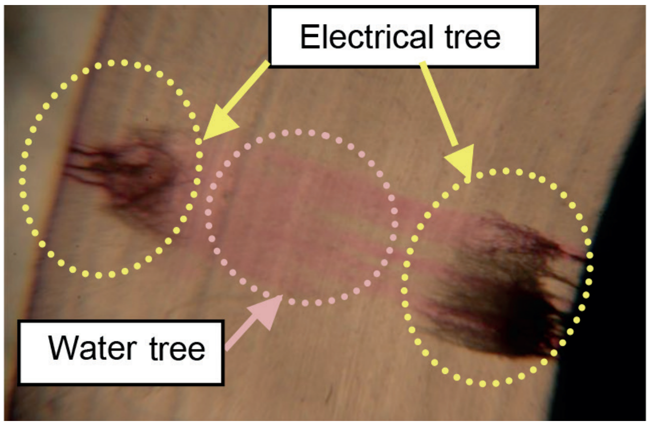
↗ Figure 86: PD localisation graph, suspicious PD activity at 37 m. Immediate breakdown during VLF test 2.



↗ Figure 87: PRPD pattern of cable section around 37 m, inner PD



↗ Figure 88: Cable dissection of area close to cable fault



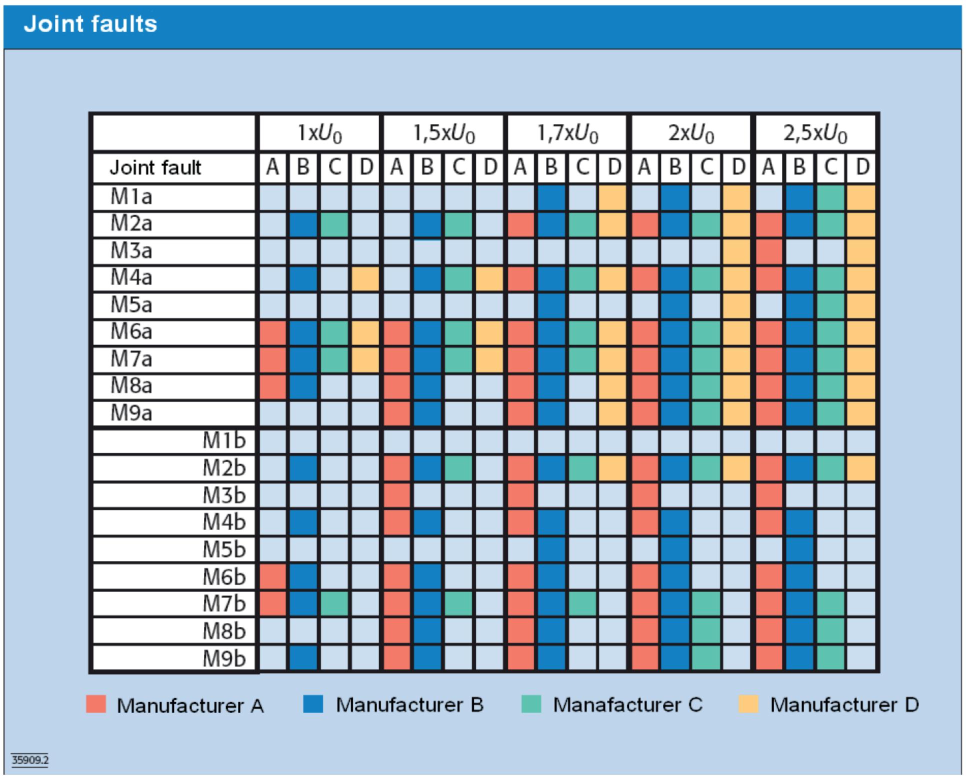
↗ Figure 89: Dissection shows water trees and electrical trees, inner PD

8.7 Partial discharge measurement at VLF and other test voltage waveforms

The VLF PD mapping and PD fault location under field conditions have been in practice for over 10 years.
In 2007, a benchmark test with different HV waveforms, on different artificial defects performed at RWE EUROTEST in Germany shows non-uniform results [19]. Interpretations of the PD magnitude and quantity results are incomparable [9]. [25]

Key questions and challenges:

- The users do not have knowledge rules to quantify the level of different types of damage.
- The magnitude does not indicate severe damage or a less dangerous situation in the cable insulation.
- It is usually not possible to predict possible failures if the cables are not tested up to the breakdown.
- Single spot defects are easily located by using impulse time domain techniques.
- PD magnitude does not always correlate with the highest or most dangerous defect since the type of fault is usually unknown.
- Only historical data might lead to better decisions for replacement or the repair process.

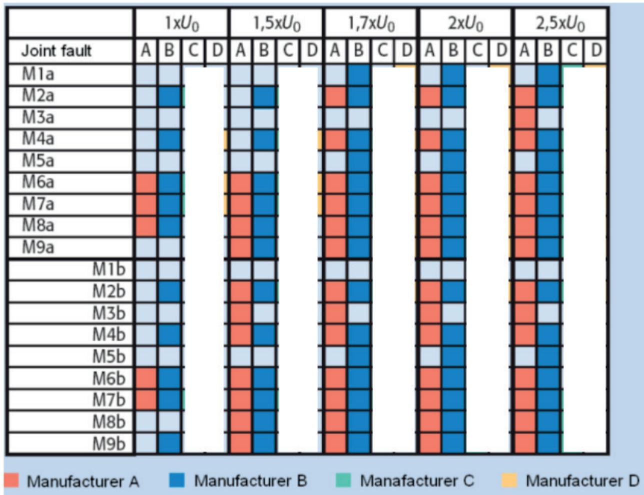


Manufacturer A:	BAUR VLF PD system
Manufacturer B:	50 Hz sinewave test equipment (laboratory equipment)
Manufacturer C:	Oscillating voltage near the operating frequency, 50 Hz, high attenuation
Manufacturer D:	Oscillating voltage of variable frequency with low attenuation, DAC

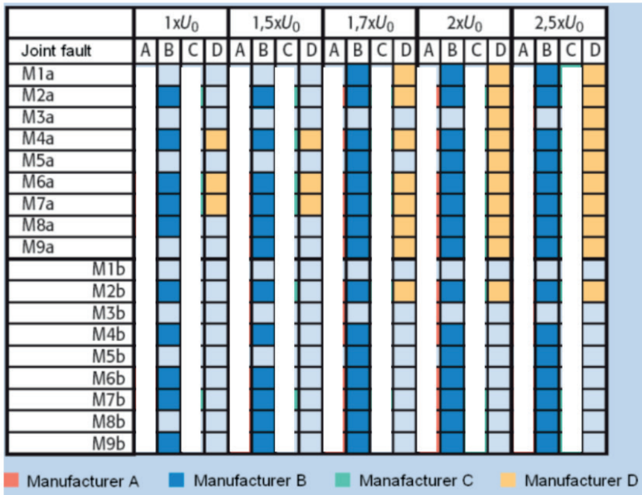
↗ Figure 90: Matrix of all the measurements performed on the model faults in joints (the boxes with a coloured background indicate detected and localised discharge activity) [25]

Based on the questions and challenges, nine different PD sources were created and investigated from both cable ends by different techniques.
As seen in **Figure 90**, all model faults in the joints except M1b can be detected with the aid of the partial discharge measurement. However, the localisation rate varies significantly between the various measuring systems. It can be seen that the partial discharge activity increases with increasing test voltage and therefore the detection of a possible fault is made easier. The distribution of the coloured boxes also shows that the test voltage shape has a significant effect on the initiation of a partial discharge. It can also be seen that the detection rate for measurements from the end furthest away from the fault (M1b to M9b) is lower than for measurements from the end near the fault (M1a to M9a).

As a general summary, the VLF PD measurement technique used by BAUR shows the closest ability to detect all kinds of PD sources compared to the 50 Hz PD detection systems that are used in laboratories. Oscillating voltage (at 50 Hz and damped oscillating wave) shows big deviations in the ability to detect weaknesses in many types of joints. 50 Hz slope technology can be considered as a fraction of a DAC cycle with similar characteristic.
Further details can be found in the full report [25] (Comparison of available measuring methods, RWE-Eurotest).



↗ Figure 91: Test result matrix of VLF 0.1 Hz PD vs. 50 Hz PD, very comparable PD recognition ability



↗ Figure 92: Test result matrix of 50 Hz PD vs. DAC PD, very inconsistent PD measurement ability by DAC

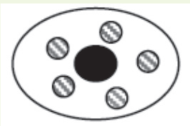
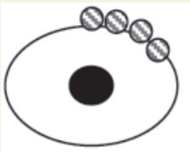
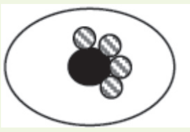
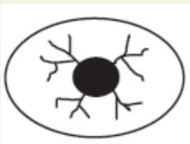
8.8 Partial discharge testing in relation to traditional testing methods

Table 42 below illustrates the relative relationships between the results of partial discharge testing and traditional testing methods. The insulation model, contained in the first column, illustrates the internal copper conductors, the outer insulation surface and various formations of voids within the insulation. The second column states the insulation condition. The third, fourth and fifth columns indicate the expected results from the following traditional testing methods:

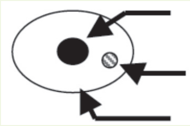
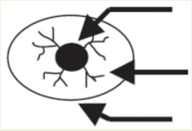
- Insulation Resistance Testing or "IR Test" which is at a reduced DC voltage,
- Polarisation Index Test (1 and 10 minute readings of the insulation resistance test to equalise the effects of humidity and temperature)
- High-Potential Testing (higher DC voltage test with leakage current monitored)
- The fifth column includes the expected results from partial discharge testing

For insulation considered "Good" or "Marginal", the results are similar for all test methods. For insulation which is "Dry but insulation delaminated", traditional test methods will provide a false sense of a "Fair" condition; whereas partial discharge testing indicates the presence of internal insulation voids. "Poor" or "Unacceptable" insulation conditions cannot be differentiated with traditional testing methods; whereas partial discharge testing identifies the regions of insulation voids, and the appropriate corrective actions. [26]

Partial discharge testing in relation to traditional testing methods

Insulation Model	Insulation Condition	IR Test	Polarisation Index Test	High-Pot Test	Partial discharge Testing
	Good	High	Good	Linear leakage current vs. voltage is minimal	Unmeasurable partial discharge activity
	Marginal	Fair	Fair	Linear leakage current vs. voltage is stable	Minimal discharge activity, balanced both positive and negative discharges
	Dry but insulation delaminated	False Fair Result	False Fair value	False linear leakage current vs. voltage	Partial discharges observed, therefore accurately showing insulation problems which are missed by traditional tests
	Poor ▪ Cleaning or overhaul required	Low	Poor	High leakage current. May be required to limited test voltage. Potential failure during testing	High positive polarity discharges indicate probable surface tracking
	Unacceptable ▪ Major repair or rewind required				High negative polarity discharges indicates internal voids near the copper conductor
	Near-failure condition ▪ PD arcing as caused carbon tracking	Very low	Very low	High leakage current and probable failure during testing	Minimal partial discharge activity. Partial discharge arcing as progressed to the point where permanent damage (tracking) has occurred

↗ Table 42: Illustration of the relative relationship between the results of PD testing and traditional testing methods [26]

	Internal copper conductor
	Insulation void experiencing internal partial discharge
	Outer insulation surface
	Internal copper conductor
	Surface tracking resulting from partial discharges
	Outer insulation surface

↗ Table 43: Legend: Insulation model description [26]

8.9 Advantages of VLF PD diagnostics

- Continuous measurement of partial discharge and tan delta during a standard test procedure can be carried out over specified time periods (MWT- Monitored Withstand Test). Repeatable test conditions to evaluate PD inception and PD extinction voltage characteristic.
- Calibration according to IEC 60270.
- Length independent measurement of PD level
- Highest accuracy in PD location
- PD monitoring over a definable time span enables the detection of PD sources that only start after a certain period of application of high voltage
- PD measurement during commissioning test with VLF testing voltage (MWT)
- PD location pinpointing for reconfirmation of prelocated location in the field
- Reproducible PD level and location measurement
- PD measurement independent of calibration charge value
- Automatic as well as manual PD result evaluation

Figure 93: Portable on-site PD detector with PD location (BAUR PD TaD62)

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

The characteristic of a partial discharge source is defined by its inception and extinction voltage.
The PD inception voltage (PDIV) is defined as the voltage level where the PD activity is started. This value is most important. In general, it is important to know whether a PD source is active at nominal voltage U_0, the nominal operation phase to ground voltage. If the PDIV is lower than or at U_0, the PD source is active during normal service operation of the cable. In such a case, the partial discharge is continuously active and permanently damaging the insulation. As the PD activity is causing the development of heat and carbonisation, PD sources with PDIV at or below U_0 are to be treated as a serious threat to the reliability of the cable performance.

In comparison, a PDIV above U_0 has to be handled in a different way. Under normal operation voltage, this PD source will not be active. Certain switching cycles or short term fault conditions may raise the operation voltage to the PDIV temporarily.
In regard to this condition, it is important to consider the PDEV level.

The PD extinction voltage (PDEV) is defined as the voltage level where the PD source stops its PD activity. Certain PD sources show characteristics where the PDEV is lower compared to the PDIV. If the PDIV is only slightly above U_0, a switching sequence where the voltage is increasing temporarily, this may initiate the PD activity. If the PDEV is below U_0, this kind of PD source may stay active even after the network voltage returns back to the nominal U_0 voltage level. Such kinds of PD sources have to be treated seriously but are very rare.

8.11 PD result interpretation – guidelines

8.11.1 PD measurements on XLPE cables

In XLPE and EPR cables, PD activities mainly occur in cable accessories. PD in the XLPE insulation itself can be detected very rarely. If PD occurs in the XLPE insulation (electrical treeing), the cable will fail within a few days or maximum weeks. Therefore, very seldom are PD diagnostics carried out exactly within this short time period.
Another reason for PD activity in the XLPE cable section could originate from severe damage to the outer protective sheath.

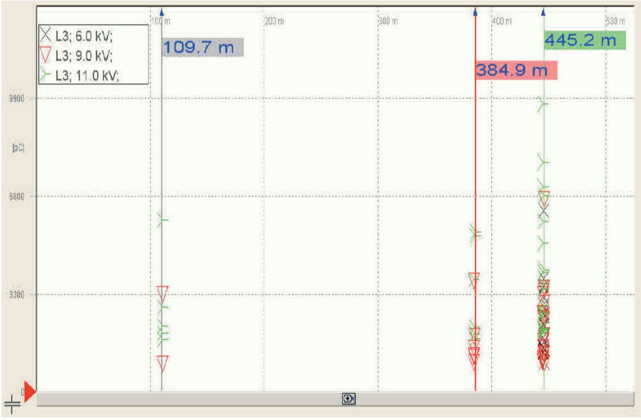


Figure 94: PD graph of XLPE cable with PD activity concentrated at 3 joints

New XLPE cable arrangements:
No PD acceptable during commissioning;
PD level up to 1.7 U_0 must be below < 100 pC
In consideration of all terminations, joints and the entire cable

Aged XLPE termination/joints - e.g. heat shrink joints
PDIV > U_0:
0 - 2,000 pC
Location to be kept in records, no urgent need for action required
Repeating measurement after 2 years is recommended
> 2,000 pC
location to be considered for medium term replacement
Repeating measurement after 1 year is recommended

PDIV < U_0:
0 - 500 pC
location to be rechecked after 6 month
500 - 2000 pC
High potential for failure; to be scheduled for replacement
> 2,000 pC
Very high operating risk; to be replaced immediately

Aged XLPE termination/joints - e.g. premolded type
PDIV > U_0:
0 - 500 pC
Location to be kept in records, no urgent need for action required
Repeating measurement after 2 years is recommended
> 500 pC
location to be considered for medium term replacement
Repeating measurement after 1 year is recommended

PDIV < U_0:
0 - 250 pC
location to be rechecked after 6 month
250 - 500 pC
High potential for failure; to be scheduled for replacement
> 500 pC
Very high operating risk; to be replaced immediately

Note: Different values to be considered for
- Different types of heat shrink joints/terminations
- Different type of cold shrink joints/terminations
- Transition joints (XLPE – PILC in mixed cables)
- Different joint manufacturers

8.11.2 PD measurements on PILC and mixed cable circuits

PD detected in joints and terminations exhibits a high concentration at a specific location. Double or even triple joints within several metres will lead to a less concentrated PD pattern.
For PILC it is very common to have non concentrated PD along the entire length (scattered PD activities). Certain levels are not harmful and are even a normal effect resulting from the cable design. If PD is more concentrated over a certain cable length, it could indicate cable damage, such as corrosion of the lead sheath, dried out sections, etc. A dried cable section where oil has drained out will show higher PD levels and can be identified accordingly. Cables installed on hillside areas often show a draining characteristic in accordance to the slope of the hill.

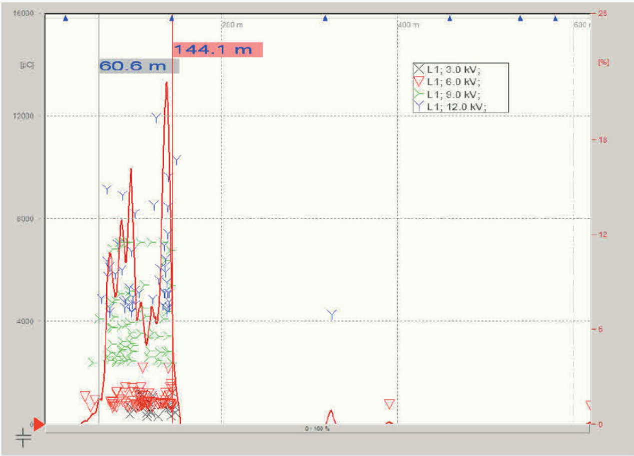


Figure 95: PD graph of mixed cable with scattered PD activity in PILC section

PD activities **along the cable** (dried out sections): ~ 9,000 pC

PD activities **in accessories** (terminations/joints):

PDIV > U_0:

20,000 pC	Location to be kept in records, no urgent need for action required Repeating measurement after 2 years is recommended
50,000 pC	Location to be considered for medium term replacement.

Repeating measurement after 1 year is recommended

PDIV < U_0:

10,000 pC	Location to be rechecked after 6 months
20,000 pC	High potential for failure; to be scheduled for replacement
40,000 pC	Very high operating risk, to be replaced on an urgent basis

Note: Different values to be considered for
- Oil filled terminations
- Paper/oil joints
- Transition joints (XLPE-PILC in mixed cables)
- Different PILC cable types

ensuring the flow

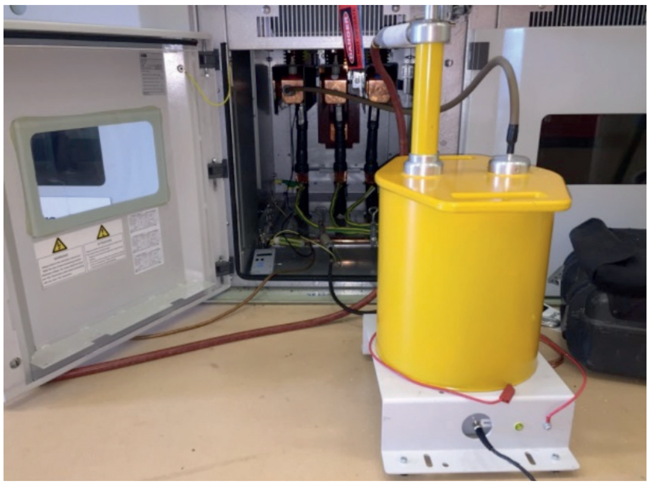
9. VLF diagnostics application examples

↗ PD TaD62 connected to 22.9 kV RMU

↗ Special PD-free L-Bow adapter, 22.9 kV

↗ Connection to RMU, L-bow with removable boot

↗ Connection in the field, before jointing

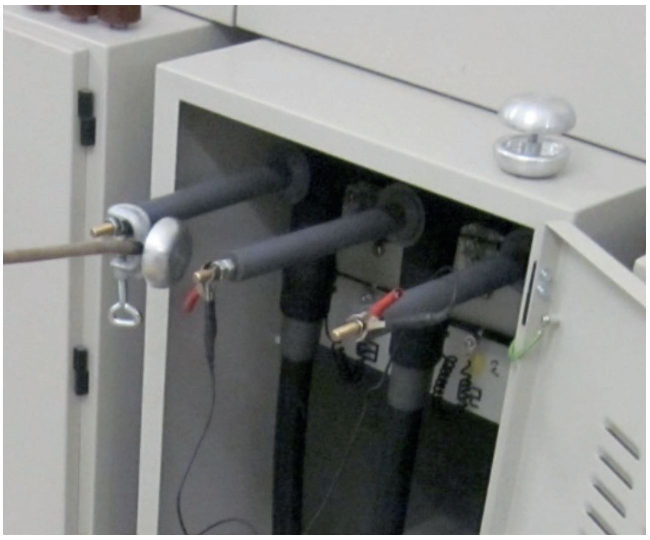


↗ Enclosed switching panel

↗ Switching yard 11 kV

↗ Pole mounted, open terminations 22.9 kV

↗ Direct connection of light-weight PD TaD62 on the tower, close to the termination



↗ Encapsulated substation, access from front busbar

↗ Encapsulated substation, access after removal of circuit breaker unit.

↗ SF 6 insulated switchgear, access from the rear

↗ PD free L-bow adapter, 22 kV

↗ Table 44: Various application possibilities of VLF TD PD diagnostics systems

10. Comparison of different voltage sources with respect to their practical usability

In order to be able to carry out a successful condition-based maintenance, the test and measuring instruments must meet a list of requirements. The essential requirements for the voltage source are:

- Suitability for cable testing / withstand voltage testing.
- High measuring accuracy for loss factor measurement (see above).
- Meaningful results with the PD measurement (inception and extinction voltage, PD level and phase resolved PD pattern) and good localisation of the PD.
- High reproducibility of results to ensure comparability of periodic measurements and different cable lengths in the network.
- Ability to perform different methods in parallel and automatically combine the test results to save time.
- Low weight, easy handling, easy connection, simple operation, short measuring time.

Requirement	**VLF Sinus**	**VLF Cos-Rect**	**50-Hz resonance systems**	**DAC**
Withstand Voltage Test according to IEC, VDE (CENELEC), IEEE	Yes	Yes	Yes	Yes; IEEE standard in preparation
Load-independent test signal	Yes	Polarity change varies representative 30-250 Hz acc. IEEE 400.2 [8], wave shape may depend on load	Test frequency depends on cable length	Test frequency depends on cable length
Tan delta measuring accuracy	High ($1*10^{-4}$)	Not suitable for tan delta	High	Medium
Tan delta sensitivity/ comparability	High	Not suitable for tan delta	Medium, sensitivity lower than with VLF	Medium, load-dependent
PD localisation possible	Yes	Yes	Yes	Yes
PD level and PD pattern comparable to measurement at 50 Hz	Yes	Not yet examined sufficiently	Yes	Yes
PD-insertion voltage comparable to measurement at 50 Hz	Yes	Not yet examined sufficiently	Yes	Yes
Compact voltage source	Yes	Yes	No	Yes

↗ Table 45: Comparison of different voltage sources in respect to their practical suitability [27]

Table 45 shows a comparison of the different voltage sources with regard to the specified requirements. The table shows that the VLF 0.1 Hz sinusoidal voltage is the only voltage source that meets all requirements. It is also suitable for partial discharge measurements and loss factor measurement (tan delta). In theory and practice, virtually all commercially available voltage sources have proven to be suitable for the Withstand Voltage Test.
However, it should be noted that the voltage form is important here.
In order to obtain reliable results independent of the load (cable distance), an ideal sinusoidal curve is advantageous. For this purpose, it is necessary for the voltage source to always deliver the same signal form and frequency if possible in order to avoid influences on e.g. the PD measurement or tan-delta measurement. The aim is to minimise the influence of the voltage source on the measurement result. This allows the user to compare the measurement results and thus to refine decision criteria for the condition assessment of cable routes. The VLF sine wave source is particularly suitable for this purpose.
With regard to the measurement of the loss factor, it has been shown that a VLF sinusoidal measurement is superior to the 50 Hz measurement due to its high precision and sensitivity. At the low frequency, the tan delta values for PE insulated cables are higher and thus an increase in tan delta can be detected more easily. It should also be mentioned that only sinusoidal voltage sources are suitable for a precise tan delta measurement. And, as mentioned above, since the 0.1 Hz sine wave has proven itself so far, standards and specifications (IEEE 400.2-2013) are available for this measurement. This is partly due to the fact that there is now a wide range of experience with the VLF sine wave. [27]

The suitability of different voltage sources (VLF sinus 0.1 Hz, 50 Hz, DAC, VLF Cos-Rect) for partial discharge measurement has been discussed in various scientific publications. For example, the behaviour of different voltage sources in the following test specimens has been investigated:

Artificially generated faults in cable sections and end termination:
- Contaminated outdoor end caps, defect on outer conductive layer / deflector
- Cable lines in operation
- Incorrectly assembled joints
- Aged plastic-insulated cables or sleeves.

Depending on the publication, the behaviour of two or more voltage sources was compared, in particular with respect to the comparability of the measurement results with those measured at operating frequency (50 or 60 Hz). In summary, the following result is derived from the publications:
According to [24], a Cosine-Rectangular voltage source for a VLF was found to produce 5.5 times the PD level when comparing measurements with 2.0 U_0 in six aged joints. 5,500 pC (compared to about 1,000 pC at 50 Hz and VLF sine wave). This corresponds to approximately 5 times the load on the cable.

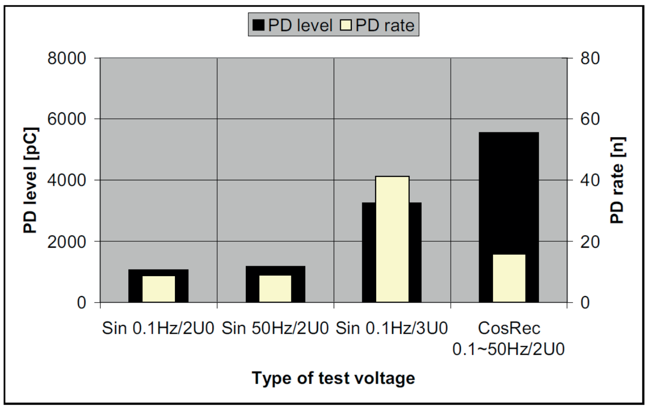


Figure 96: PD level and PD rate at selected types of test voltage [24]

These higher measured values mean that a measurement with the Cos-Rect voltage source represents a higher load for ageing joints. However, for a more gentle diagnosis, it is important that the cable and fittings are not overloaded or even damaged by the measurement. In addition, it is stated in [6], that the waveform of the test voltage has a greater influence than increasing the level from 2.0 U_0 to 3.0 U_0 (compare sine with cos rect). It can also be seen that sinus 50 Hz and sinus 0.1 Hz have practically identical levels.

To date, only a few scientific investigations have been carried out regarding PD measurement with a VLF Cos-Rect voltage source. Practical experience on the suitability of the VLF Cos-Rect voltage form for PD measurement, especially in aged cable lines, is not yet available.

11. Guideline for establishing a diagnostic evaluation logic

Cable diagnostics deliver a wide range of details and test results, making it possible to conclude when and which accessories of a cable section need to be replaced.
The timeline for a part replacement or a retest depends on the component that is identified as being weak. In many cases, cable diagnostics make it possible to assess whether the cable is suitable for service, but also to recognise ageing parameters early on.
A timeline can then be defined depending on the diagnosed weakness. Utilities usually develop a detailed timeline depending on the cable type, available resources and maintenance budget.
The general idea of how to look at the diagnostics results is similar among all utilities.
The judgement guidelines outlined below are a summary of experience from different power utilities.

11.1 Action requirements – example

Classification of cables into four severity levels with action plan.
S … Severe
H … High operating risk
M … Medium operating risk
L … Low operating risk

Cable condition level	Action(s) required
S	▪ The cable condition is severely degraded with definite component(s) and **urgent replacement** action has to be taken. ▪ The urgent replacement should be handled under an emergency excavation permit. ▪ The cable condition should be reclassified in accordance with the guidelines given in Section 2 after the replacement of weak component(s).
H	▪ The cable is in a deteriorating condition without a definite weak component identified or with weak components in their early stage of degradation. The cable can be put back into service and be retested in **1 year** to reassess its condition. ▪ The cable condition should be reclassified in accordance with the guidelines given in Section 2 after retest.
M	▪ The cable condition is fairly stable with some defects developing. The cable can be retested in **3 years** to re-assess its condition. ▪ The cable condition should be reclassified in accordance with the guidelines given in Section 2 after retest.
L	▪ The cable is in a normal condition and only needs to be retested in **10 years** to reassess its condition. ▪ The cable condition should be reclassified in accordance with the guidelines given in Section 2 after retest.

↗ Figure 97: Example 1, action plan for different cable condition levels

11.2 Classification according to complex evaluation criteria

Cables are classified according to six severity levels using measures TD, DTD, STDEV and with interaction of an additional “Skirt” value to deliver the final result (second result) for indicating abnormal ageing parameters.

Six levels of tan delta and delta tan delta are categorised. Whenever the result exceeds level B, the standard deviation (STDEV) and “Skirt” values are considered. With this method, cables with ageing characteristic are not generalised but analysed. Any irregular ageing (e.g. water ingress in a joint, humidity at termination, tracking, etc.) will be reflected in the STDEV and/or Skirt value. Using these additional measures takes the result delivered from TD and DTD to a higher level.

Result types	TD ($1.0U_0$)	DTD ($1.5U_0$-$0.5U_0$)	STDEV ($1.0U_0$)	Skirt ($1.0U_0$)	Final Result
A (normal)	≤ 1.0	≤ 0.5			
B (attention)	≤ 2.0	≤ 1.2			
C (caution)	≤ 6.0	≤ 6.0	≥ 0.10	≥ 0.30	D (이상)
D (이상)	≤ 10.0	≤ 12.0	≥ 0.20	≥ 0.60	E (defect)
E (defect)	≤ 27.0	≤ 60.0	≥ 0.70	≥ 2.20	F (임박)
F (임박)	› 27.0	› 60.0			
1st Result	OR		OR		
	AND				2nd Result

Figure 98: Example 2, action plan for different condition levels A-F

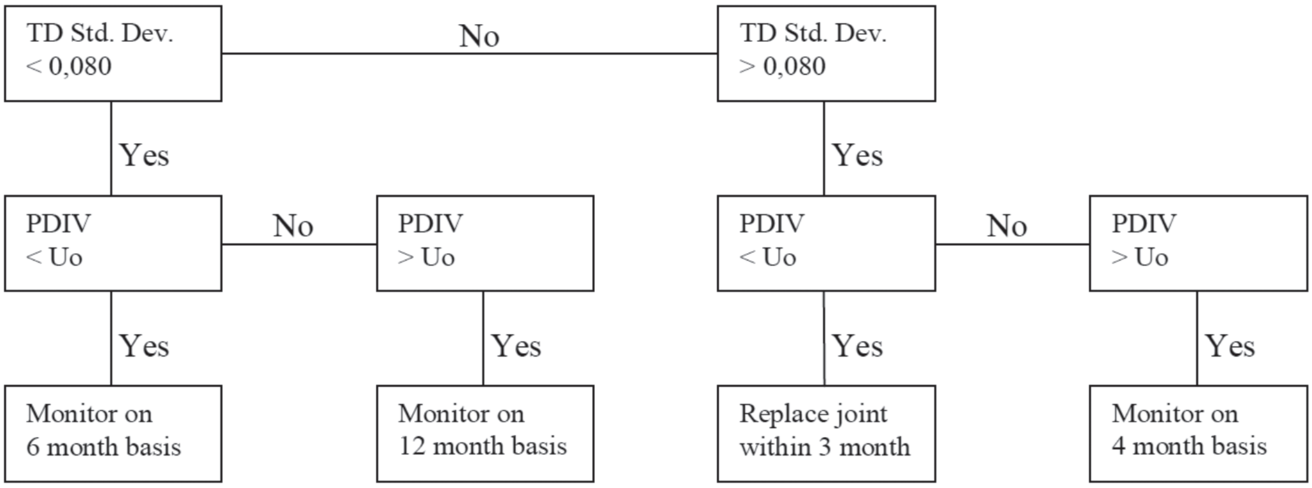
11.3 Categorisation of PD activities in joints and action plan depending on TD STD, PDIV, PD level – example

TD information is an important partner to PD results. Only if a cable circuit can be confirmed as “dry”, can PD activities be judged as true values. TD Standard Deviation STD is an indicator of the presence of humidity or water ingress in at least one of the joints.

Guideline for the PD judgement of joints in respect to PD magnitude, PDIV, TD Std. Dev., „to be adjusted to local network conditions“

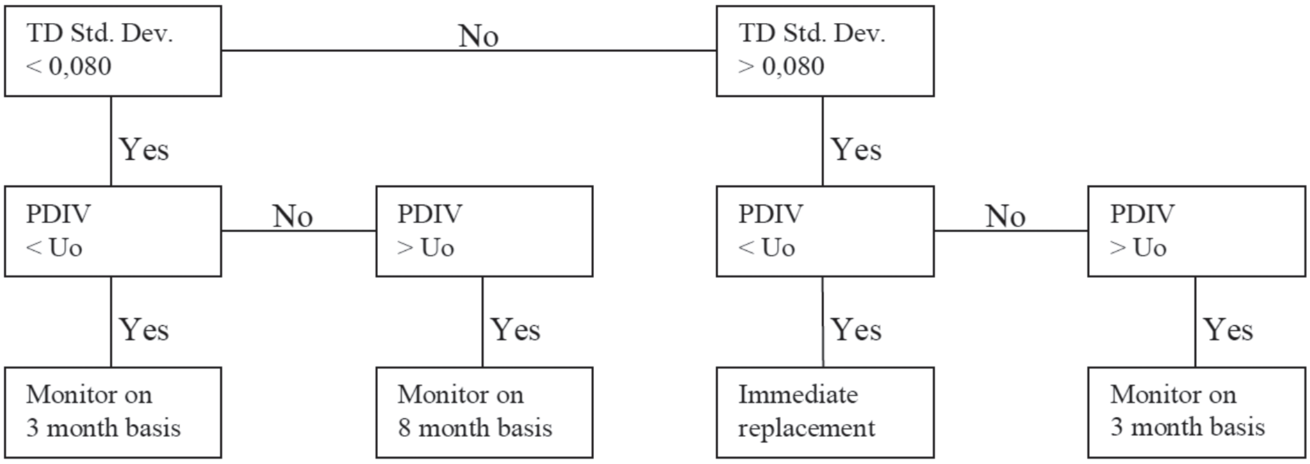
PD activity at joint

< 1,000 pC LD (low discharge level)



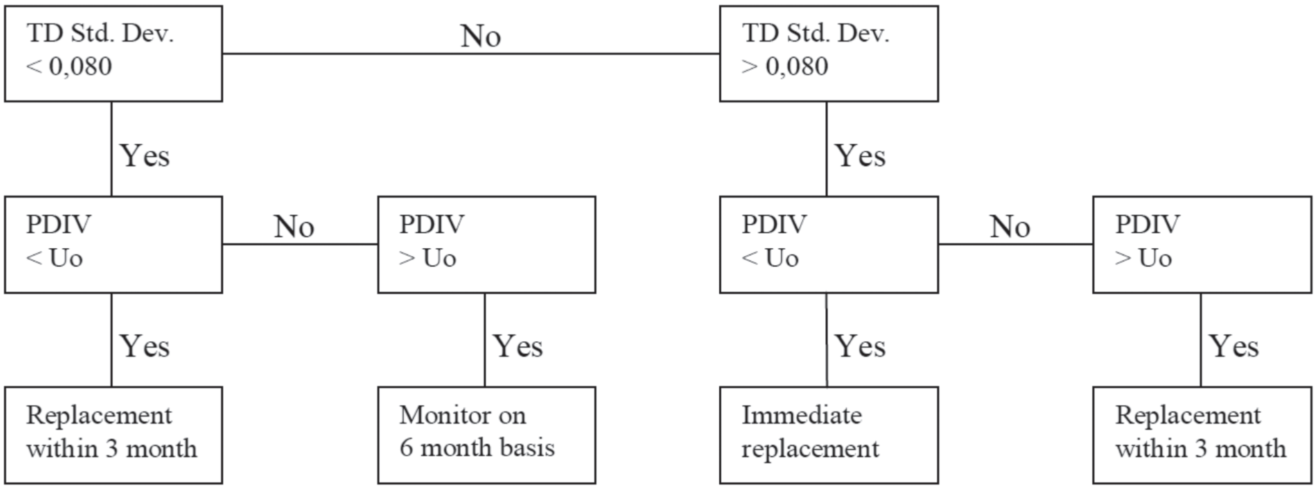
↗ Figure 99: Joint PD categorisation logic < 1,000 pC

1,000 pC – 2,000 pC MD (medium discharge level)



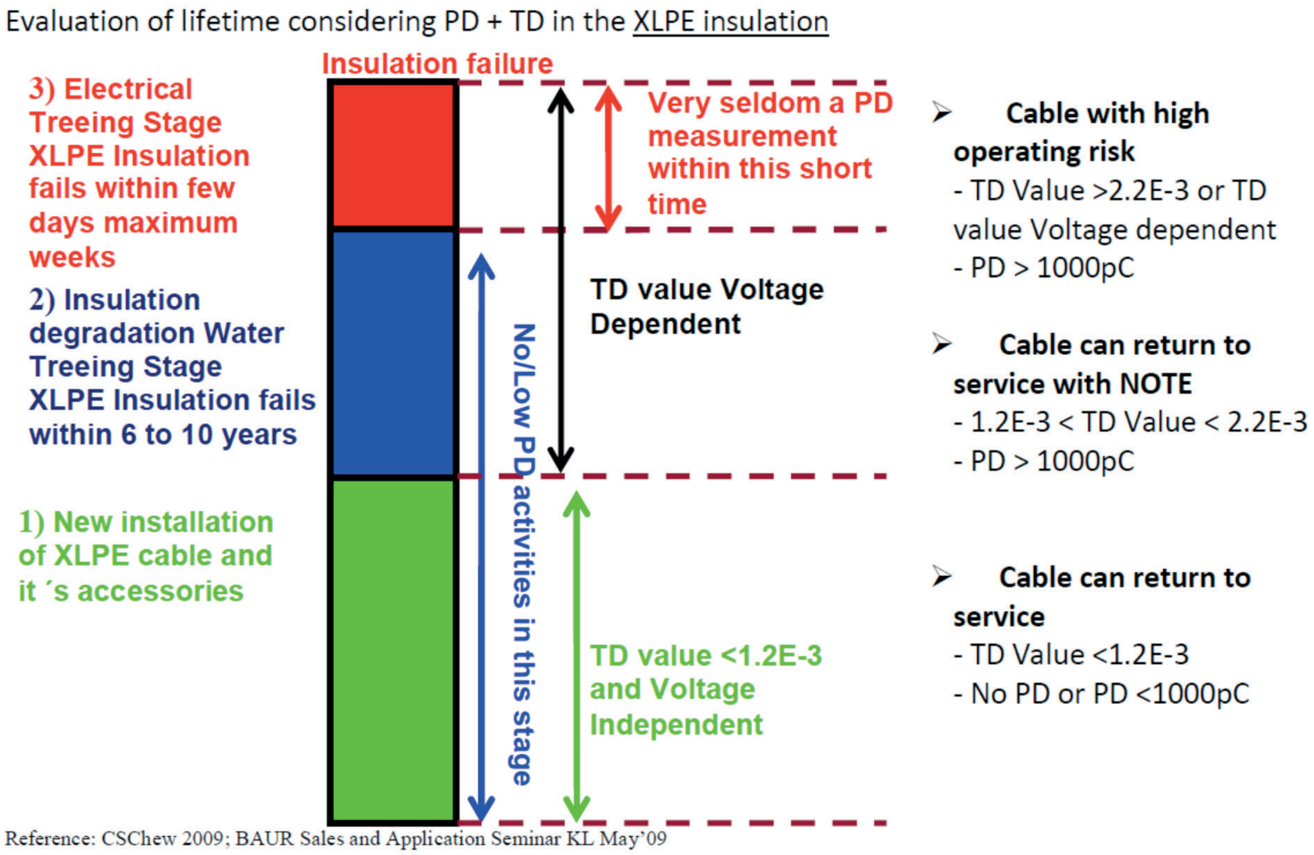
↗ Figure 100: Joint PD categorisation logic 1,000 pC – 2,000 pC

> 2,000 pC HD (high discharge level)



↗ Figure 101: Joint PD categorisation logic > 2,000 pC

11.4 Combined evaluation of VLF TD and VLF PD diagnostics in a new XLPE cable – example



↗ Figure 102: Evaluation example for combined diagnostic criteria

11.5 General logic for combined evaluation of VLF TD and VLF PD diagnostics

TD Recommendation	PD Recommendation	Final Recommendation
No Action Required	No Action Required	No Action Required
	Further Investigation Advised	No Action Required
	Action Required	Further Investigation Advised
Further Investigation Advised	No Action Required	No Action Required
	Further Investigation Advised	Further Investigation Advised
	Action Required	Repair/Replace Required
Action Required	No Action Required	Further Investigation Advised
	Further Investigation Advised	Repair/Replace Required
	Action Required	Repair/Replace Required

↗ Table 46: Final recommendation out of TD and PD recommendation

Further investigation advised:

- It is necessary to understand what is causing the elevated values
- This guides to efficient improvement works with either single replacement of accessories or sectional cable replacement

PD result:	TD result:
▪ PD … High level ▪ PD concentration ▪ PDIV … at or above 1.0 U_0 ▪ PD in XLPE cable body ▪ PD in XLPE/XLPE joint ▪ PD in PILC cable body ▪ PD in PILC/XLPE transition joint ▪ PD in PILC/PILC joint ▪ Is PD influenced by water ingress (refer to TD result)?	▪ Standard Deviation STD ▪ Trend characteristic ▪ DTD ▪ MTD ▪ Recognise the ageing characteristic and influential parameter ▪ Joint with humidity/water ingress ▪ Water tree ageing ▪ Cable in good condition ▪ Aged PILC cable ▪ Different trend pattern allows and understanding of the ageing influence

12. Diagnostic experience and messages from BAUR – VLF testing and diagnostics users

12.1 FNN – Forum Netztechnik Netzbetrieb im VDE – Germany

Extract: Commissioning test of medium-voltage cables – technical note [28]

This technical report focuses on commissioning tests of medium-voltage cable systems as a possible means of quality assurance and thus serves to ensure safe and reliable network operation. The recommendations contained in this technical note are intended to provide a better understanding of this topic.
The technical note was prepared by the project group "Kabelprüfung MS" of the Forum Netztechnik/Netzbetrieb im VDE (FNN):

Project Group: Power utilities and universities in Germany
Westnetz GmbH, DREWAG NETZ GmbH, N-ERGIE Service GmbH, Stromnetz Berlin GmbH, IPH Berlin GmbH, University of Applied Sciences Zittau-Görlitz, Dortmunder Energie- und Wasserversorgung GmbH, Westnetz GmbH, EWE NETZ GmbH, University of Applied Sciences Kiel, EnBW Regional AG, FNN in VDE

Commissioning test

Stage D – Visual inspection, cable sheath testing, voltage testing and PD measurement
The PD measurement provides additional proof of the assembly and material quality of cables and fittings.

Partial discharge measurements should be carried out:

- For newly installed cable systems requiring increased supply reliability
- To control material and assembly quality (especially in the case of changed technologies/processes)
- To identify local defects

Alternatively, the voltage test can be carried out within the scope of the PD measurement according to Table 4, but with a significantly reduced test duration (e.g. 10 minutes) and/or test voltage (e.g. 1.7 U_0).

NOTE: Practical experience has shown that defects can be detected during PD measurement, even with reduced test voltage/time.

Fact box	
+ clear definition of cable after-laying test	VLF 0.1 Hz, 3 U_0, 30 min Withstand Test
	Alternative: VLF 0.1 Hz, 1.7 U_0, 10 min Withstand Test with parallel PD monitoring
▪ No definition of maintenance test	

12.2 EW Mittelbaden, Germany

Approximately ten years ago, Elektrizitätswerk Mittelbaden Netzbetriebsgesellschaft GmbH (short: E-Werk Mittelbaden) carried out a comparison of the VLF 0.1 Hz sine wave and a 50 Hz method for PD measurement on the basis of more than 40 cable routes. Since the 50 Hz method at that time led to very different evaluations and, above all, more negative prognoses, which have not yet appeared as faults, the company adopted for the VLF 0.1 Hz sinus method. In the meantime, the VLF measurement with sinusoidal voltage has proven itself in hundreds of measurements. This has been demonstrated by 240 kilometres of diagnostic measurements with 500 sections in the 20-kV network of E-Werk Mittelbaden in paper mass cable and mixed cable sections.

At E-Werk Mittelbaden, such cable sections are diagnosed with a VLF sinus 0.1 Hz by means of PD and for about seven years now, also with the tan delta measurement. According to Mr. W. B., the head of grid operations, the application of both diagnostic methods provides a good overall view of the ageing and condition of the grid. Subsections classified as endangered are promptly replaced. The containment of defective sections results in considerable savings, as not all cable runs have to be replaced.

For commissioning tests of new or modified cable systems, the VLF measurement has proven to be suitable in practice for precisely locating fault locations and also for detecting faults in the accessories in the future with simultaneous PD measurement, so that the workload for troubleshooting e.g. assembly faults or in maintenance, for example excavation work, is reduced.

As a major advantage of the VLF sine wave source, W. B. emphasises weight and suitability for everyday use. The 0.1 Hz technology can be transported and operated by one employee, which would certainly not be possible with a 50 Hz system.

The use of a two-person measuring trolley is rarely necessary, as the portable measuring and testing device is sufficient for most cable lengths. Only about every seventh measurement requires the use of a measuring carriage.

The use of VLF 0.1 Hz technology results in a clear cost advantage for E-Werk Mittelbaden: measurements can be easily carried out by one employee in a short period of time. Due to the short connection time and measurement duration, as well as the low personnel requirements, a relatively large number of cable distances can be measured per year. The sections or subsections assessed as critical by the measurements are intended for prompt repair or replacement. Maintenance budgets can thus be used in a targeted manner. Due to the knowledge of weak points in the network and condition-oriented maintenance, it is possible to operate the medium-voltage network with a low failure rate in a cost-optimised manner despite the increased number of cables.

The maintenance plan at E-Werk Mittelbaden amounts to approximately € 4 million, of which € 2.5 million are relevant for the distribution network. The cost for the cable diagnosis is currently € 90,000/year.

From the comparative tests before purchasing the VLF equipment, W. B. knows that there were clear differences between VLF 0.1 Hz sine and 50 Hz measurements in his measurements.

In practice, however, a switchover is no longer relevant because E-Werk Mittelbaden has become very well integrated into the VLF 0.1Hz measurements and their interpretation and can use measurement values with high reliability to classify the cable routes. Even the prediction of whether a cable route is susceptible to failure in the short or medium term can be made relatively accurately with the wealth of experience, so that maintenance measures are prioritised accordingly. [27]

Fact box	
+ VLF TD diagnostics	Detection of aged cable sections. Replacement of sections, high cost saving.
+ after-laying test: VLF + PD	Detect weaknesses in new installations.
+ condition based maintenance	Efficient use of maintenance budget.
+ Wide experience in diagnostics result interpretation	
+ Experience in life-time prediction	

12.3 Mitnetz, Germany

Until 2011, maintenance was event-driven. Faulty circuits were repaired and those where more than three faults occurred in five years were completely replaced. However, these measures and the technical aids used at that time did not make it possible to reduce the failure rate with a given budget. In 2011, when the number of technical breakdowns exceeded previous years' figures, the decision was therefore taken to invest in cable diagnostics. The measurement and evaluation of important medium-voltage cable sections should provide information on the condition of the cable insulation and fittings, which allows for predictive maintenance of the approx. 16,000 km of buried medium-voltage cables (**Figure 103**). The investment decision was based on the assumption that the average duration of breakdowns caused by technical malfunctions could be reduced by up to 40 percent in the medium to long term.

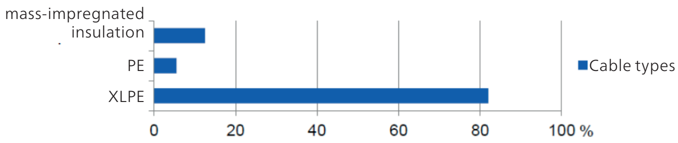


Figure 103: Total 16,000 km of MV cable (Source: Mitnetz)

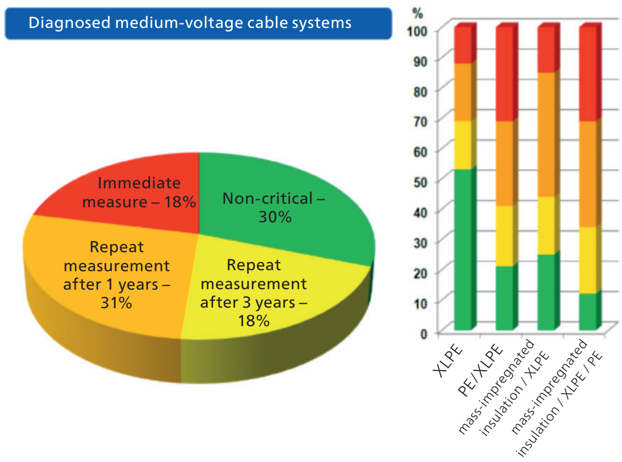


Figure 104: The result of cable diagnostics shows that pure XLPE cable circuits seldom require immediate action. With old types of PE cables and PE mixed with PILC cables, the diagnostics often reveal hidden and critical defects that have to be repaired within a few weeks or month. (Source: Mitnetz)

Since the purchase of the first Baur cable test vehicle, diagnostic measurements have been carried out on a regular basis. They have been carried out on selected cable routes. When selecting the sections to be tested, many factors play a role: the age of the cable route, defect and condition data, as well as the significance of the network section for the power supply or the power flowing through the cable. Furthermore, priority will be given to cable lines, in addition to which construction measures (such as the replacement of gas/water/telecommunication lines) are planned, so that any repairs or cable renewals can be carried out at the same time as other utility projects. The criteria are incorporated into an evaluation algorithm that determines the cable routes to be measured in the near future. With this prioritisation, it follows that a disproportionately high number of the routes to be diagnosed are mixed cables (**Figure 103**). The investment decision was based on the assumption that the average duration of breakdowns caused by technical malfunctions could be reduced by up to 40 percent in the medium to long term.

After more than three years, repeat measurements are now also increasingly taking place.
On existing sections in which the main focus is on condition determination, tan delta measurement and partial discharge measurement are carried out, and in the case of plastic-insulated cables, an additional cable sheath test is done.
In less than four years, the network operator had diagnosed exactly 1,859 cable routes with a length of approx. 2,000 km by the end of 2015. On average, each cable kilometre accounted for about six joints. Of the total routes investigated, tan delta or partial discharge measurements of just under one fifth showed that there is an acute need for action and that measures to remedy the (latent) defects must be taken within a few weeks. About 30 percent of the measured cables are uncritical, and with almost half of those, taking a new measurement after one to three years makes sense. In the case of repeating measurements, approximately one quarter of the subsequent measurements yield better values than before, but for three quarters of the cables, identical or poorer results can be expected for the new measurement (**Figure 104, Figure 105**).
Despite the learning curve, which probably all users of cable diagnostics will have to follow initially, the failure rate of medium-voltage cables has improved rapidly. As early as 2012, when the first measurements were carried out, there were fewer failures than in the previous year. In 2015, the number of technically induced medium-voltage cable failures was just over two thirds of the figure for 2011 (**Figure 106**).

Assured by the technical successes, the cable diagnosis in 2014 was also evaluated in terms of economic efficiency. This study showed that the additional investment and measuring time required to maintain the system pays off, as maintenance can be carried out in a targeted manner and at reasonable cost. The reduction of the ASIDI value also contributes to profitability in the medium term: already part of the theoretical reduction potential (40% fewer technical failures), it corresponds to an equivalent value of more than € 1 million for a company like Mitnetz Strom.

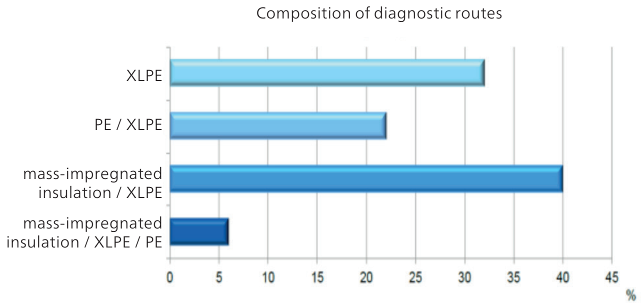


Figure 105: The selection of cables to be diagnosed; focus is placed on mixed cable circuits that are more prone to cable failures. (Source: Mitnetz)

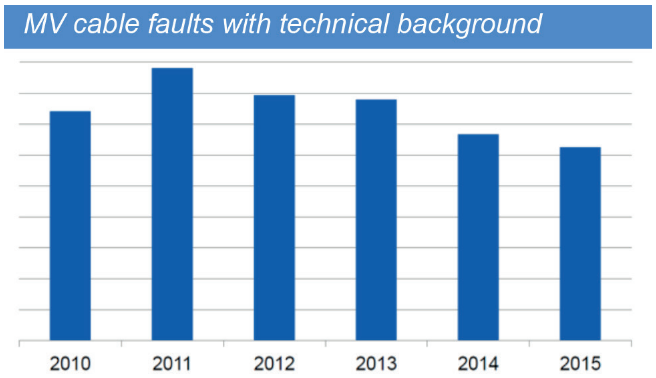


Figure 106: Since the implementation of cable diagnostics in Mitnetz in 2012, the number of faults has continually decreased by approx. 30% to 2017.

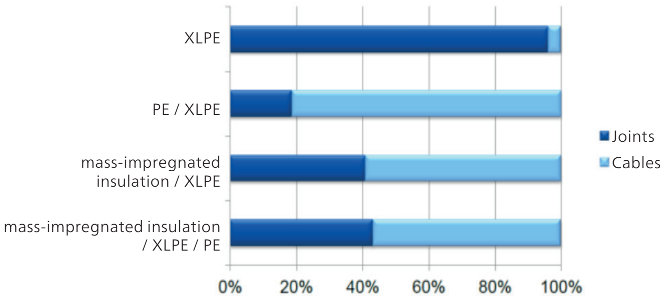


Figure 107: XLPE cables, mostly joint problems. Cable ageing in older cable systems. (Source: Mitnetz)

Due to the positive technical and economic experience, diagnosis has become an integral part of everyday life. In the meantime, nine cable test vans at Mitnetz are equipped with VLF diagnostics technology and new test vans are only ordered with diagnostic devices. Meanwhile, about two to three cable routes can be measured per working day (approximately 600 per year). The goal of reducing the number of technical failures by 40% is within reach in view of the diagnostic possibilities and the successes achieved so far.

Fact box	
+ selection of cables to be diagnosed	Based on: age, cable constellation, history in terms of outages, importance, loading
+ VLF TD and PD diagnostics	Detection of aged cable sections. Replacement of sections, high cost saving.
+ evaluation of diagnostics application	In terms of economic aspects ▪ Additional time invested in diagnostics is paying off ▪ Efficient usage of resources is possible
+ Nine cable test vans are equipped with cable fault location & VLF TD PD equipment	New test vans will only be purchased that include VLF TD PD diagnostics
+ 600 cables can be diagnosed per year	
+ Reduction of cable failures since 2011	Target of annual failure reduction by 40% should be possible

12.4 Berliner Netze (former BEWAG) – Berlin, Germany

Significance of condition assessment for asset management.

Expectations of BEWAG
- Threatening cable faults could be detected/avoided by measurements
- Determination of the risk potential of a certain cable type

Measures
- Evaluation of different measuring systems on real distances (learning curve) 2003/5
- In-house research: assessment of the condition of plastic-insulated cables since 2006
- Postulation of the evaluation logic for PE cable 2009

Today: Status recording (measurement + evaluation) is the most important maintenance task for MV cables

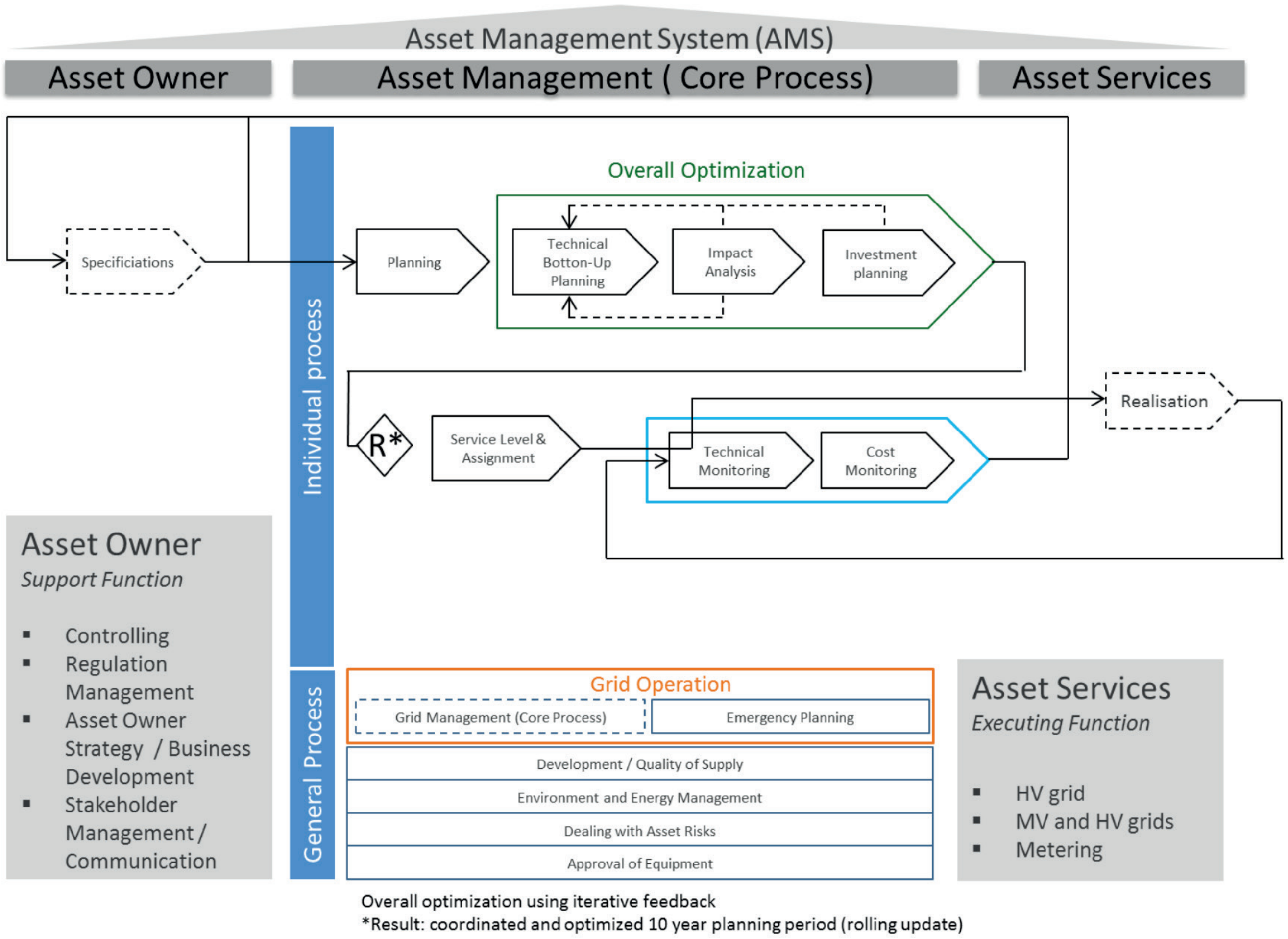


Figure 108: Asset Management System – most important aspect – effect analysis

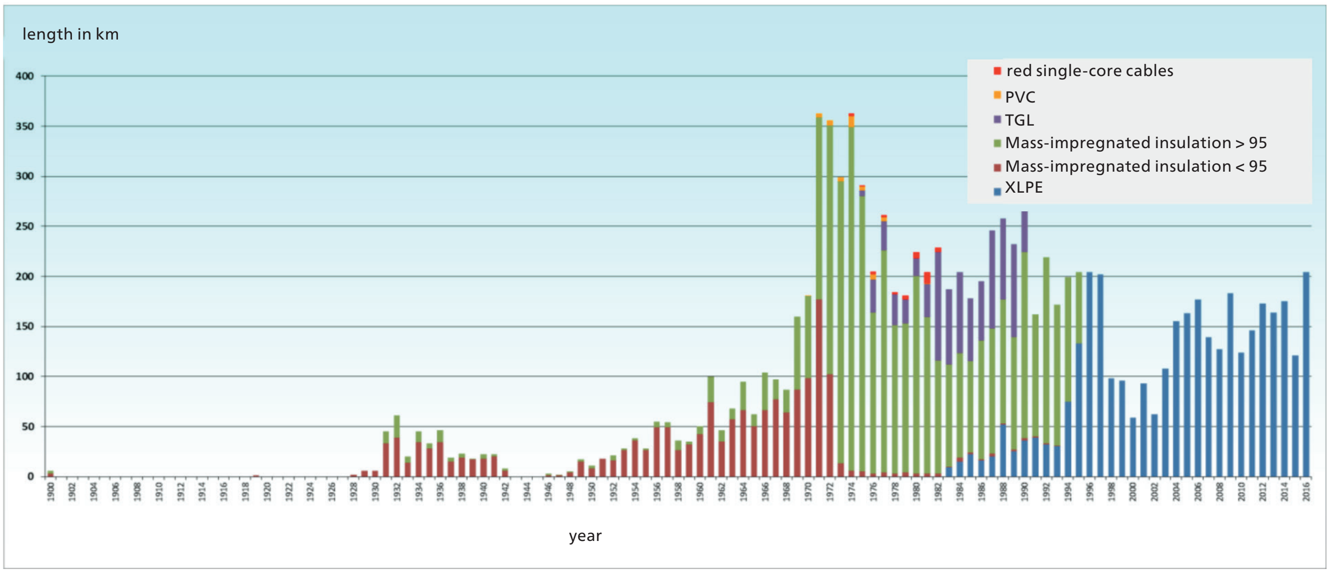


Figure 109: Type and ageing structure of 6/10 kV cables in Stromnetz Berlin GmbH, date 31.12.2016

- Collect data-inventory, condition, reliability
- Evaluate data
- Disseminating results/knowledge within the company-transparency
- Formulate strategies – assess risks
- Consolidate medium- and long-term planning
- Check the effectiveness of the measures
- Asset management with status data is a benefit for everyone

Fact box	
Collect data	Asset, condition, reliability
Evaluate data	Categorise
Results and knowledge to be shared	Transparency inside the organisation
Define the strategy – measures	Calculate the risk of cable outage
Consolidate mid-term and long-term planning	
Evaluate the effect of the implemented measures	Asset management with condition based maintenance is a benefit for the organisation

12.5 EDF, France

EDF France is the power distribution company for France and operates approx. 50 regional offices, which are in charge of acceptance and maintenance tests according to EDF regulations.

Nowadays, for new cables, VLF testing is defined with VLF (sin or cos^2) at 3 U_0 + 1 kV for new cables, and at 2 U_0 + 1 kV for 15 minutes for older cables.

Combined cable diagnostics is performed for cable condition monitoring purposes:
TD with VLF sin 0.1 Hz with 8 measuring points at 3 voltage steps (0.5 U_0 / 1 U_0 / 1.5 U_0)
PD with VLF sin 0.1 Hz at 3 steps (0.5 U_0 / 1 U_0 / 1.5 U_0)

However, the recommendation committee is also planning to adapt the regulation in the near future according to the latest standards:

- CENELEC HD 620 (3 U_0 / 30') for after-laying test
- IEEE 400.2-2013 with monitoring withstand test for maintenance test

Future recommendation:
Maintenance test, after fault repair, the approval for re-energising shall be in two steps depending on the TD/PD condition:

- Standard diagnostics VLF TD & PD up to 1.5 U_0 … 1.5 U_0 is sufficient if all parameters are within range
- Standard diagnostics VLF TD & PD up to 2.5 U_0 … 2.5 U_0 is required if certain ageing parameters are exceeding limits

Monitored Withstand Test:

- For aged cable: MWT TD/PD during 15' – 60' at 2.5 U_0 … testing duration depending on the condition
- For new cables / commissioning test: MWT TD||PD during 15' – 60' at 3.0 U_0 … testing duration depending on the condition

The results of the diagnostics are exploited inside a detailed calculation board that has been developed by EDF LAB based on more than 20,000 measurements, mainly with BAUR equipment.

General message: A VLF test with 2.0 U_0 is known to be a rather low stress and 2.5 U_0 appears to be more appropriate for the health verification of a cable circuit. Fifteen minutes is only appropriate if the cable is in good condition. Whenever hidden weaknesses are present in a cable, a 15 minutes test appears to be inappropriate. Whenever possible, the test duration shall be conditional on the TD and PD result during the Withstand Test.

Fact box	
1. VLF testing After-laying test on new cables	3 U_0 + 1kV for new cables MWT anticipated with parallel PD 15' / 30' / 60' depending on the PD activities
2. VLF testing Maintenance test on aged cables after repair works	2 U_0 + 1kV for aged cables MWT anticipated with parallel TD‖PD 15' / 30' / 60' depending on the TD characteristic and PD activities
3. Condition monitoring On aged cables	TD diagnostics … 0.5 U_0, 1.0 U_0, 1.5 U_0 PD diagnostics … 0.5 U_0, 1.0 U_0, 1.5U_0 Based on 0.1Hz VLF sinus
4. Future plans – anticipation	VLF test for maintenance … 2.5 U_0
5. Experience	20,000 measurements
6. Time constant	Determine a time constant – recognise ageing based on the applied load characteristic

12.6 Städtische Werke Magdeburg, Germany

The German power utility has been using the BAUR VLF TD and PD diagnostics system for the past two decades. The last development of the BAUR PD system with PD phase resolving pattern recognition represents a big additional value for the power utility.
Based on experience, the engineers understand that partial discharge activities along the cable might be influenced by humidity or moisture. The first important parameter for analysing PD results is to understand the possible influence of humidity on the whole cable circuit. Whenever moisture is recognised by means of the TD Standard Deviation showing unstable conditions, the PD result might be influenced.
Further, it is understood that various different sources of PD can be present in joints. Städtische Werke Magdeburg has to deal with different types of cables and accessories. It has recently been observed that neither heat shrink nor premoulded cold shrink joints are free of issues. The installation process has many possibilities to incorporate mistakes.

The new PD phase resolving PRPD pattern allows an understanding the type of PD source. The example below shows one new heat shrink joint that has been recognised with high PD activity right after the installation. PRPD made it possible to recognise that an air pocket may be present. Detailed investigation confirmed the severe issue of inappropriate shrinking.

The PRPD pattern correlated with a void inside the insulation. Inappropriate jointing left an air pocket remain inside the joint. Potential joint failure could be eliminated.

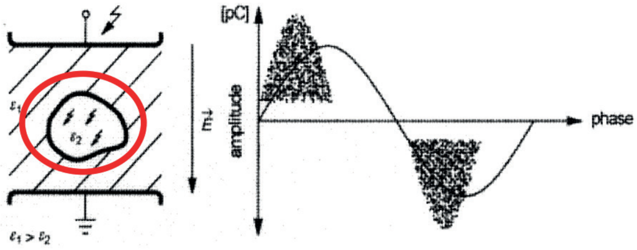


Figure 110: PRPD pattern matching with reference void pattern; non- conducting material without direct contact with the metal electrode

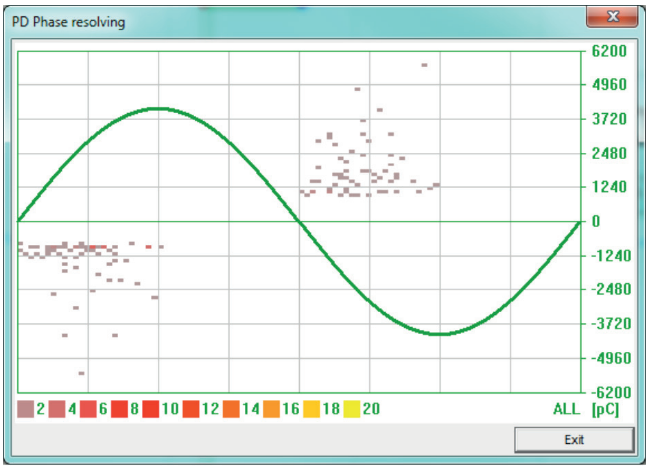


Figure 111: PRPD pattern of suspicious joint

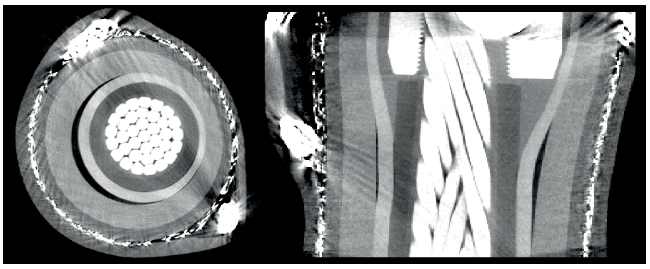


Figure 112: X-ray investigation of joint

Fact box	
Combining TD and PD diagnostics	To understand whether humidity is influencing the PD result
Vast experience in diagnostics	
Implementation of new PRPD	To understand the type of PD source
Joint dissections	Learning process ▪ Read PRPD pattern ▪ Improve workmanship

12.7 Veitur, Iceland

Veitur is the power distribution company of Iceland. In 2008, the financial crisis forced the power utility to cut investments and operate the distribution network with a minimum budget. Following this pressure, the decision was made to invest in a cable diagnostics test van in order to operate cable maintenance in the most efficient way. The target was to reduce costs to a minimum and improve grid reliability.
Approximately 1,200 distribution cables (11 kV and 33 kV networks) are installed in Reykjavik, the capital city of Iceland. Some of these cables are PILC cables that are up to 50 years old. XLPE has been implemented since 1981. Many cable circuits are also mixed circuits.
In 2008, approximately 2-3 cable faults happened every month. Measures had to be taken to minimise the outage rate and, more importantly, to ensure power supply reliability to key customers, such as an aluminium smelting factory.
Based on this background, the utility decided to invest in the implementation of a preventive maintenance strategy. One group of experienced engineers formed a team and implemented the VLF testing and diagnostics methodology.

Time efficiency and appropriate categorisation:
In order to optimise the utilisation of the BAUR VLF TD PD diagnostics system, a key factor was to understand the correlation between the most severe ageing parameters with the simplest regular testing methods, such as the Insulation Resistance (IR) test. It was found that a periodic IR test with 5 kV DC can be performed easily and serve as tool to prioritise and identify the cables that should be scheduled for an outage for further diagnostics.

The prioritisation further started with main feeder cables and continued to distribution cables. This approach made it possible to utilise the VLF TD PD diagnostics in a most efficient way. Since the implementation of cable diagnostics in 2009, the cable failure rate reduced to 1 fault per month (reduction of > 50%).

Furthermore, the diagnostics system was utilised to diagnose 6.3 kV cable circuits as being suitable for upgrading to 11 kV. Eight circuits out of 54 were judged to require further investigation. The diagnostics team gathers regularly to discuss the action required for each circuit. This kind of discussion has turned out to be a very powerful tool for establishing the experience required to interpret diagnostic results and draw up action plans.

Fact box	
1. Categorisation	Regular 5 kV IR test Schedule circuits for outage Prioritise
2. VLF TD measurement	Understand the ageing characteristic Criteria acc. to IEEE for XLPE circuits Adapted IEEE criteria for mixed cables
3. PD diagnostics	Localise and identify PD sources
4. Sheath test	Maximum leakage 1.50 µA/km
5. Time constant	Determine a time constant – recognise ageing based on the applied load characteristic

12.8 Singapore Power Grid – SP Group

Condition monitoring is key to SPPG for preventing power supply interruptions to its customers. Condition monitoring using the Damped Alternating Current (DAC) method has helped SPPG to avert many incipient cable joint failures since its implementation in 2006 [1]. However, DAC has some limitation in detecting non-partial discharge (PD) defects, such as moisture ingress into the cable insulation. Moisture ingress usually extinguish PD and it is likely to develop into a failure through the water treeing process. Also, a short duration of DAC applied voltage might not be sufficient to excite the PD under test.

Insulation resistance (IR) measurements are a quick common practice in SPPG for evaluating the cable insulation condition before and after PD measurement by DAC. However, IR results can vary over time and are subject to location and environmental conditions. There have been cases where cables with low or unbalanced IR readings detected with no PD using DAC had failed within a short period of time after re-energisation.

Limitations of OWTS (DAC) test

- Short duration of applied voltage for PD detection
- Not suitable for cables where IR readings are low
- Difficult to pinpoint PD sources in long cables (more than 3 km with 10 joints)

Limitations of IR measurement

- Varies with temperature, humidity and shutdown time
- Is an integrated value of the whole cable
- Cannot localise the weak insulation location

Moisture or water ingress was observed more on Aluminium (Al) conductor cross-linked polyethylene (XLPE) cables and their accessories, which were installed in the early 1990s. It is the main cause of early degradation of a distribution cable. It will lead to a premature failure if this degradation is not fixed. It becomes a challenging task to predict and detect the weak insulation links along the cables.

In view of this, SPPG explored an improved version of VLF diagnostic measurements to supplement the condition monitoring gap arising from using the DAC technique and IR measurements. Past experience in SPPG [1] and other reports [2] [3] indicate that prolonged VLF testing on existing aged XLPE cables is harmful and destructive. Particular caution is needed when using the new VLF diagnostic test on these aged XLPE cables.

The tan δ (TD) measurement with VLF sinusoidal wave voltage is also confirmed to be an enhanced diagnostic technique for evaluating insulation degradation caused by water ingress [4] while at the same time overcoming the drawback of IR measurements.

Time Domain Reflectometry (TDR) was used to expose the weak insulation along the distribution cables in the laboratory [5] [6]. SPPG uses it on site to identify the location of weak portions of in-service cable after the confirmation of abnormality through tan δ measurements.

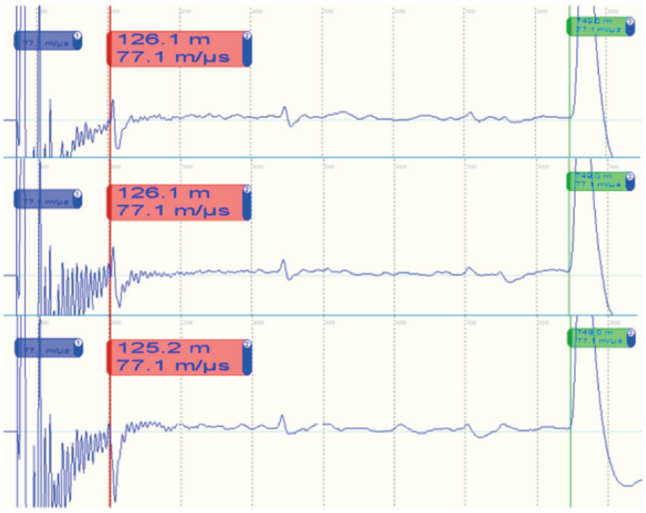


Figure 113: TDR waveforms are inconsistent in polarity for three phases, Figure 2 of [29]

TDR waveforms together with cable details, such as joint positions, year of installation, fault history, cable route, type of joint and switchgear structure – are used to determine whether the impedance changed due to the moisture ingress effect. The analysis is carried out to differentiate and pinpoint the location of joints with the moisture ingress. Beside these, TDR waveforms can also be used to locate any old missing joints or identify the mixed type of cables.

Categorisation	Conditions	Actions
Category 1	tan δ > $12*10^{-3}$ at 1.5 U_0 and TDR shows clear abnormal waveform or Al cable more than 30 years	Repair immediately
Category 2	tan δ >2. $2*10^{-3}$ and <$12*10^{-3}$ at 1.5 U_0, aged more than 20 years, TDR shows abnormal waveform	Repair on scheduled date
Category 3	More than 2,000 pC detected at PD joint	Replace the joint
Category 4	Others	No immediate action

↗ Table 47: Cable condition categorisation and further action criteria, SPPG

Summary:

Moisture or water ingress into cable insulation is the main cause of the early degradation of distribution cables. It will lead to a premature failure of the cable if this degradation is not fixed. The tangent delta (TD or tan δ) measurement with very low frequency (VLF) sinusoidal wave voltage and other diagnostic checks is regarded as an improved technique for evaluating the degradation of distribution cable insulation. The tan δ measurement indicates the true cable health condition as compared to insulation resistance (IR) measurements. When the tan δ measurements are found to be abnormal, Time Domain Reflectometry (TDR) will then be used to uncover the weak insulation section or cable joint along the distribution cable. Having identified the weak link, a VLF diagnostic test with control of applied voltage and test duration can be used to monitor the partial discharge (PD) inception to further confirm the integrity of the cable. The VLF diagnostic test set is a complementary tool for locating the moisture ingress into the cable. It has produced good results and has made a significant contribution and improvement to SP PowerGrid Ltd's (SPPG) network performance.

Conclusion:

This paper introduces the improved VLF diagnostic test using tan δ, TDR and PD mapping in distribution cables. One hundred and fifty weak cables with no uniform age have been tested using the new test method. After pinpointing and replacing the deteriorated insulation at discrete locations identified by TDR, the circuits were again tested with similar VLF diagnostics to confirm its effectiveness. Most of the circuits had shown significant improvement in cable insulation. SPPG will continue to explore further by using the VLF diagnostic technique to deal with the weak cable insulation that is related to moisture ingress. [29]

Fact box	
1. Old method: IR test, DAC-test	+ Replacement of joints with PD + Identify which circuits are suspected to suffer from water ingress (low IR) - Cannot diagnose water-tree ageing - Cannot diagnose water ingress in joints - Cannot localise water ingress in joints - Cannot perform PRPD diagnostics
2. New method: IR test, VLF TD, VLF PD, TDR	+ IR test result … routine test, simple + VLF TD … understand the general cable condition, identify characteristic of ageing + Identify water-tree ageing + Identify water ingress in joints + Localise water ingress in joints + Monitored Withstand Test + Accurate PD localisation + PD result with PRPD pattern
3. Main learning points There is a big difference between	VLF withstand test … destructive test VLF diagnostic test … non-destructive

12.9 Endesa, Spain – case studies on PILC cables

In reference to the published paper on "Improving Cable System Reliability with Monitored Withstand Diagnostics", several interesting aspects have been illustrated by Endesa, Spain, and are reflected below. [15]
As a key point for the condition based maintenance (CBM), the implemented Monitored Withstand Diagnostic made it possible to overcome numerous different ageing characteristics, especially in old PILC cables.
A considerable part of the cable networks is not only outdated statistically, but even the frequency of faults has increased over the years. Effective maintenance strategies are now required, particularly for careful detection of weak insulation spots in aged cable networks.
First of all, this means avoiding unnecessary investment caused by the complete replacement of the cable. Many old cable systems are still intact, despite their advanced age, and can easily be classified as reliable after rectifying the weak spots. An efficient reconstruction programme based on cable diagnostics was developed for these purposes: on the one hand ensuring a reliable power supply and on the other hand, saving the expensive replacement of cable routes thanks to useful diagnostic findings. In this process, potential defects in the cable system are detected on time, making refurbishment of insulation defects or partial cable sections possible.

A condition-based maintenance strategy takes place for aged cables. To avoid high-voltage stress and unnecessary cable defects, the combined cable diagnostics is used as a smart solution for condition evaluation. VLF-based partial discharge measurement is used for the cable diagnostics, which can show faults in cables as well as cable joints and cable terminations in particular. PD diagnostics help to locate weak insulation spots such as hollows, delamination and electrical treeing, as well as insulation components with local high electric field strength that are often caused by installation mistakes.

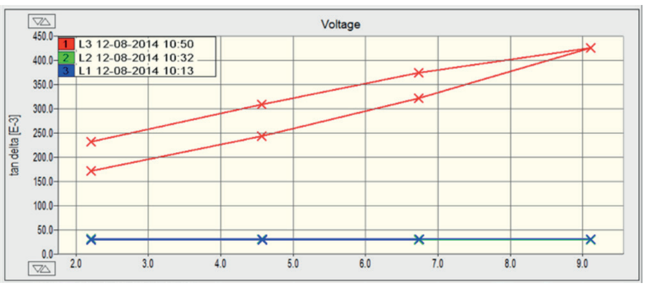


Figure 114: VLF tan delta hysteresis measurement on PILC cable

Combined use of diagnostics procedures and holistic considerations:
The use of partial discharge measurement in aged cable networks as the sole diagnostics procedure has only been proven to a limited extent, whilst the use of a combination of partial discharge measurement and dissipation factor measurement has proven to be successful. The dissipation factor measurement at a standard test frequency of 0.1 Hz (VLF) is used worldwide to determine the age of medium-voltage cables. In particular, the ageing condition is determined here according to the insulating material type. The tan delta measurement at 0.1 Hz was originally developed for detecting harmful water trees in the PE and XLPE insulating material. However, it has also proven to be especially suitable for detecting moisture ingress in cable joints. Statistically, moisture ingress in joints is one of the most frequent causes of cable faults especially in hybrid cable systems. The tan delta measurement is achieved over three or more voltage levels. There, the tan delta mean value, the standard deviation and the tan delta tip-up is measured and evaluated automatically during a tan delta ramp-up.

Attention should be paid to the PD trending during the diagnostics procedure, especially on PILC cables with a non-migrating compound (MIND). Often, PILC cables are diagnosed as aged due to the presence of PD. PD and tan delta trending offers additional information on the ageing condition, which may lead to initial decisions being made based on the conventional short-time PD analyses being revised.

12.9.1 Trending behaviour of a non-critical PILC cable section

The case study on cable 10-1964 provides detailed information on PD activity that is widely spread along the cable length and also pointed to a PD cluster at 154 m. A common short-period PD measurement would rank the cable as critical. (**Figure 115**)
In contrast, the applied diagnostic trending provides even more useful information. During PD trending over 10 minutes, a significant change of PD activity took place. The tan delta trending remains stable over time. During a ten-minute PD trend, the PD activity disappeared on the large cable section and on the PD cluster at 154 metres (**Figure 116**).
By combining the good tan delta results and the important information on PD trending, the cable can be ranked as non-critical. Further periodic diagnostics are recommended to monitor the long- term trend.

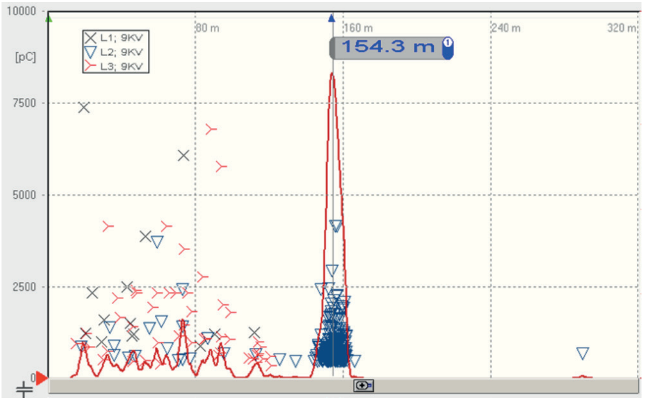


Figure 115: PD on PILC cable, widely spread and PD cluster

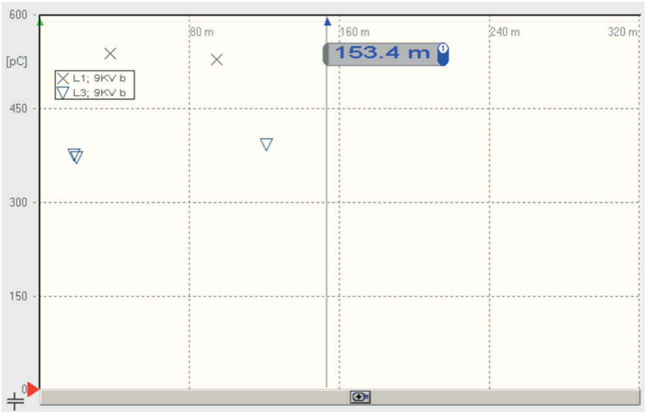


Figure 116: PD on PILC cable after 10 min trending

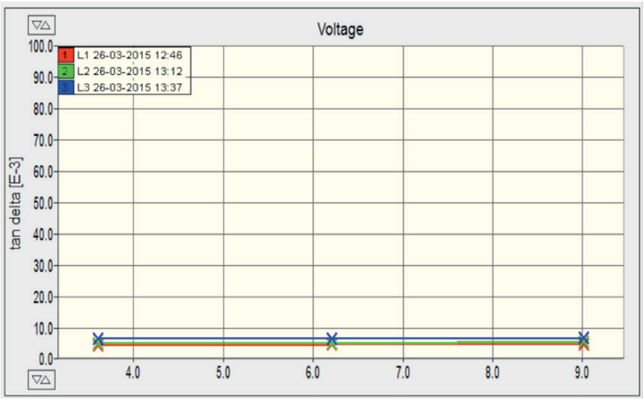


Figure 117: Tan delta ramp-up

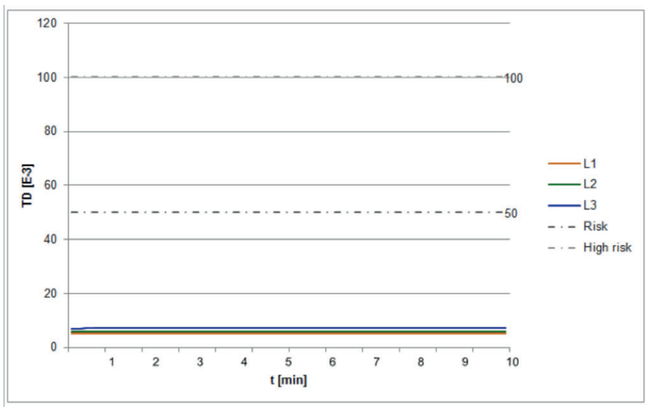


Figure 118: Tan delta trending over time

12.9.2 Trending behaviour of critical XLPE/PILC cable section

The dissipation factor measurement indicates considerable ageing of the hybrid cable consisting of XLPE cable, 3-lead PILC dated 1966, XLPE dated 2005, and 3-lead PILC dated 1975. Investigation on L2 initially showed no PD during PD trending. Suddenly, after 11 minutes of Monitored Withstand Diagnosis carried out at nominal operation voltage U_0, a critical PD spot appeared at L2, indicating high PD density at a distance of 4.6 m, close to a transition joint, as shown in **Figure 120**. The PD spot has to be classified as a high operational risk due to low inception voltage at U_0 and the high PD density of up to 160 pulses per cycle. The PD trend monitoring could detect a weak insulation spot. It could be considered that a commonly short duration PD test would not be adequate to detect this harmful insulation defect. Replacing the front 10-m cable section of the 3-lead PILC dated 1966 and re-testing the circuit after the refurbishment process is advised. [15]

For further details, please refer to the full paper.

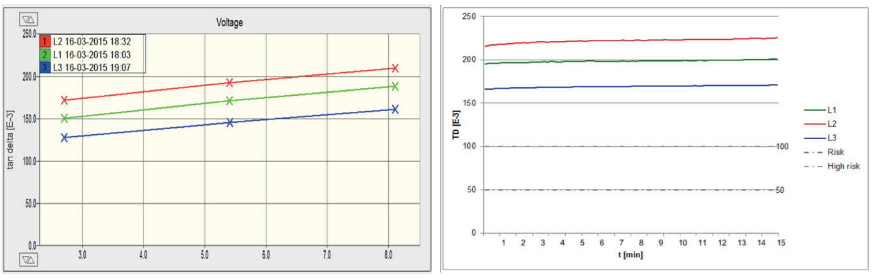


Figure 119: Tan delta ramp up, tan delta trending MWT

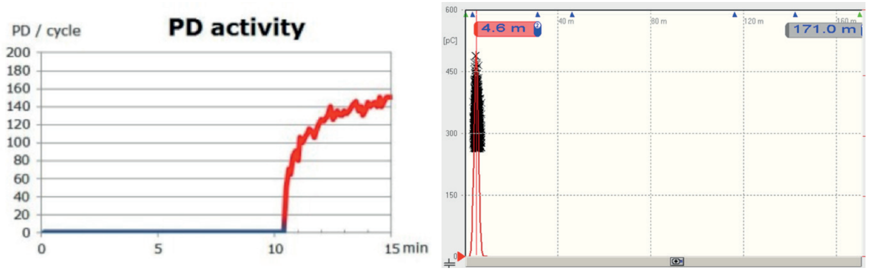


Figure 120: PD trending L2, PD cluster L2, at 4.6 m joint

Figure 121: MWD diagnostics on aged cable system – PD TaD 62

12.10 Middle East Power Utility

Several Power Utilities in the Middle East have established the use of cable diagnostics over many years. Some of them have already evaluated different types of cable diagnostic tools and accordingly, have implemented different approaches for the evaluation and categorisation of the cable conditions.

Old way / low end diagnostics

IR test 5 kV	Overall information on cable integrity ▪ If IR values are < 20 MOhm; indicator of possible water ingress
PD diagnostics DAC ▪ PDIV ▪ PDEV ▪ PD localisation ▪ PD level ▪ PD concentration	
Advantages	**Disadvantages**
+ Focus on PD in joints	- Wrong judgement for cases with joints with water ingress - Not sensitive to water-tree ageing - No PD phase pattern available
	Judgement on the remaining life time is not possible, as two important components are not addressed (water ingress in joints, water-tree ageing)

New way – comprehensive diagnostics

IR test 5 kV	Overall information on cable integrity ▪ Mandatory test
VLF TD 0.5 U_0 – 1.5 U_0	Address all details regarding the integrity Indicator of humidity presence Stability and TD trending result can deliver detailed information on cable status
VLF PD diagnostics ▪ PDIV ▪ PDEV ▪ PD localisation ▪ PD level ▪ PD concentration ▪ PRPD	PD results are considered in correlation with the TD result. Clear PD localisation graphs PD measurement over time or based on events, consistent recording PRPD for judgement of the type of PD source
Monitored Withstand Test on demand: If the TD result indicates a cable condition that would not be safe for operation, and if the weak spot cannot be identified by PD, a VLF Monitored Withstand Test is applied.	With this approach, any water-tree related degradation will show up as a cable breakdown and it can be repaired (sectional replacement). Joints with water ingress might take a longer period of VLF testing to break down. A MWT test makes it possible to determine the optimum testing duration.
Advantages	**Disadvantages**
+ Coverage of all types of degradation effect + Diagnostic approach can be done based on the diagnostic result + It is possible to understand whether the PD result can deliver a true picture + VLF MWT in the case of very severe cable conditions (Split-MWT)	- TDR pattern recognition has not yet been implemented This approach would help to localise joints with water ingress.

12.11 SA Power Networks, Australia

Underground cable condition and performance rating system

SA Power Networks Australia has been operating VLF cable diagnostics since 2014.
Numerous field tests have been conducted and experience gathered on the evaluation of

- PD online spot-testing
- VLF tan delta
- VLF partial discharge diagnostics

↗ Figure 122: Cable test van, cable fault location including VLF TD PD (Viola TD + PD)

The underground cable condition and performance rating system covers the following parameters and compares all of them to one another:

a) Online partial discharge – spot testing
Collects the information, depending on cable type (XLPE/PILC/mixed)

- PD pattern (strong, moderate, weak)	⇨ Categorisation into 3 categories
- Concentration (Yes – High, No – Low)	o Offline Verification Required
- PD magnitude (dBmV/pC)	o Further Investigation Advised
	o No Action Required

b) Offline cable testing / diagnostics

i. Tan Delta Test – evaluation depending on cable type (XLPE/PILC/mixed) (acc. to IEEE 400.2-2013)

- TD temporal stability	⇨ Recommendation
- Differential TD	o Action Required
- Mean TD	o Further Investigation Advised
	o No Action Required

ii. Partial discharge diagnostics

- Testing voltage ($\leq U_0$ | $> U_0$)	⇨ Recommendation
- Concentration (Yes/No)	o Action Required
- Hit (concentration) (Low < 10, High ≥ 10)	o Further Investigation Advised
- Hit (total) (Low < 10, High ≥ 10)	o No Action Required

PD magnitude: Low (0-500pC) | Medium (500-2,000pC) | High (≥ 2,000pC)

Overall assessment logic

TD Recommendation	PD Recommendation	Final Recommendation
No Action Required	No Action Required	No Action Required
	Further Investigation Advised	No Action Required
	Action Required	Further Investigation Advised
Further Investigation Advised	No Action Required	No Action Required
	Further Investigation Advised	Further Investigation Advised
	Action Required	Repair/Replace Required
Action Required	No Action Required	Further Investigation Advised
	Further Investigation Advised	Repair/Replace Required
	Action Required	Repair/Replace Required

↗ Table 48: Overall evaluation logic – TD recommendation plus PD recommendation = Final recommendation

13. Latest projects of BAUR Diagnostic Services

13.1 Hong Kong Electric

Hong Kong Electric started to implement the idea of Modern Asset Management in 2008. The basic motivation of HK Electric resulted in the common dilemma of ensuring power supply reliability in the city of Hong Kong that has of several thousands of 11kV underground cables.
The cable network consists of old PILC cables that have been installed since 1950, water-tree-prone first generation XLPE, as well as water-tree-retardant XLPE cables from 1986.

22 kV / 11 kV distribution network	HK Electric's 22 kV / 11 kV network comprises cables buried directly underground. The total length of cables is over 3,000 km. The company has adopted the use of XLPE insulation for all its cables since 1980. As a standard, all cables use 300 mm2 copper conductor with corrugated aluminium metal sheath / steel wire armour and PVC/MDPE outer jacket.	Electricity supply network at the 22 kV / 11 kV level is in the form of a closed or an open ring. Any 22 kV / 11 kV substation is normally fed from one source zone substation. An alternative route is always available from another source substation in case of a fault or a cable being taken out of service.

↗ Figure 123: HK Electric company profile 10/2010 [30]

Practical diagnostic experience started to be collected in Hong Kong in 2010. The step was made when HK Electric Asset Management decided to take action on the maintenance of the medium-voltage cable network in order to improve the reliability of the power supply to the city of Hong Kong, the financial centre of Asia.
With the implementation of new technology for the diagnostics of underground cable networks, it became possible to develop a strategy and philosophy for preventive maintenance in the medium-voltage network. Difficulties arose with the interpretation of diagnostic results being the core issue when performing condition based maintenance.

ensuring the flow

HK Electric has purchased numerous portable and test-van based VLF TD / PD test instruments. After conducting the operators' training, a diagnostics team has been setup. Engineers performed cable diagnostics for condition assessment at an extremely high frequency. Since 2010 more than 1,500 cables have been diagnosed.
The key challenge faced by the asset management team was involved analysing the diagnostic results and defining measures. The BAUR team supported the asset management team with numerous training sessions and field investigations. Action plans were worked out on numerous cases and action was taken. The success rate of correctly identified weak cable sections and joints in XLPE, as well as PILC components, was impressively underlined by the dissection and visual inspection of replaced components.

As a result of intensive cooperation, BAUR supported HK Electric in establishing a Cable Testing Philosophy that defines the required action plan for maintenance work in respect to the individual cable condition.

Departmental Technical Manual **11kV & 22kV Distribution Plant**

Part 0 Work Instruction

T&D/WI/HV/52 HIGH VOLTAGE TESTING FOR 11KV AND 22KV CABLE

Note: Major parts of this instruction is revised based on the experience gained on VLF diagnostic testing of 11kV cables since its introduction in early 2010.

Action

1. TESTING PHILOSOPHY

11kV cable system comprises of PILC cables (as early as 1950's), XLPE cables with water tree prone cable sections (WTPCS) and water tree retardant XLPE cables introduced since 1986.

Figure 124: HK Electric Testing Philosophy 2012

The confidence in the professional support provided by BAUR developed and led to consultancy service contracts.

Contract 1:	2010	50	cables
Contract 2:	2011	100	cables
Contract 3:	2012	250	cables
Contract 4:	2013	350	cables
Contract 5:	2014-2017	350	cables/year
Contract 6:	2017-2019	350	cables/year

Beside the diagnostics service provided by BAUR, more than 2,000 cables have been diagnosed by HK Electric engineers. The statistical evaluation of the categorisation data revealed that only 1.5% of the diagnosed cables were judged wrongly or unexpected/unidentified weaknesses lead to cable failures. Therefore, a confidence level of 98.5% underlined the developed Cable Maintenance Philosophy.
The last revision was done in 2017.

Type of Diagnosed "S" Cables	Percentage	Longest Service Period from Date of Last Test
Retested STILL "S" after replaced weak components	20.90%	763
Retested NOT "S" after replaced weak components *	32.80%	681
Prior tested in "H/M/L" conditon but cable went faulty then re-tested "S" after fault	1.50%	522
No replacement carry out after test	44.80%	637

* Weak component in 1 cable not replaced after test but cable failed at the weak component and repaired

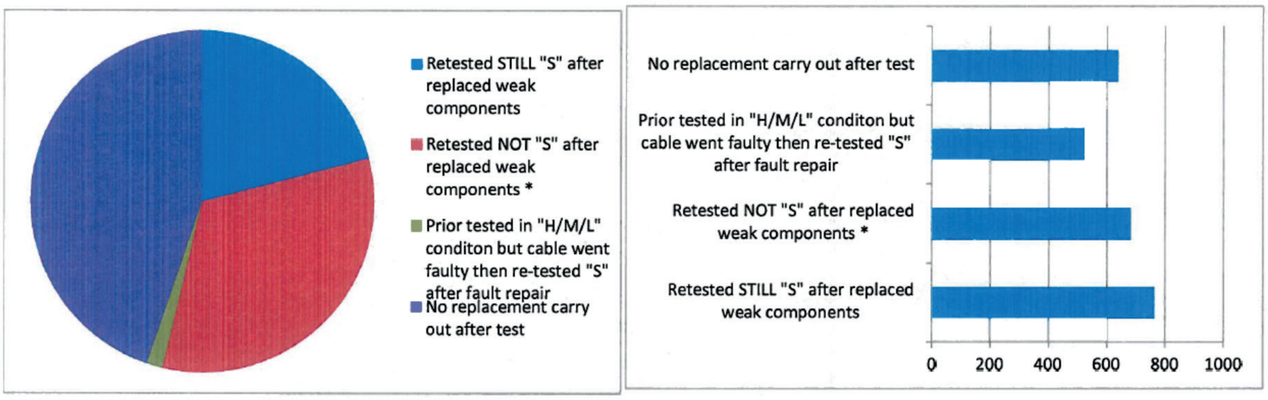


Figure 125: HKE statistical review of cable categorisation

Figure 126: BAUR VLF TD / PD systems used

13.2 KEPCO, Korea

The Korean Electric Power Company (KEPCO) handles all power generation, power transmission and power distribution in the Republic of South Korea. The cooperation between BAUR and KEPCO started in 2005 when the research institute of KEPCO (called KEPRI) started evaluating the right tool for assessing dielectric loss measurement and water tree detection. KEPRI is a well-known research institute. Close cooperation and support has allowed KEPRI to team up with research institutes worldwide. The continuous support and experience of BAUR developed KEPCO's confidence in the VLF diagnostic technology developed by BAUR. In 2010, KEPCO ordered ten cable test vans for VLF testing and diagnostics. In 2012, another five test vans were delivered. With the purchase of the first batch of diagnostic equipment, each KEPCO operational region setup a diagnostics team. An expert diagnostics team was formed at KEPCO headquarters. All regions reported their diagnostic results to the experts at the headquarters. BAUR has been supporting the diagnostics team with numerous visits and user seminars. Three papers have since been published by KEPCO at international conferences, illustrating the experience and professional assessment of the cable condition throughout South Korea. The latest paper mentions that 14,000 cables have been diagnosed and registered in the database.

ABSTRACT:
Recently, diagnostics on medium-voltage cables using a tan δ measurement that measures the dissipation factor with a 0.1 Hz VLF (Very Low Frequency) high-voltage source has emerged as an efficient way to assess water-tree ageing of MV (medium-voltage) cables. This study verified the validity of diagnostic evaluation criteria defined by IEEE 400.2-2013 and its pervious drafts of DTD (delta tan δ) and STDEV (standard deviation) – indicating voltage stability and time stability of tan δ respectively – by applying a tan δ measurement to KEPCO's (Korea Electric Power Corporation) power distribution system and suggesting a new assessment factor being defined as skirt, and a new formula in order to identify the precursor of insulation breakdown with patterns of tan δ. By visualizing complex correlations between various assessment factors and proposing a 3-dimensional assessment standard that can normalize the deterioration condition of a cable into a uniform value, this study has established a foundation to calculate the remaining life time of a cable through VLF tan δ diagnostics.

Index Terms — VLF, tan δ, TD, DTD, STDEV, Skirt, 3-dimensional matrix

↗ Figure 127: Extract from recent paper by KEPCO 2013 [31]

Since then (up to September 2019), KEPCO gone on to engage approximately twenty service providers that perform cable diagnostics for KEPCO. In total, over 31,000 cables have been diagnosed. Based on this huge volume of diagnostic results, further studies on the development of new diagnostic criteria have been in progress. In 2015, KEPCO established a Technical Diagnostics Department that is in charge of the collection and evaluation of numerous diagnostic data.

BAUR is proud of having signed a memorandum of understanding with the KEPCO Technical Diagnostics Department in July 2016. This cooperation shall bring us further in the sharing of experience and development of new solutions for customers worldwide. The new BAUR statex® has been developed out of the close cooperation.

KEPCO's latest development is a tool that enables the automatic evaluation of VLF cable diagnostics data, and calculation of the date of expected failure as well as the remaining life time of a cable circuit.
KEPCO Korea can be considered the country with the highest VLF diagnostics coverage worldwide.

Figure 128: KEPCO Technical Diagnostics Department, remote control for field operators, 3D evaluation of TD data

13.3 Western Power, Australia

BAUR's cooperation with Western Power started in 2007 with the delivery of the first cable diagnostics equipment in Australia. At that time, there was no previous diagnostics experience and support was required. Numerous visits and case study investigations made it possible to combine the experience of European power utilities with local conditions in Australia. Western Power very soon gained confidence in their understanding of successful cable condition assessments and started to setup a new division which now offers cable diagnostics services to other organisations and utilities in Australia. BAUR supported Western Power in continuing the experience sharing on a management basis and started cooperation with a German power utility, publishing a joint paper at the IEEE 2010 International Conference on Condition Monitoring and Diagnosis in Taiwan.

III. CASE STUDY IN WESTERN POWER PERTH AUSTRALIA

A. Strategic Plan

Background
Western Power operates its distribution network in an open ring configuration and the normal arrangement is achieved predominantly by the use of underground 22 kV distribution feeder circuits. The circuits interconnect either with panels in other zone substations or to panels in the same zone substation with a normally open point present.
Two main types of medium-voltage underground cables are utilised to achieve this interconnection:

- PILC normally steel-wire armoured multi-core (in service for more than 50 years with a high level of reliability)
- XLPE single-core cross-linked polyethylene 1 cables installed in trefoil configuration (in service for less than 15 years with questionable reliability in some geographic areas)

The dissipation factor measurement was used to determine the overall integrity of the cable insulation and associated accessories and to give an indication of the in service age2.

Long-term strategy at Western Power
The long term focus has been to ensure that further extended outages do not occur and this has led to the initiation of a strategic project to ultimately improve the reliability of the medium-voltage underground network in general.
An all-encompassing asset management plan for medium-voltage underground cables is currently being developed and includes focuses on the key areas of the business.

Short-term strategic plan
Objectives were developed into short-term and long-term goals and the initial focus was to urgently improve the reliability of the underground network. To achieve an immediate reduction in the number of supply outages, Western Power embarked on a VLF diagnostics programme in order to determine the extent of the cable issues and establish the root cause.

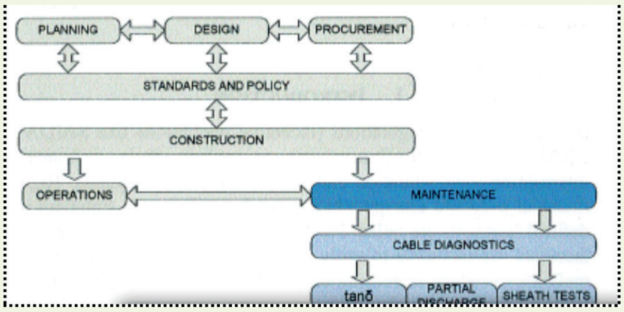


Figure 129: Benefits of a combined diagnostic method CMD 2010 [33]

13.4 Other cooperation projects

- BAUR Germany
  A subsidiary of BAUR Austria, operating as a service provider for cable condition assessment and consultancy for power utilities and private organisations in Germany since 2005. Diagnostic experience of approximately 100 cables per year.

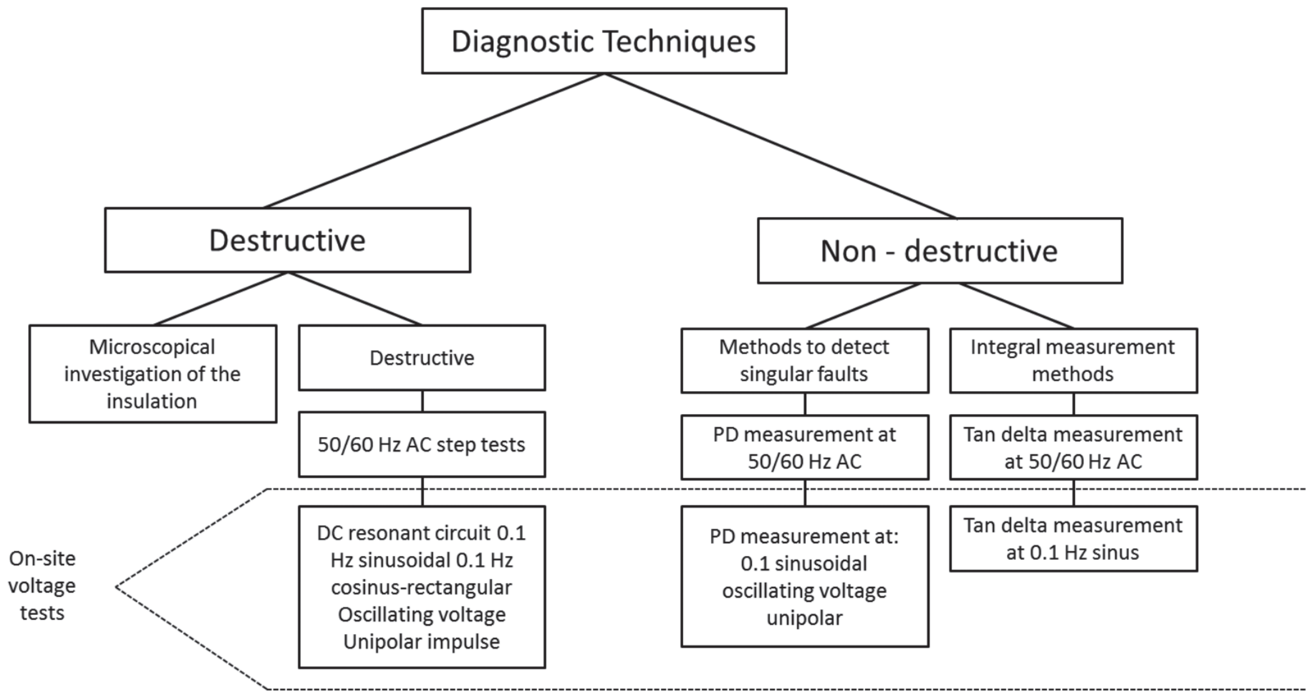
- Gasenzer AG Switzerland
  Gasenzer AG has been operating as a diagnostics service provider for power utilities, all nuclear power plants, airports and other private customers throughout Switzerland since 2004. Up to now, Gasenzer AG is the only trusted partner and service provider for condition assessment of underground cables throughout Switzerland.

13.5 The BAUR diagnostics platform

During recent years, diagnostic experience has been collected throughout the world. The BAUR diagnostics platform is a forum where experts share their experience from all around the world, which allows the exchange of sharing new understandings and findings in order to benefit from the experience collected under all kinds of possible field conditions. BAUR experts are considered to be highly experienced when it comes to competency and flexibility in the analysis of underground cable networks.

14. Other dielectric diagnostic methods – their theory and suitability

Testing procedures are extremely important before putting cable systems into service, to ensure high reliability during permanent operation. Additionally, the users of cable systems are also interested in more detailed information about the ageing stage of the insulation. **Figure 130** shows an overall view of the diagnostic techniques used and explained.



↗ Figure 130: Survey of diagnostic techniques [34]

Polarisation and conduction processes in an insulating material such as XLPE are a direct function of the structure of the material. These processes are also influenced by the ageing, the water-tree deterioration, the moisture content and thickness of the insulation, etc. The dissipation factor measurement on XLPE-insulated medium-voltage cables show that it is possible to evaluate the ageing state.

Furthermore, it may be the case that the return voltage measurement, which is also based on polarisation and conduction processes and which is used in testing oil-paper-insulated transformers, can also characterise the ageing state of polymer-insulated cables. [35]

Both methods shall be explained briefly. A detailed technical description can be found in dedicated papers.

In addition, the application of a frequency swept method applied to cables is also explained.

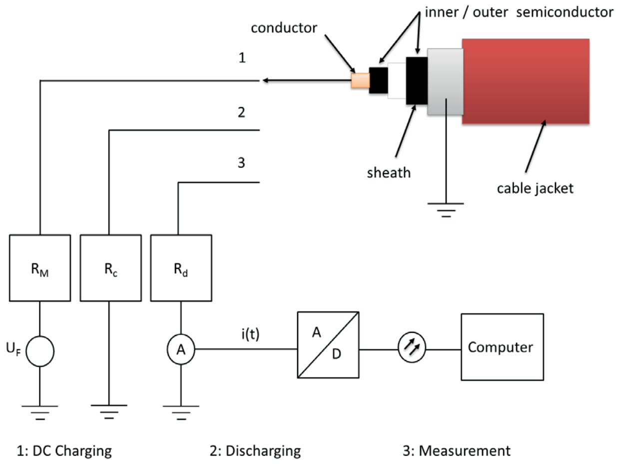
14.1 Cable diagnostics system KDA 1 – IRC Analysis

The cable diagnostics instrument KDA 1 (Seba-Dynatronic) is based on the measurement of the depolarisation current. The cable under test is charged at 1kV DC for 30 minutes. Then the cable is short-circuited for 5 seconds, and the depolarisation currents are measured for the following 30 minutes (**Figure 131**). The measured data are saved and processed with Isothermal Relaxation Current (IRC) analysis. The depolarisation current measured is described as the sum of three experimental functions where parameters aj, τi correlated strongly with the material properties. The time constant τ3 is related to the water tree degradation of the cable insulation.

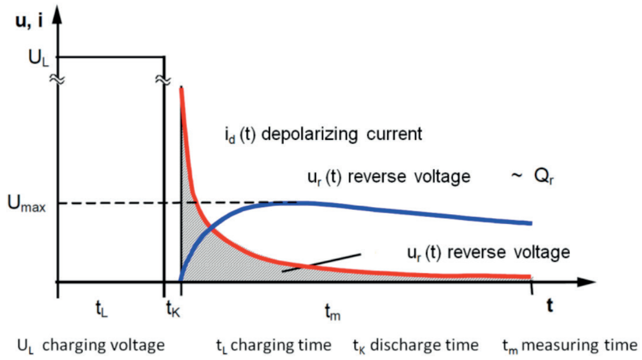
An empirical ageing factor (A-factor) is calculated to classify the ageing condition of the cable. This factor is calculated from the depolarisation current based on time constants.

Suitability of KDA1 for underground cables:

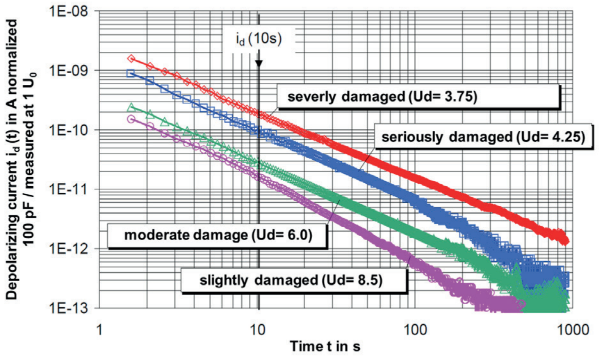
- Studies found that the IRC result is not very conclusive with respect to the details of the result.
- Time-consuming diagnostic method



↗ Figure 131: Basic measurement circuit for the IRC analysis, KDA1



↗ Figure 132: (Fig. 5 of [34]) The principle of selected time-range based diagnostic methods



Depolarisation current normalised on 100 pF for differently water-tree-aged PE/XLPE homopolymeric cables.
Parameter: charging duration 15 min, short-circuit duration 1 sec., measurement duration 15 min, charging voltage 1 U_0

↗ Figure 133: (Fig. 7 of [34]) The depolarisation current of different water-tree damaged PE/VPE cables

14.2 Cable diagnostics system CD30/31- Return Voltage Method

The CD30 cable diagnostics system is used to evaluate the ageing degree and the damage condition of 1 kV to 30 kV PE and XLPE cables. The model CD31 is for oil-paper cables. The device is based upon the measurement of **return voltages** at different charging voltages (**Figure 134**). The tested cable is charged with DC voltages (0.5, 1.0, 1.5, 2.0 U_0) for 5 minutes (switch S1). Then, the high-voltage source is turned off and the switch S2 closed for two seconds to discharge the cable capacitance over a resistor RD. (Hagenuk)

After this time, the return voltage is measured for 10 to 40 minutes, depending on the cable length. To do so, the cable is connected to the high input impedance measurement receiver U (switch S1). The measured value of return voltage is digitised and forwarded to the PC. The maximum values of the return voltages are plotted as a function of the charging voltage. This relationship can be linear or non-linear. The linearity factor is calculated as the ratio between the maximum values of the return voltage at 2 U_0 and U_0 and used as an indicator of the ageing condition. A factor greater than 2 is considered a non-linear response and signifies ageing of the cable and a factor 3 indicates a strongly aged cable. [16]

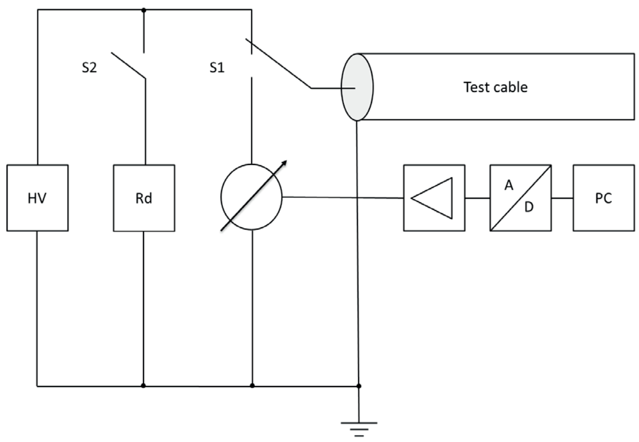
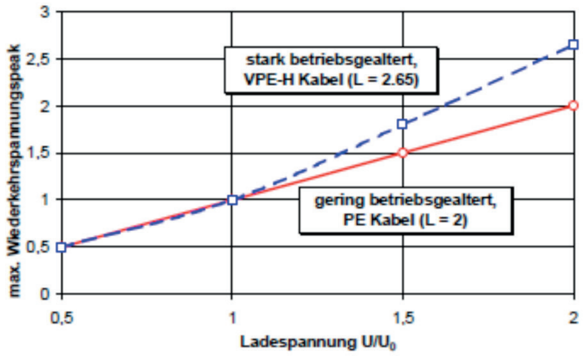


Figure 134: Block diagram of the return voltage method [16]



Peak of return voltage in relation to the charging voltage for differently aged PE/XLPE. (measurement example, tL = 5 min, tK = 2 sec.)

Figure 135: (Fig. 9 of [34]) Return voltage peak for differently aged PE/VPE cables

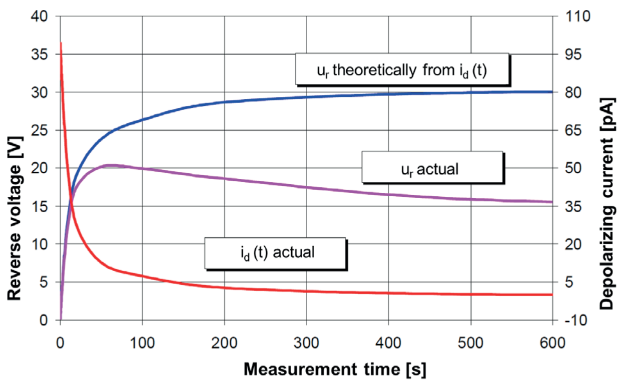
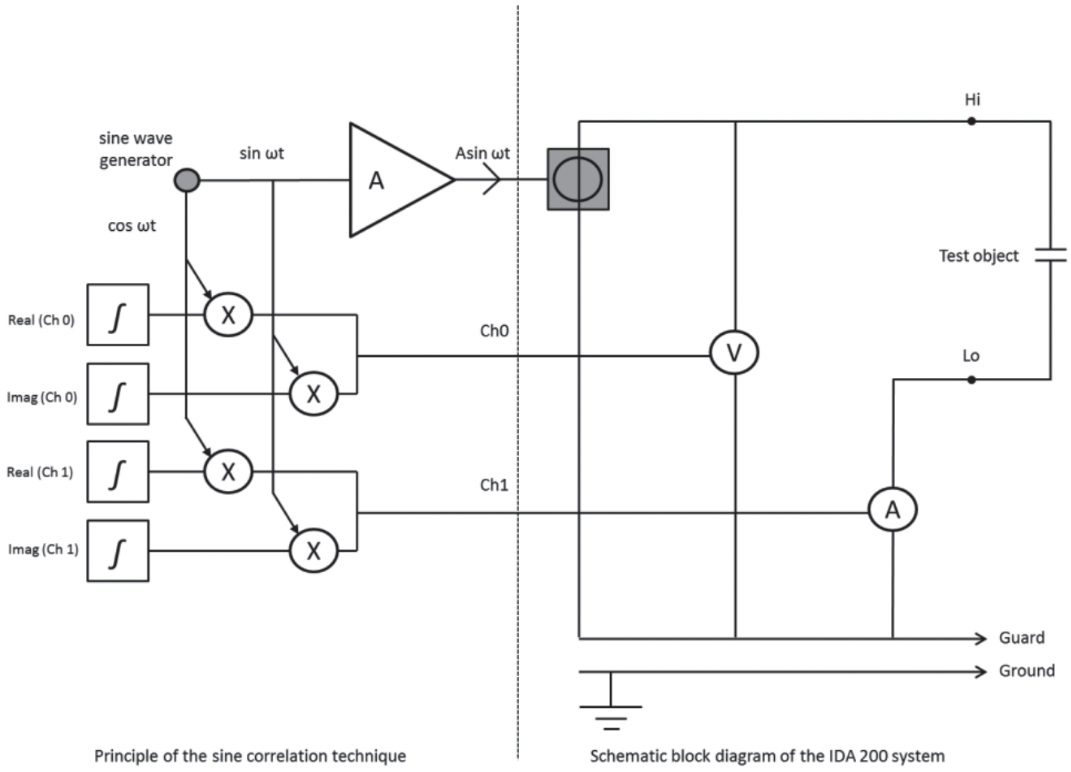


Figure 136: (Fig. 6 of [34]) Comparison between the return voltage calculated from depolarisation current and the practically measured return voltage

14.3 Insulation diagnostics system IDA 200 – Sine Correlation Technique

The IDA 200 insulation diagnostics system is a system that measures the complex impedance of a cable at variable voltage and frequency (capacitance and tan δ at 0.0001-1000 Hz). A digital signal processing unit (DSP) generates a test signal with the desired frequency (**Figure 137**).



↗ Figure 137: (Fig. 10 of [23] Schematic block diagram of the IDA 200 system

The signal is amplified with an internal amplifier and then applied to the cable. The voltage over and the current through the specimen are measured with high accuracy using a voltage divider and an electrometer.
For the measuring input, the IDA 200 uses a DSP unit that multiplies the input (measurement) signal with a reference sine voltage, and then integrates the results over a number of cycles. With this method, noise and interference is rejected, allowing the IDA 200 to work with voltage levels up to 200 V and still achieve high accuracy and detail of analysis. (Programa) [16]

Suitability of IDA 200 for underground cable networks

- Frequency domain spectroscopy in XLPE cables cannot identify water-tree ageing
- Designed for analysing the ageing condition of paper oil insulation
- Determination of dielectric losses over the voltage request for high-voltage source
- Not designed for dielectric response analysis of XLPE cables
- Ageing condition of XLPE and mixed cables request 0.1 Hz VLF source

14.4 50 Hz slope technology / DAC

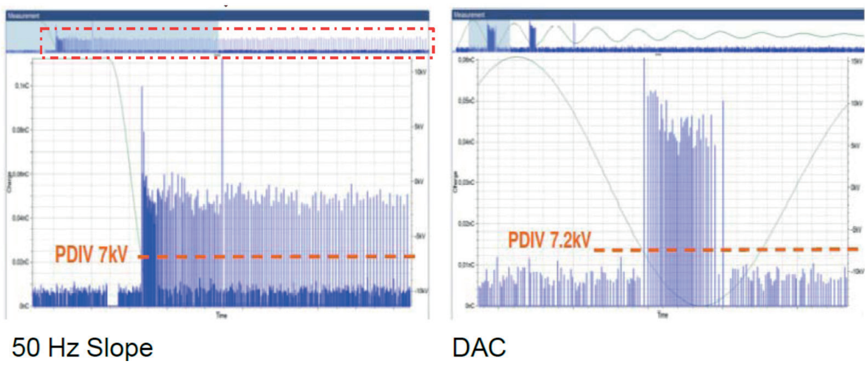
50 Hz slope technology is described as being a partial discharge measurement technology that makes use of the sequence of change of the polarity of a 0.1 Hz cosine-rectangular waveform. It is claimed that this change of polarity slope is similar to the slope of a 50 Hz power cycle.
The characteristic is further described as being very similar to a DAC PD measurement cycle.

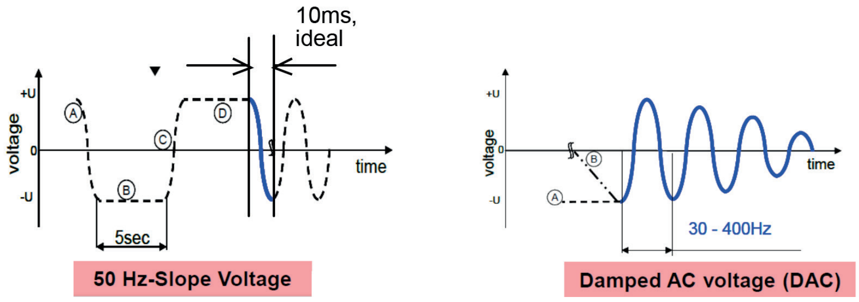
In theory, the change of polarity of a 50 Hz cycle from U P+ to U P- happens within 10 ms. A 50 Hz slope therefore requests to be close to a dU/dt that happens within 10 ms.
In practical application, this slope depends on the capacity of the cable. A power source is never able to change a cable with approx. 300 nF (e.g. 1 km MV cable) from + 36 kV to -36 kV within 10 ms.
(Example: 22 kV, U_0 = 12.7 kVrms, 2 U_0 = 25.4 kVrms sinewave ; 36 kV CR)

Practical tests show that the cycle's duration is in the range of approximately 1 second.

Claims have been made that the VLF 0.1 Hz PD diagnostics based on sinusoidal waveform does not represent the characteristic of 50 Hz voltage.

These claims are wrong. Please refer to chapter 8.6.2.





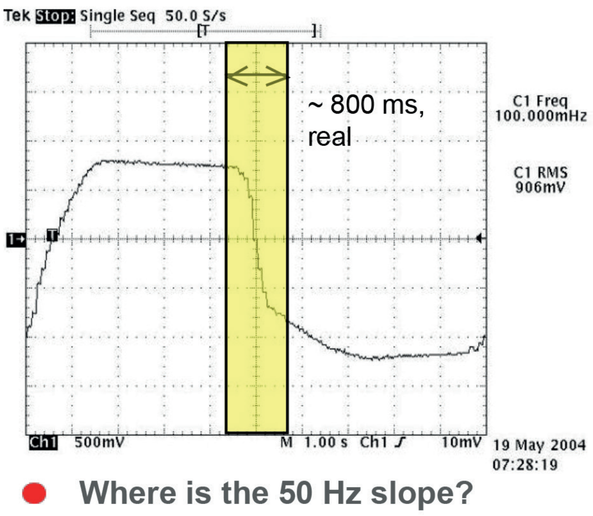
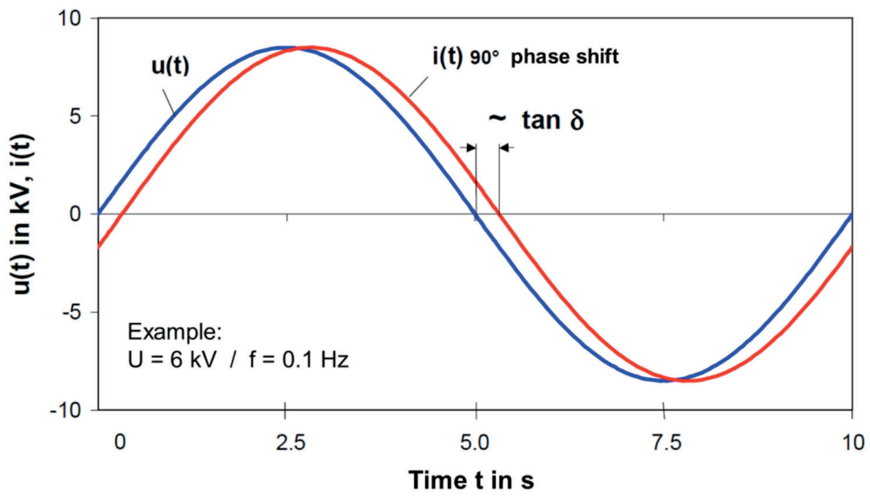


Figure 138: Actual oscilloscope diagram of CR slope; dU/dt in approx. 1 second

14.5 PHG TD cable testing and diagnostics system

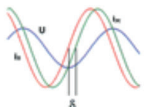
The PHG TD instrument measures tan δ at different sine voltage levels maintained at 0.1 Hz. The tan δ at 2 U_0 and the difference between 2 U_0 and U_0 values are used as diagnostic criteria. A tan δ value larger than 1.2 E-3 at 2 U_0 or the difference of tan δ at 2 U_0 and U_0 larger than 0.6 E-3 signifies water tree deterioration. (Baur)



↗ Figure 139: Tan delta measurement illustration [16]

ensuring the flow

15. Report example for combined TD/PD diagnostics



BAUR VLF Testing and Diagnosis Report
Combined TanDelta & Partial Discharge Diagnosis

Report No. H1011025

HEC ref:	EHT 423
Date of test:	27/10/2011
Weather:	Fine
Humidity:	60%
Requested by:	Power utility
Cable location:	**From point:** Zone substation 1, Sw. #1 **To point:** Substation 7, Sw. #3
Cable type:	XLPE
Near end (from):	Zone Substation 1, Sw. #1
Far end (to):	Substation 7, Sw. #3
Pulse velocity (m/µs):	88.0
Cable length:	1,183 m
Nominal voltage:	11 kV
Number of phases:	3
Soil condition:	n.a.
Joint positions:	18 joints
Test site:	Zone Substation 1, Sw. #1

BAUR VLF Testing and Diagnosis Report
Combined TanDelta & Partial Discharge Diagnosis

Rated Voltage	Material Code	Size	Length(m)
11	AX	300sqmm	651
11	CX	300sqmm	465
11	CXS	300sqmm	67

Jnt	MAKE	DATE	WEATHER	LUG	ENGINEER	JOINTER	SWITCH	REMARKS	MAP	CO-ORDINATE	SKETCH NO
X	RAYR	08-JUN-1995	FINE		5542		1		11SW15B2	837263.657,815545.966	0600/1995
1	RAYR	08-JUN-1995	FINE		5542	J 713			11SW15B2	837270.382,815521.578	0600/1995
						J1393					
2	RAYR	08-JUN-1995	FINE		5542	J 713			11SW15B2	837297.962,815550.756	0600/1995
						J1297					
						J1393					
3	RAYR	24-MAR-1993	UNKNOWN		4392	J 839			11SW15B2	837337.785,815556.677	290/1994
4	RAYW	01-SEP-2006	CLOUDY		4388	S5079			11SW15B2	837360.844,815579.569	2270/2006
						S5006					
5	RAYW	01-SEP-2006	CLOUDY		4388	S4995			11SW15B2	837363.599,815582.470	2270/2006
						S6158					
6	RAYW	03-SEP-2000	CLOUDY		4238	J5001			11SW15B2	837405.580,815559.358	2265/2000
						J5686					
7	RAYW	20-AUG-2003	FINE		4243	S5637			11SW15B2	837408.714,815556.776	1928/2003
8	RAYW	14-AUG-2003	RAIN		5963	W1299			11SW15B2	837441.388,815546.672	2147/2003
9	RAYW	20-AUG-2003	FINE		4243	S6297			11SW15B2	837497.537,815533.381	1928/2003
10	RAYR	09-DEC-1994	UNKNOWN		4228	J1250			11SE11A1	837527.192,815537.379	0516/1995
						J 934					
11	RAYW	21-JUL-2005	RAIN		2994	S5686			11SE11A1	837610.954,815517.753	2168/2005
						S5191					
12	RAYW	21-JUL-2005	RAIN		2994	S5004			11SE11A1	837614.570,815516.965	2168/2005
						S5014					
13	RAYR	09-DEC-1994	UNKNOWN		4228	J1250			11SE11A1	837628.291,815510.023	0516/1995
						J 934					
14	RAYW	21-JAN-2002	FINE		5542	S6297			11SE11A1	837778.936,815424.549	0716/2002
15	RAYW	18-JUL-2000	RAIN		5542	S5446			11SE11A1	837739.534,815468.068	2210/2000
						S5047					

Jnt	MAKE	DATE	WEATHER	LUG	ENGINEER	JOINTER	SWITCH	REMARKS	MAP	CO-ORDINATE	SKETCH NO
16	RAYW	26-MAR-2003	FINE		5850	W1297			11SE11A1	837714.288,815530.492	0712/2003
17	RAYW	25-FEB-2003	FINE		5850	W 407			11SE11A1	837735.084,815545.155	0712/2003
18	RAYW	07-JAN-2003	FINE		5850	W 407			11SE11A1	837727.767,815559.969	0712/2003
Y	RAYR	26-FEB-2003	FINE		5850	W1239	31		11SE11A1	837700.071,815569.544	0712/2003

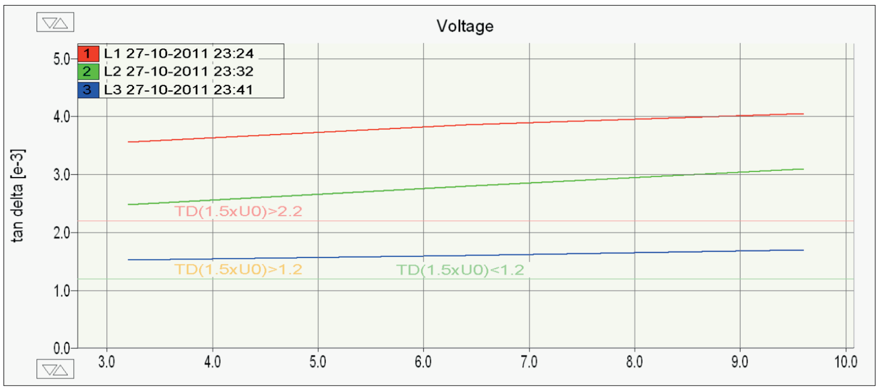
```
X  0                  1                  2                  3                  4                  5                  6                  7                  8
                                                                            Z  Z               A  A                                 Z  Z               Z
R- |      48        | - |      70        | - |      58        | - |      37        |1-3|      4         |3-2|      80        |3- |      3         |1-3|      67        |3-
Y- |----------------| - |----------------| - |----------------| - |----------------|2-1|----------------|1-1|----------------|1- |----------------|2-2|----------------|2-
B- |  300 SQMM AX   | - |  300 SQMM AX   | - |  300 SQMM AX   | - |  300 SQMM AX   |3-2|  300 SQMM CX   |2-3|  300 SQMM AX   |2- |  300 SQMM CX   |3-1|  300 SQMM CXS  |1-
      JUN-1995             OCT-1993             MAR-1993             MAR-1993          01-SEP-2006             MAR-1993          03-SEP-2000          10-JUL-2003
      BICC    0            BICC    0            BICC    0            BICC    0          PIRE2004               BICC    0          BICC2000             PIRE2003

8                  9                  10                 11                 12                 13                 14                 15                 16
Z                  Z  A                                  Z  A               Z  Z                                  Z  A               A  A               Z
3|      66        |3-2|      47        | - |      97        |2-1|      4         |1-2|      22        | - |      192       |1-1|      113       |1-2|      115       |2-
2|----------------|2-1|----------------| - |----------------|1-3|----------------|3-3|-------FW-------| - |----------------|2-2|----------------|2-1|----------------|3-
1|  300 SQMM CX   |1-3|  300 SQMM AX   | - |  300 SQMM AX   |3-2|  300 SQMM CX   |2-1|  300 SQMM AX   | - |  300 SQMM AX   |3-3|  300 SQMM CX   |3-3|  300 SQMM CX   |1-
   01-AUG-2003           DEC-1994             DEC-1994          21-JUL-2005            DEC-1994             DEC-1994          16-JUN-2000          28-APR-2000
     PIRE2003            BICC    0            BICC    0           PIRE2004             BICC    0            BICC    0          BICC1999             BICC1999

16                 17                 18                 Y
A                  Z  A               Z  Z               A
1|      35        |1-1|      39        |1-2|      86        |2-R
2|----------------|2-2|----------------|2-1|----------------|1-Y
3|  300 SQMM CX   |3-3|  300 SQMM CX   |3-3|  300 SQMM CX   |3-B
   18-FEB-2003          20-DEC-2002          01-AUG-2002
     PIRE2002             PIRE2002             TAIH2002
```

Note: FW - Free Water Ingress; WT - Water Tree.
%RPT-I-NORMAL, normal completion - end of report

BAUR VLF Testing and Diagnosis Report
Combined TanDelta & Partial Discharge Diagnosis

TD & PD measurement on 27 October 2011

TD result recorded on 27 October 2011:



TD analysis was obtained on 27 October 2011:

Results were obtained for L1, L2 and L3. Based on the 1.5 U_0 XLPE cable evaluation, the results show that L2 and L3 were above the limit (high operating risk) and L1 has a highly service-aged condition. The same characteristics can be observed for all cables. The average TD values increase as the voltage steps up. The TD standard deviations of L1, L2 and L3 indicate a rather good condition (< 0.01 E-3). The slightly fluctuating stability trend could indicate the presence of low humidity in L1, L2 and L3 (terminations). The delta TD values in L1, L2 and L3 indicate a good cable condition (< 0.6 x E-3). The potential water tree indication (increasing delta TD) could be visible due to the cable length.

Table of average tan delta values (E-3):

Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L1	3.560	3.859	4.046
L2	2.476	2.803	3.094
L3	1.526	1.605	1.700

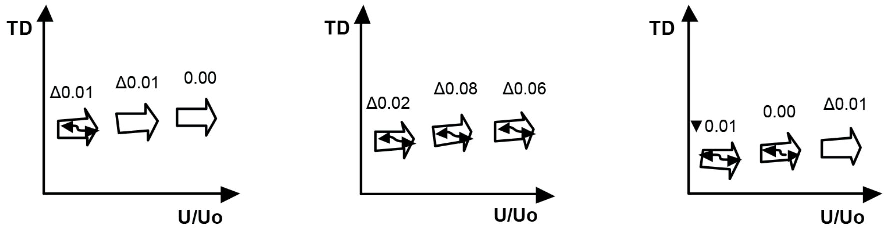
Table of standard deviations:

Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L1	0.005	0.004	0.006
L2	0.023	0.024	0.024
L3	0.003	0.003	0.004

Summary:

Phase	Step	Voltage kV	Avg. value tan delta [e^{-3}]	Std. dev. [e^{-3}]	No.	Load
L1	1	3.2	3,560	0.005	8	484.8
L1	2	6.4	3,859	0.004	8	482.8
L1	3	9.6	4,046	0.006	8	480.9
L2	1	3.2	2,476	0.023	8	482.4
L2	2	6.4	2,803	0.024	8	480.4
L2	3	9.6	3,094	0.024	8	478.4
L3	1	3.2	1,526	0.003	8	484.5
L3	2	6.4	1,605	0.003	8	482.4
L3	3	9.6	1,700	0.004	8	480.5

TD stability trend:

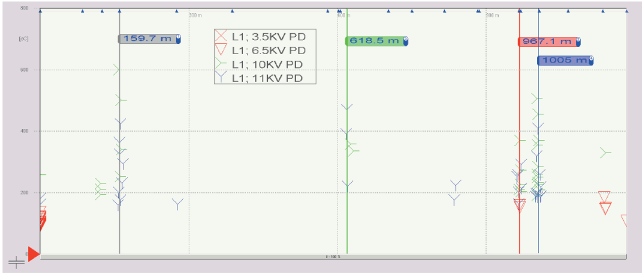


BAUR VLF Testing and Diagnosis Report
Combined TanDelta & Partial Discharge Diagnosis

PD result recorded on 27 October 2011:

PD activity in L1:

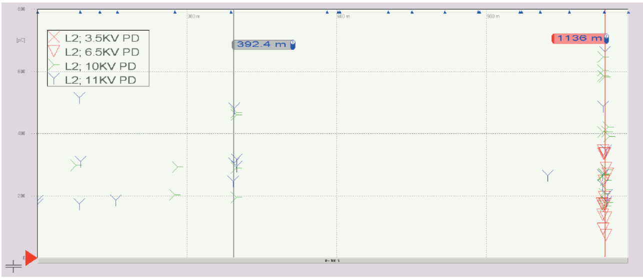
- Concentrated PD (up to ~150 pC) at the near end, with PDIV starting at 1.0 U_0.
- Concentrated PD (up to ~300 pC) at the location of the joint **160 m** away from the near end with PDIV starting at 1.5 U_0.
- Concentrated PD (up to ~400 pC) at the location of the joint **619 m** away from the near end with PDIV starting at 1.5 U_0.
- Concentrated PD (up to ~300 pC) at the location of the joint **967 m** away from the near end with PDIV starting at 1.0 U_0. (Close joints)
- Concentrated PD (up to ~300 pC) at the location of the joint 1,005 m away from the near end with PDIV starting at 1.5 U_0.



Descriptions
1 L1; truesinus®; 0.1 Hz; 28.10.2011 00:14:21; 3.5KV PD
2 L1; truesinus®; 0.1 Hz; 28.10.2011 00:18:04; 6.5KV PD
3 L1; truesinus®; 0.1 Hz; 28.10.2011 00:22:15; 10KV PD
4 L1; truesinus®; 0.1 Hz; 28.10.2011 00:23:54; 11KV PD

PD activity in L2:

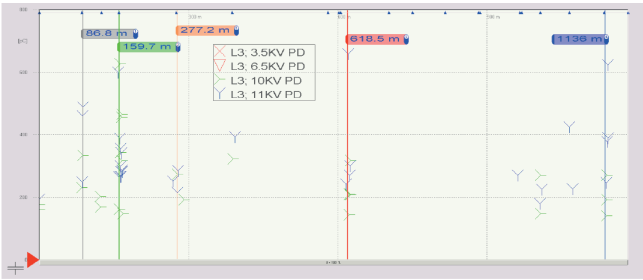
- Concentrated PD (up to ~300 pC) at the location of the joint **392 m** away from the near end with PDIV starting at 1.5 U_0.
- Concentrated PD (up to ~400 pC) at the location of the joint **1,136 m** away from the near end with PDIV starting at 1.0 U_0.



Descriptions
1 L2; truesinus®; 0.1 Hz; 28.10.2011 00:40:40; 3.5KV PD
2 L2; truesinus®; 0.1 Hz; 28.10.2011 00:43:16; 6.5KV PD
3 L2; truesinus®; 0.1 Hz; 28.10.2011 00:45:22; 10KV PD
4 L2; truesinus®; 0.1 Hz; 28.10.2011 00:46:35; 11KV PD

PD activity in L3:

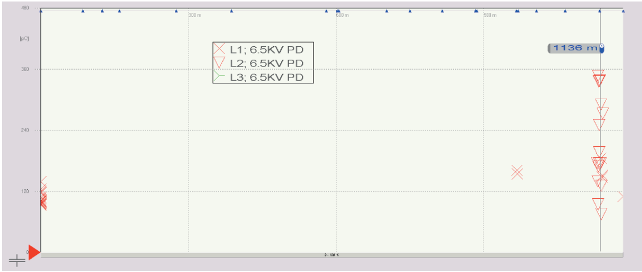
- Concentrated PD (up to ~300 pC) at the location of the joint **87 m** away from the near end with PDIV starting at 1.5 U_0.
- Concentrated PD (up to ~400 pC) at the location of the joint **160 m** away from the near end with PDIV starting at 1.5 U_0.
- Concentrated PD (up to ~300 pC) at the location of the joint **277 m** away from the near end with PDIV starting at 1.5 U_0.
- Concentrated PD (up to ~300 pC) at the location of the joint **619 m** away from the near end with PDIV starting at 1.5 U_0.
- Concentrated PD (up to ~300 pC) at the location of **1.136 m** joint away from the near end with PDIV starting at 1.5 U_0.



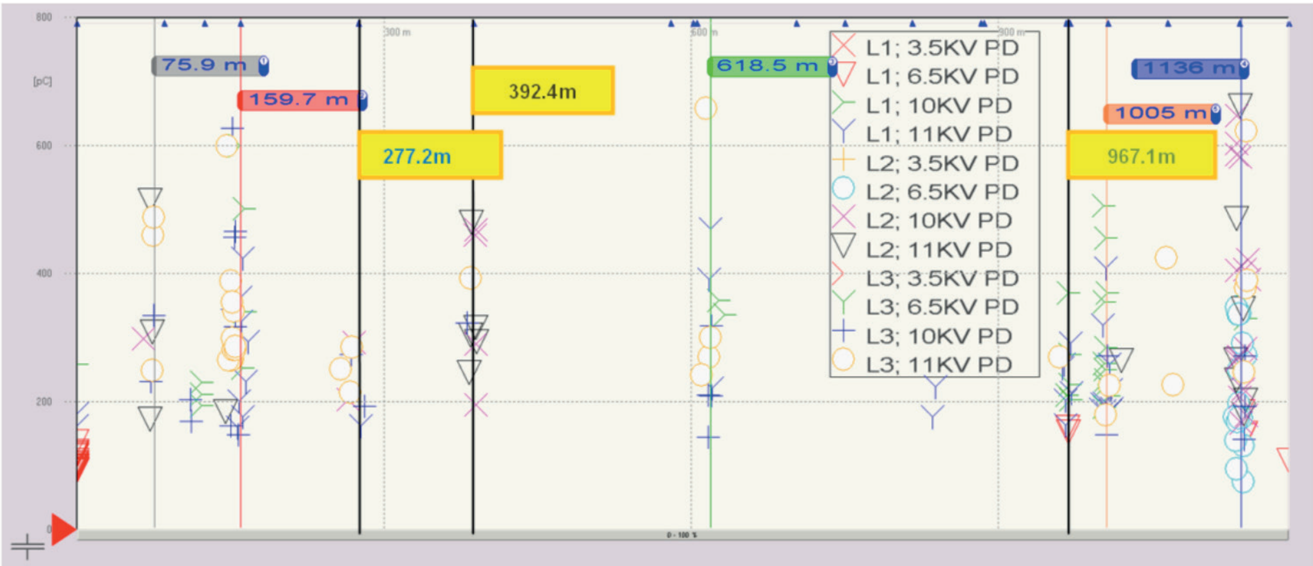
Descriptions
1 L3; truesinus®; 0.1 Hz; 28.10.2011 00:49:28; 3.5KV PD
2 L3; truesinus®; 0.1 Hz; 28.10.2011 00:53:08; 6.5KV PD
3 L3; truesinus®; 0.1 Hz; 28.10.2011 00:54:24; 10KV PD
4 L3; truesinus®; 0.1 Hz; 28.10.2011 00:55:13; 11KV PD

PD activity in daily operation, 1.0 U_0:

- Concentrated PD (up to ~120 pC) at, the near end, Moreton Terrace Z/S, in L1.
- Concentrated PD (up to ~240 pC) at the location of the joint **1,136 m** away from the near end in L1 & L2.



Descriptions
1 L1; truesinus®; 0.1 Hz; 28.10.2011 00:18:04; 6.5KV PD
2 L2; truesinus®; 0.1 Hz; 28.10.2011 00:43:16; 6.5KV PD
3 L3; truesinus®; 0.1 Hz; 28.10.2011 00:53:08; 6.5KV PD



PD summary for L1, L2 and L3:

In summary, concentrated PD at the joints 160 m and 1,005 m away from the near end with the PDIV at 1.5 U_0 (10 kV) was up to approx. 300 pC in L1. Concentrated PD also occurred at the joint 619 m away from the near end with the PDIV at 1.5 U_0 (10 kV), at up to approx. 400 pC in L1. Concentrated PD also occurred at the joint (close joint) 967 m away from the near end with the PDIV at 1.0 U_0 (6.5 kV), at up to approx. 300 pC in L1.
Concentrated PD occurred at the joint 392 m away from the near end with the PDIV at 1.5 U_0 (10 kV), at up to approx. 300 pC in L2. Concentrated PD also occurred at the joint 1,136 m away from the near end with the PDIV at 1.0 U_0 (6.5 kV), at up to approx. 400 pC in L2.
Concentrated PD occurred at the joints 87 m, 277 m, 619 m and 1,136 m away from the near end with the PDIV at 1.5 U_0 (10 kV), at up to approx. 300 pC in L3. Concentrated PD also occurred at the joint 160 m away from the near end with the PDIV at 1.5 U_0 (10 kV), at up to approx. 400 pC in L3.
Concentrated PD (up to ~150 pC) at the near end was also noted when recording L1 with the PDIV at 1.0 U_0.

BAUR VLF Testing and Diagnosis Report
Combined TanDelta & Partial Discharge Diagnosis

Required action and conclusion

PD evaluation:
In conclusion, the PD level of ~120 pC @ 1.0 U_0 at the near end in L1 has no affect during normal operation on XLPE cables. A normal joint with a PD level of ~240 pC @ 1.0 U_0 at 1,136 m away from the near end in L1 and L2 also has no affect during normal operation. PD activity in general does not affect the TD results.

TD evaluation:
TD results show that L2 and L3 have a high operating risk according to the 1.5 U_0 XLPE cable evaluation, whereas L1 is in a highly service-aged condition. The TD standard deviation of L1, L2 and L3 are in rather good condition. The slightly fluctuating stability trend could indicate the presence of low humidity in L1, L2 and L3 (terminations).
According to the generally highly aged condition, retesting all three phases after several months or performing a VLF test to recognise certain highly aged locations is recommended

13.01.2012
TN/GIC

ensuring the flow

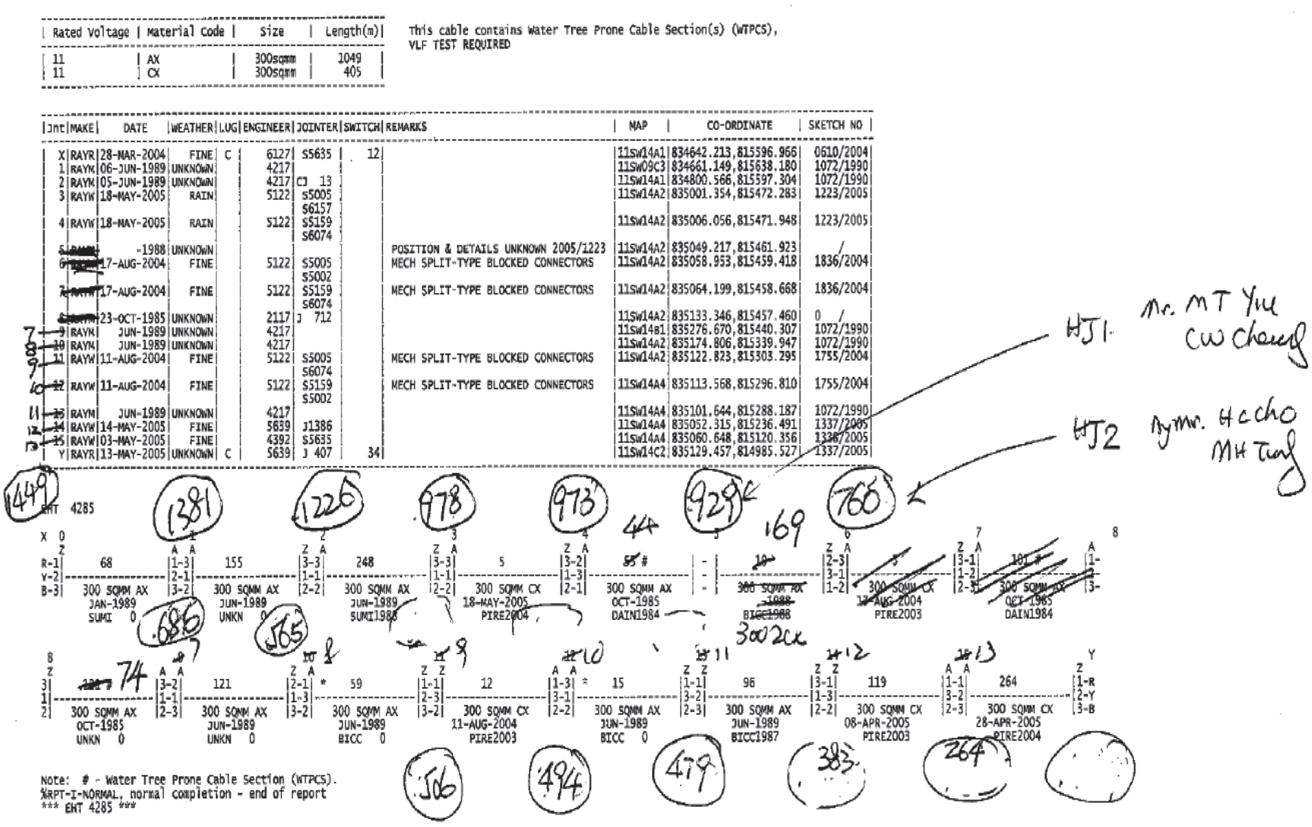
16. Case study on combined diagnostics

Case Study H 4 – 4285

Key points:
- 1,449 m, 11 kV, XLPE cable with WTPCS, 13 joints
- Water-tree ageing in water-tree-prone cable section
- Replacement of WTPCS shows improvement in TD value
- TD results by sectioning the cable (high TD in WTPC, 2nd section)
- Water ingress in joint Jt. 1 (High std. dev.), no PD
- Water tree development in joint Jt. 1 area
- Dissection shows water tree and electrical tree

HEC ref:	H4 – 4285
Date of test:	13.07.2011
Weather:	Fine
Humidity:	45%
Requested by:	Electricity Company Hong Kong
Cable location:	Hong Kong Island
Cable type:	XLPE
Near end (from):	East Road Zone Substation, Sw. #1
Far end (to):	Bank Building 1, Sw. #12
Pulse velocity (m/µs)	80.6
Cable length:	1,449 m
Nominal voltage:	11 kV
Year of manufacture:	1985 (WTPC), 1989 (WTPC), 2004, 2005
Number of phases:	3 core
Soil condition	n.a.
Joint positions	13 joints
Test site:	East Road Zone Substation, Sw. #1
Tests performed: VLF TD … BAUR Frida TD VLF PD … BAUR Frida TD + PD portable	

16.1.1 Cable layout/structure



Overview:

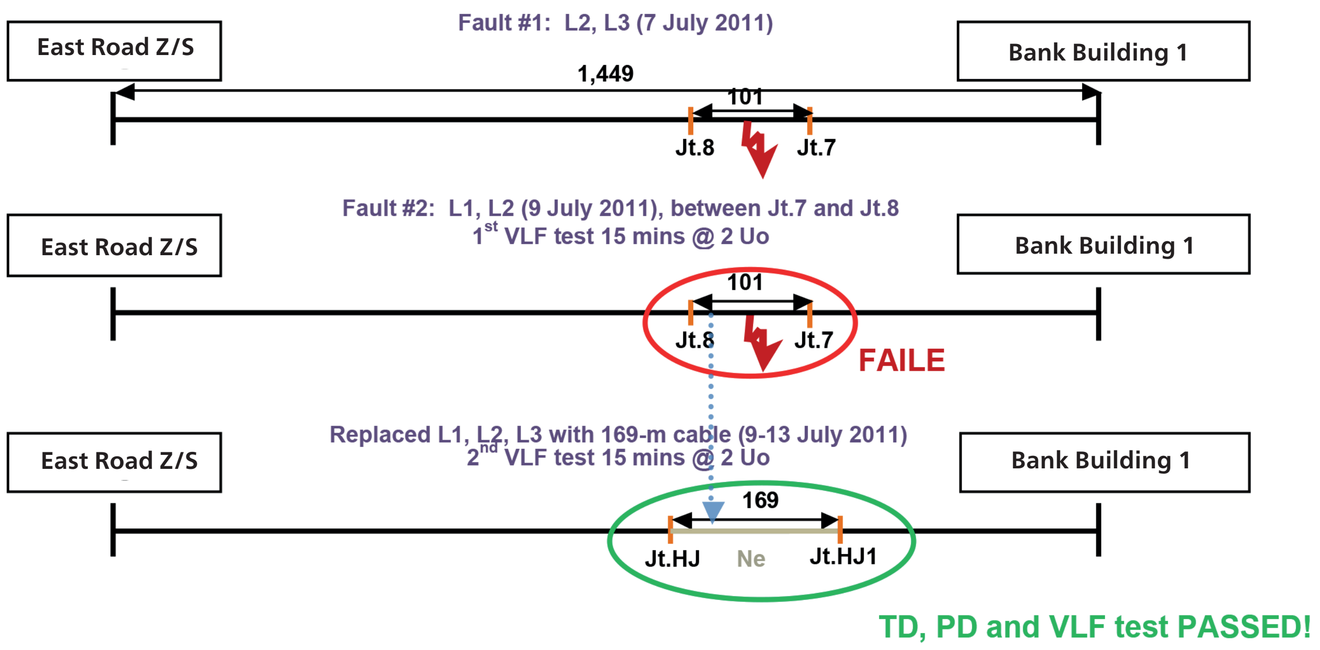
The cable in between East Road Zone substation and Bank Building 1 had tripped. It was necessary to find the root cause of this problem by using VLF testing and diagnostics equipment. TD and PD measurements were performed and high TD values were recorded. The suspected sections were replaced by the new cable. However, one joint failed unexpectedly after two weeks. After the investigation, it was found that this joint was located in the WTPCS and this has caused the joint to fail.

16.1.2 History

On 7 July 2011, the cable in between East Road Zone substation and Bank Building 1 tripped and a cable fault was found in the cable body (XLPE insulation) of L2 and L3. The fault between Jt.7 and Jt.8 was repaired immediately.

On 9 July 2011, a 15-minute VLF test was performed with 2.0 U_0 and L1 and L2 failed the test. The second fault was located in the same section (between Jt.7 and Jt.8).
The fault area was investigated in detail. The section was considered to be a water-tree-prone cable section (WTPCS). Serious corrosion on the cable sheath and some signs of water ingress were observed. Therefore, it was decided to replace a 169-m cable from joint HJ#1 to joint HJ#2, which also covered Jt.7 and Jt.8.

On 13 July 2011, a 15-minute VLF test was performed at 2 U_0 and all 3 phases passed the TD, PD and VLF test.



16.1.3 TD & PD measurement results

TD result recorded on 9 July 2011

- **After Fault #1 repair**
- **Before VLF test**

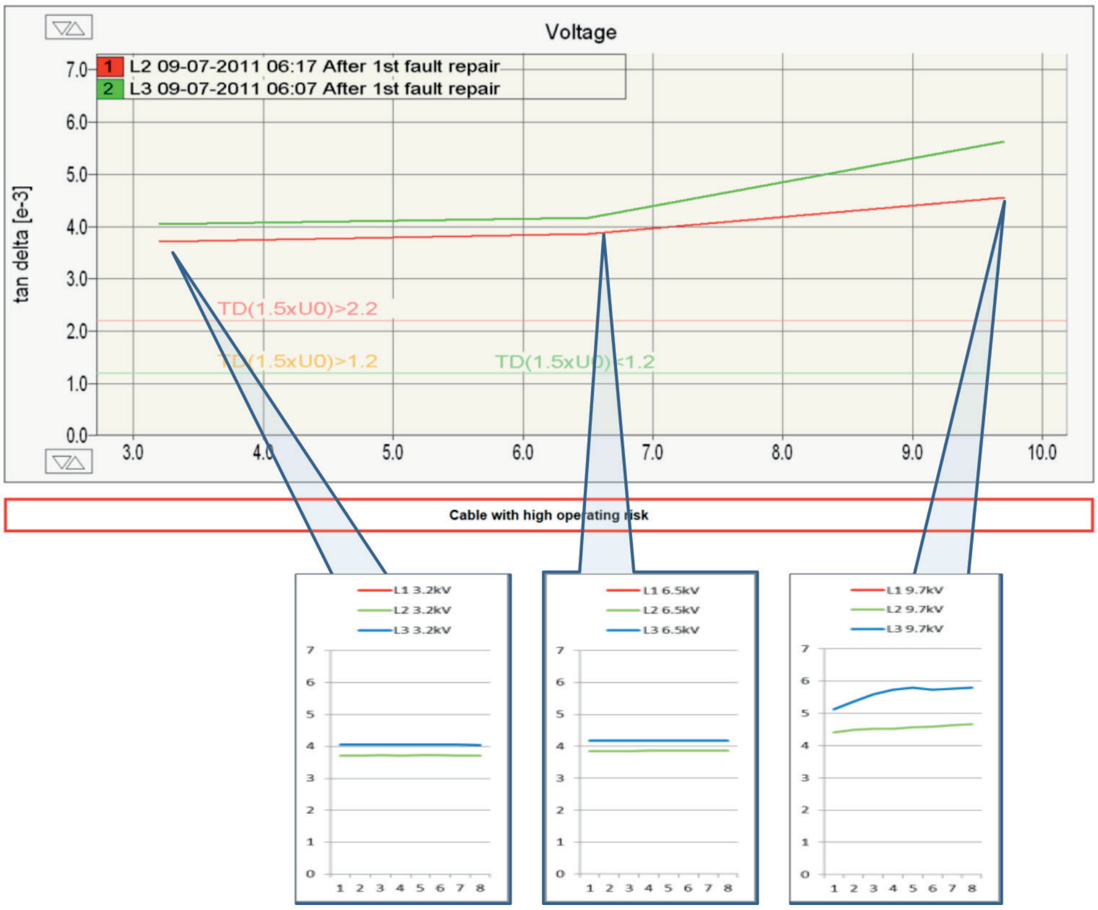


Table of average tan delta value MTD:

Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L2	3.713	3.855	4.550
L3	4.052	4.174	5.620

Table of standard deviations:

Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L2	0.003	0.006	0.076
L3	0.005	0.003	0.225

Summary:

Phase	Step	Voltage kV	Avg. value tan delta [e-3]	Std. dev. [e-3]	No.	Load
L2	1	3.2	3.713	0.003	8	655.5
L2	2	6.5	3.855	0.006	8	656.1
L2	3	9.7	4.550	0.076	8	649.4
L3	1	3.2	4.052	0.005	8	658.1
L3	2	6.5	4.174	0.003	8	658.7
L3	3	9.7	5.620	0.225	8	652.0

- No PD measurement was carried out.
- VLF test @ 2 U_0 was carried out for 15 minutes before putting into service.
- **L1 and L2 failed**, -> 169-m cable replaced on 9-13 July 2011

TD result interpretation:

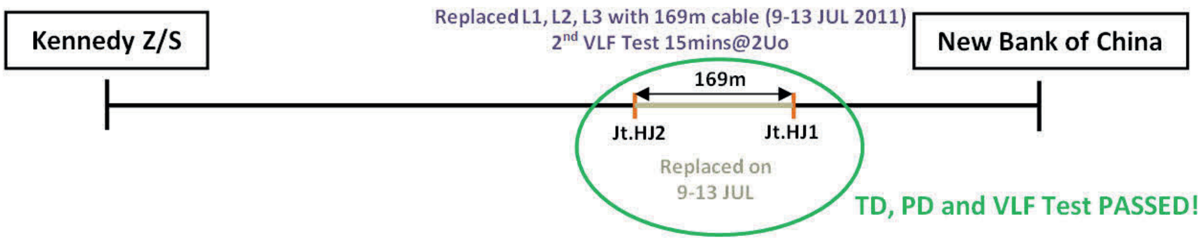
Overall cable condition … high operating risk

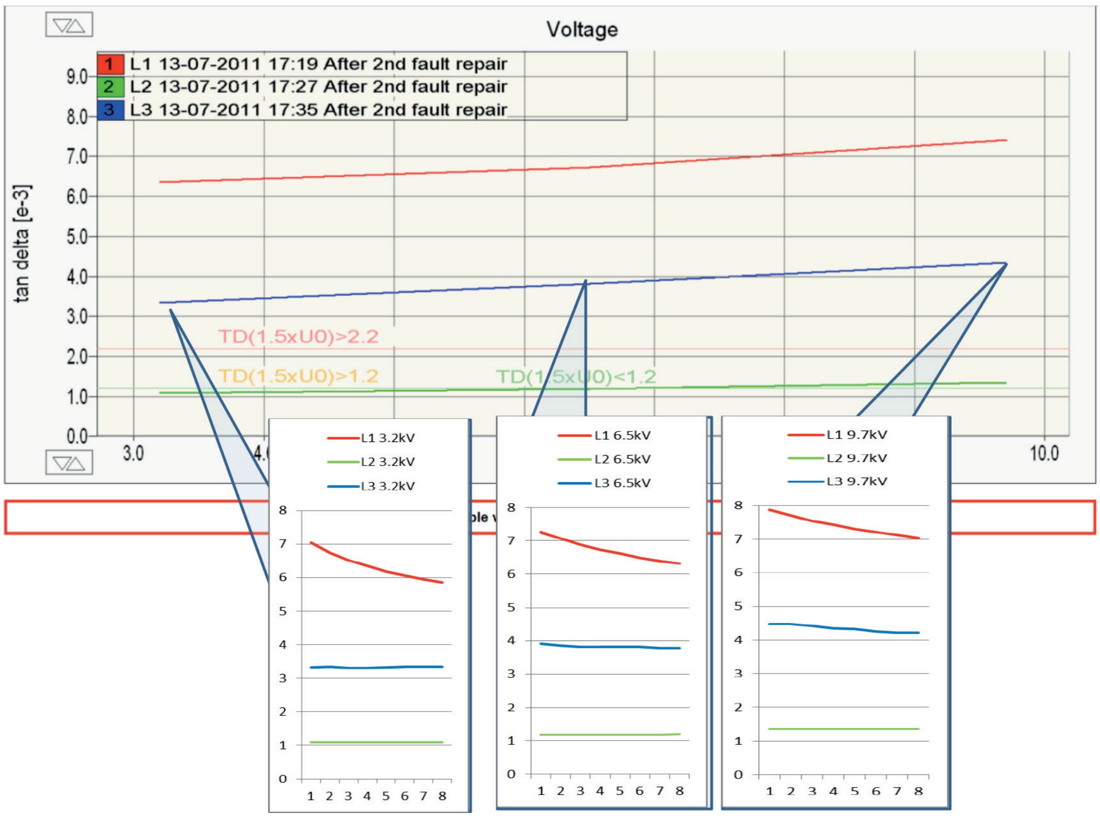
Absolute TD values	TD of L2, L3	High values … high operating risk
TD standard deviation	STD L2, L3	Increased values at 1.5 U_0 … rather unstable conditions
DTD (Delta TD)	DTD of L2, L3	Increasing TD over the voltage … indication of water-tree ageing
TD trend analysis	L2 and L3	Rather stable trend condition at 0.5 U_0 and 1.0 U_0, slight **increasing** **Trend behaviour at 1.5 U_0 … indication of water-tree ageing**

- **VLF test was expected to fail**
- **TD of L1 was not observed as only L2 and L3 failed on 7 July 2011**

16.1.4 TD result recorded on 13 July 2011

- **After Fault #2 repair**
- **Section replacement**





The results of L1, L2 and L3 were obtained after the replacement of the cable section on 13 July 2011. L1 indicated very high TD values (not recorded on 9 July 2011). L2 improved significantly, the TD value @ 1.5 U_0 dropped from 4.5 x E-3 to 1.3 x E-3. L3 improved slightly, the TD value @ 1.5 U_0 dropped from 5.6 x E-3 to 4.3 x E-3.
Average TD values of L1 and L3 still indicate a high operating risk. The delta TD value of L1 is approx. 1.1 x E-3 which represents a 'highly service-aged condition'. The delta TD value in L2 is approx. 0.3 x E-3 which represents a 'good condition'. The delta TD value in L3 is approx. 1.0 x E-3 which represents a 'highly service-aged condition'; it is therefore necessary to investigate the cables in further detail. The TD standard deviation of L1 and L3 indicates water ingress in at least one of the joints. The decreasing TD stability trend of L1 and L3 is a further indication of humidity or that moisture is present.

Table of average tan delta values:

Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L1	6.352	6.727	7.405
L2	1.087	1.185	1.354
L3	3.340	3.824	4.342

Table of standard deviations:

Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L1	0.385	0.310	0.271
L2	0.001	0.006	0.003
L3	0.013	0.035	0.099

Summary:

Phase	Step	Voltage kV	Avg. value tan delta [e^{-3}]	Std. dev. [e^{-3}]	No.	Load
L1	1	3.2	6.352	0.385	8	636.2
L1	2	6.5	6.727	0.310	8	636.8
L1	3	9.7	7.405	0.271	8	630.1
L2	1	3.2	1.087	0.001	8	638.4
L2	2	6.5	1.185	0.006	8	638.9
L2	3	9.7	1.354	0.003	8	632.3
L3	1	3.2	3.340	0.013	8	640.7
L3	2	6.5	3.824	0.035	8	641.4
L3	3	9.7	4.342	0.099	8	634.7

- L1… High DTD, very high water-tree ageing, very high operating risk, signs of **water ingress in at least one of the joint**s
- L2… Stable, considered as reference
- L3… High DTD, high water-tree ageing, high operating risk, signs of water ingress in at least one of the joints (less than L1)

16.1.5 PD measurement result after replacement of 169-m section on 13 July

PD activity in L1:

- PD activity at joint at 679 m.
- PD inception voltage at 1.5 U_0
- PD up to 1,000 pC at 1.5 U_0 / 1.7 U_0.

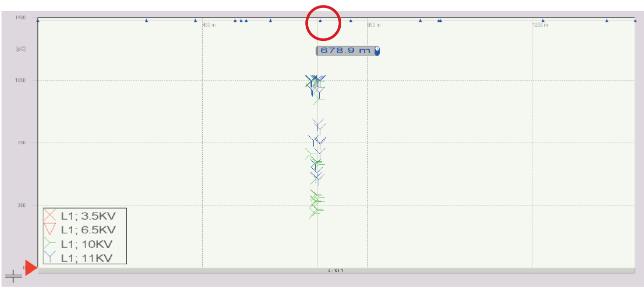


Figure 140: PD result of Phase 1 13.07.2011

PD activity in L2:

- PD activity in joint at 1,223 m
- PD inception voltage at 1.0 U_0
- PD up to 800 pC at 1.7 U_0.

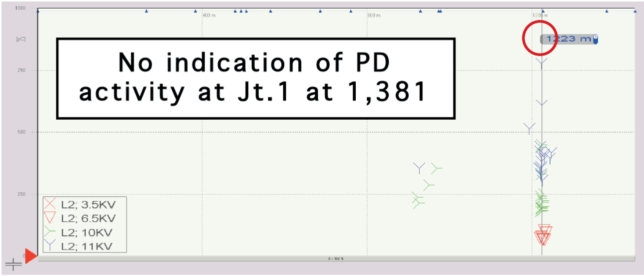


Figure 141: PD result of Phase 2 13.07.2011

PD activity in L3:

- PD activity in XLPE cable body at 458 m
- PD inception voltage at 1.5 U_0
- PD up to 1,000 pC at 1.7 U_0.
- The location needs to be analysed if external damage or an electrical tree is present, or a hidden joint is causing the PD.

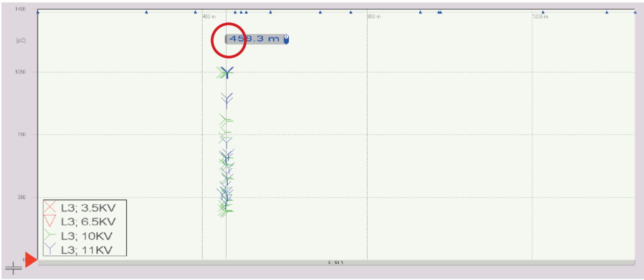


Figure 142: PD result of Phase 3 13.07.2011

Overall PD activity:

- Two joints show PD activity
- PDIV at 1.0 U_0 at 1,223 m
- PDIV at 1.5 U_0 at 679 m, 458 m
- 458 m is along the cable, no joint, investigation required

No PD at Joint #1 at 1,381 m!

After the TD and PD measurements, a 15-minute VLF test was performed @ 2 U_0. All 3 phases passed the test. According to the power utilities regulations, the cables belong to Category A-1 type cable and they were judged to be M (Medium Risk Condition). A retest has been scheduled to take place after 3 years of operation (13 July 2014).

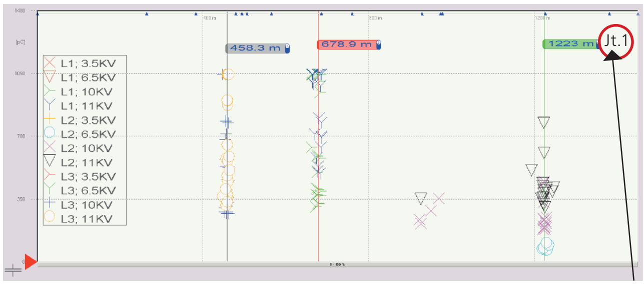


Figure 143: PD result of all three phases 13.07.2011

16.1.6 TD PD diagnostics summary

- L1 and L3 are in high operating risk condition
- The TD DTD values indicate a high increase of TD over the voltage
- Indication of severe water-tree ageing in L1 and L3, signs of water ingress in at least one of the joints
- The PD measurement confirmed that water-tree ageing is causing the high TD value
- Several joints also indicated PD activity
- Jt.1 at 1,381 m did not show any PD activity

16.1.7 Cable fault on 30 July 2011

- After two weeks of normal operation.
- L3 failed at joint Jt.1, located 1,381 m away from Kennedy Zone S/

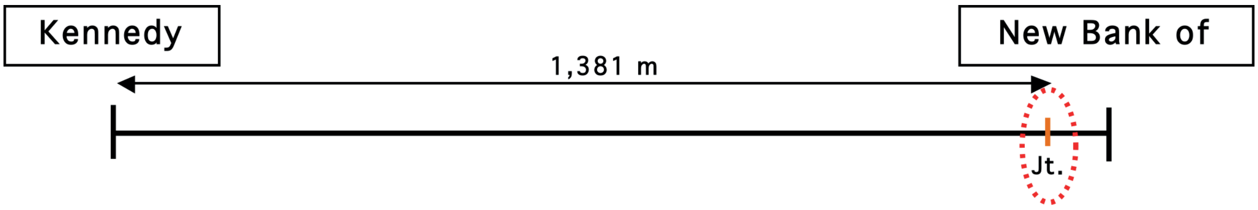


Figure 144: Picture of joint before dissection

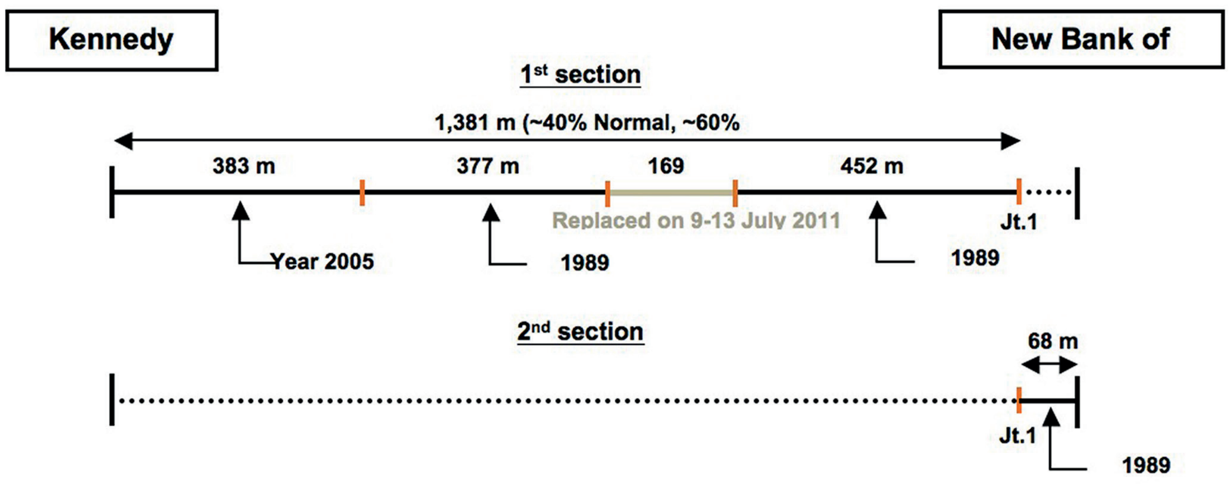
Figure 145: Picture of dissected joint Jt.1

This cable failure was unexpected. A detailed investigation had to be performed.

Step 1: Cable was cut at 1,381 m

Step 2: Both sections of the cables were tested individually
(1st section: 1,381 m, 2nd section: 68 m)

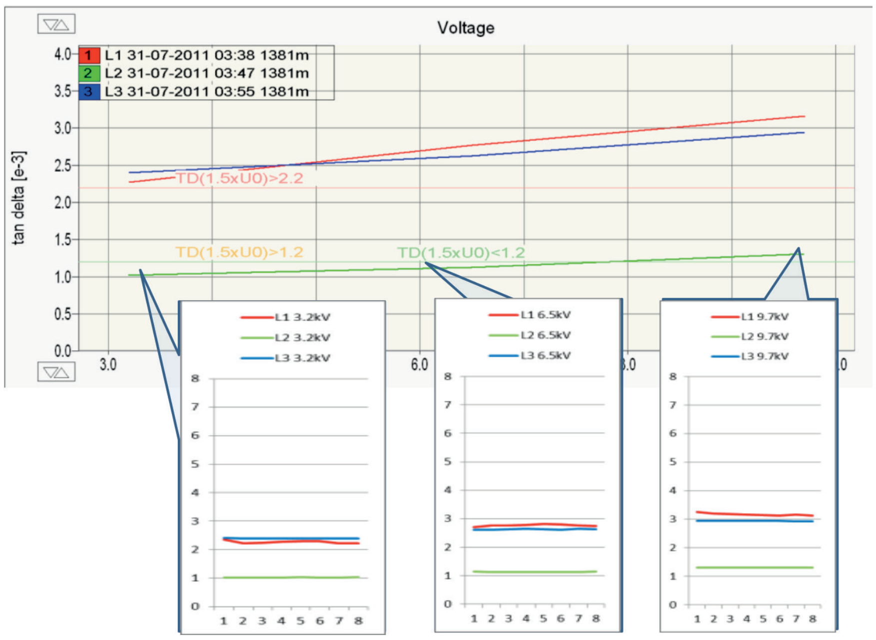
16.1.8 TD measurement on 31 July 2011



1st section: TD result recorded on 31 July 2011

- 1,381 m, several sections with WTPC included, 610 nF

TD result 31.07.2011, 1,381 m section



Full length cable results of all three phases were obtained after the cable failure on 30 July 2011. Average TD values of L1 and L3 were rather high. L1 indicated the most unstable behaviour but improved significantly due to the eliminated influence of the joint Jt. 1. L2 remained the same. L3 also improved significantly. Standard deviation indicates water-tree ageing in L3. The dissection indicated water marks on the surface of the XLPE in the termination and water tree development in L3. It can be assumed that the area around the joint was also affected by high water-tree ageing. The delta TD value in L1 was approx. 0.9 x E-3 which represents a 'highly service-aged condition'. Therefore, it is necessary to investigate the cables in further detail. The TD value of the whole section was an integral indication of the 40% non-WTPC and 60% WTPC sections.

Table of average tan delta values:

Voltage:	3.2 kV	6.5 kV	9.7 kV
L1	2.270	2.768	3.165
L2	1.024	1.129	1.307
L3	2.401	2.628	2.941

Table of standard deviations:

Voltage:	3.2 kV	6.5 kV	9.7 kV
L1	0.048	0.031	0.042
L2	0.002	0.008	0.003
L3	0.003	0.007	0.010

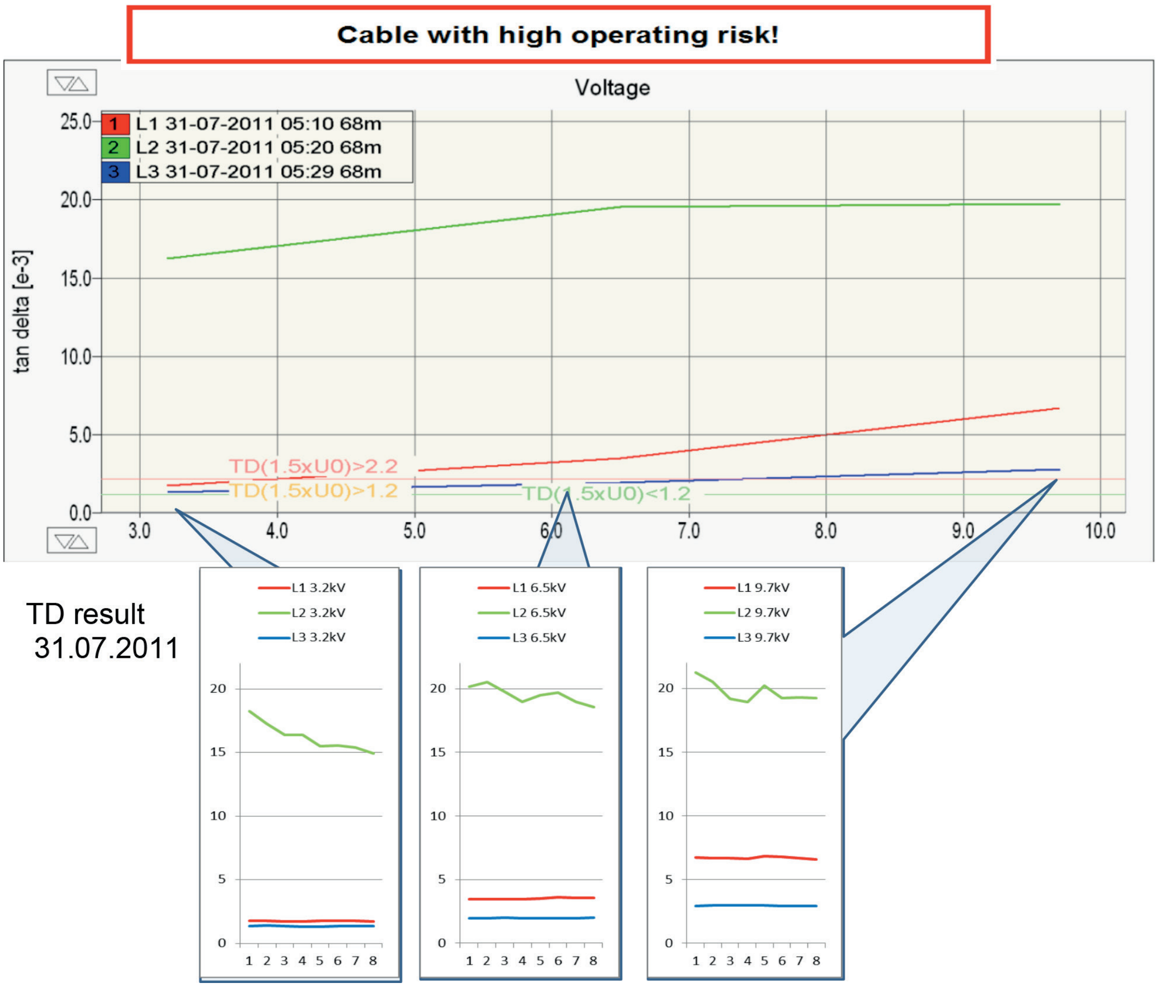
Summary:

Phase	Step	Voltage kV	Avg. value tan delta [e^{-3}]	Std. dev. [e^{-3}]	No.	Load
L1	1	3.2	6.352	0.385	8	636.2
L1	2	6.5	6.727	0.310	8	636.8
L1	3	9.7	7.405	0.271	8	630.1
L2	1	3.2	1.087	0.001	8	638.4
L2	2	6.5	1.185	0.006	8	638.9
L2	3	9.7	1.354	0.003	8	632.3
L3	1	3.2	3.340	0.013	8	640.7
L3	2	6.5	3.824	0.035	8	641.4
L3	3	9.7	4.342	0.099	8	634.7

- L1… High DTD, high water-tree ageing, high operating risk
- L2… Stable, considered as reference
- L3… High DTD, high water-tree ageing, high operating risk

2nd section: TD result recorded on 31 July 2011

- 68 m, 1 section with WTPC and no joint, 27 nF



The results of the last 68-m section (distance from the cut-point to the termination) of all three phases were also obtained after the cable failure on 30 July 2011. The TD results changed due to the cable length and homogeneous cable composition (WTPCS without joints) and show that all cables have a high operating risk and L2 has the worst result. The delta TD values for all three phases are extremely high, which is far beyond the acceptable limit, and high water-tree ageing and water ingress in a joint in L2 is to be expected; it is therefore necessary to investigate the cables in further detail.

Table of average tan delta values:

Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L1	1.745	3.507	6.702
L2	**16.242**	**19.529**	**19.755**
L3	1.336	1.970	2.815

Table of standard deviations:

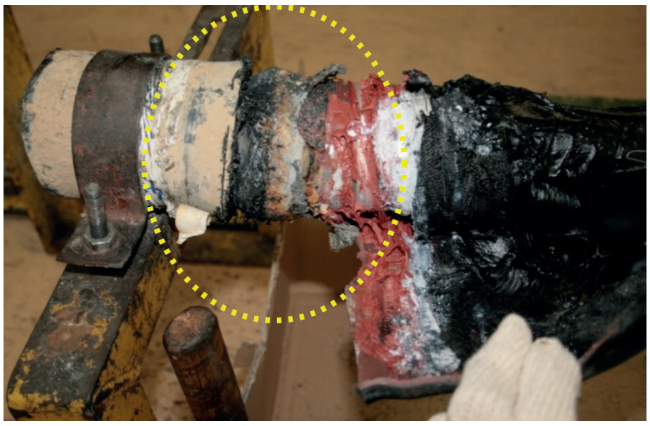
Voltage:	**3.2 kV**	**6.5 kV**	**9.7 kV**
L1	0.021	0.052	0.074
L2	**1.037**	**0.624**	**0.771**
L3	0.028	0.024	0.041

- L1… High DTD, high water-tree ageing, high operating risk
- L2… Very high TD value and DTD, very high water-tree ageing, very high operating risk, high water-tree aged condition of the cable section (Sumitomo) from the far end to joint Jt. 1 can only be recognised in this way because of the relatively small portion (< 5%) of total cable length
- L3… High DTD, high water-tree ageing, high operating risk
- Jt.1 failed at 1,381 m on 30 July 2011

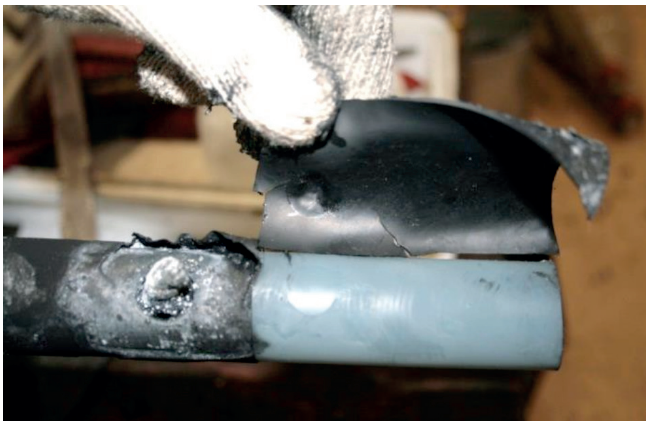
16.1.9 Joint dissection

↗ Figure 146: Joint prepared for dissection

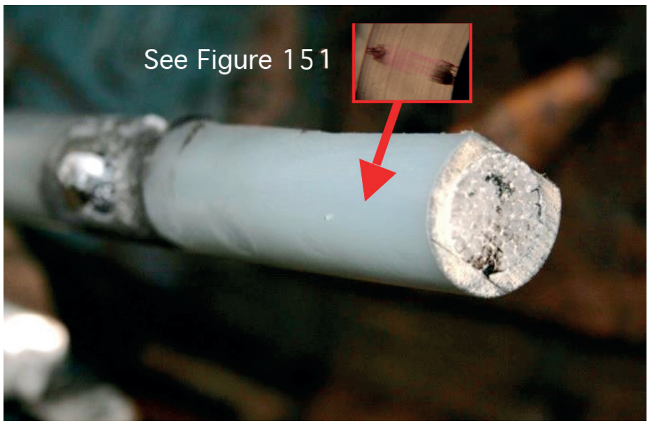
↗ Figure 147: Fault point on L3 at Sumitomo cable side near solder



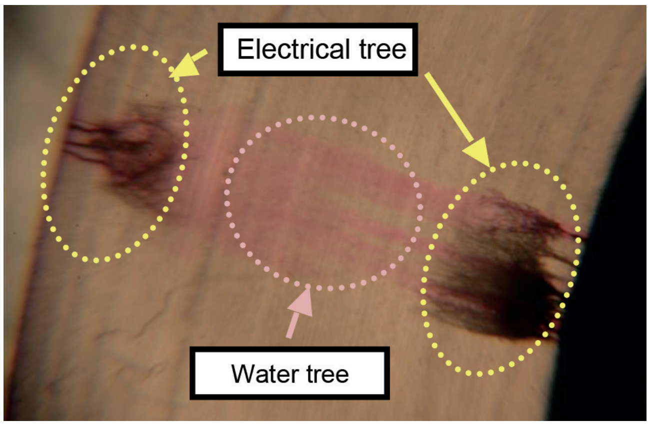
↗ Figure 148: Water found in cable during joint recovery. CAS corroded at Sumitomo cable side inside inner sleeve



↗ Figure 149: Signs of water noted in insulation screen



↗ Figure 150: Suspected water tree developed near to fault point



↗ Figure 151: Photo of actual water tree and electrical tree after dissection (XLPE cross section)

16.1.10 Required action and conclusion

After joint dissection, it was found that Joint 1 failed due to water ingress, which caused corrosion inside the inner sleeve. The fault location was found in the cable body near the joint. It was suspected that water had penetrated into the joint and caused the water tree to develop inside the cable body in the joint area. To prevent further cable failures, the whole of the second section was replaced.

Concluding all test results, the reason why the PD results did not indicate the corroded joint Jt.1 is that the wet/moist condition of the joint influenced the PD activity behaviour. The visible corrosion can further indicate the pulse damping effect in the cable.

Furthermore, in such a situation that 60% of the cable is WTPCS, the information provided by the TD results should be handled with respect to the VLF test. It is necessary to keep an eye on the '1989 WTPC', it being the main reason for the high TD. It was observed that the WTPC of 1989 have reached a status that no longer guarantees safe operation. The VLF testing regulation defined by the utility specifying a VLF test with 2.0 U_0 be applied for 15 minutes on XLPE cables with WTPCS was understood to be inappropriate and had to be revised in order to avoid such misjudgements in future. A Monitored Withstand Test (MWT) would help to find a way to understand the condition of the cable during the VLF test and to determine the testing time depending on the cable condition and behaviour during the VLF test sequence

17. Acronyms

PE	Polyethylene
XLPE	Cross-linked polyethylene cables
TRXLPE	Tree-retardant cross-linked polyethylene
EPR	Ethylene propylene rubber
PILC	Paper insulated lead shielded cables
VLF	Very Low Frequency
TD	Tangent delta, tan delta, loss factor, dissipation factor
VLF TD	VLF – tan delta measurement
VLF MTD	VLF tan delta measurement – mean tan delta value
VLF DTD	VLF tan delta measurement – delta tan delta
VLF TDTS	VLF tan delta measurement – tan delta time stability
VLF DS	VLF dielectric spectroscopy
VLF MW / MWT	VLF – Monitored Withstand Test
VLF PD	VLF – Partial Discharge
VLF LC	VLF – Leakage Current
VLF LCH	VLF – Loss Current Harmonics
VLF PDIV	VLF – Partial Discharge Inception Voltage
VLF PDEV	VLF – Partial Discharge Extinction Voltage
PLF	Power Line Frequency

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18.2 Table of Figures and Tables

ensuring the flow

18.3 Acknowledgements

Great appreciation is expressed to the power utilities and organisations that provided detailed information and case studies, as well as a good insight into their implemented and planned best practices. Further thanks must be addressed to the colleagues at BAUR, who greatly supported in working out the details and case studies.

The author:

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