Asset owners and system managers of distribution networks are increasingly aware of the necessity to be able to demonstrate the condition of their network. A combination of, at the one hand, a strong growth of the demand to be able to prove the condition of network components and at the other hand the technical possibilities led to a strong growth in the development of applicable diagnostics for condition assessment. The article, an initiative of NUON, Delft University of High Voltage and Pirelli Cables and Systems, aims at giving directives for the application of diagnostics for the different cable-types in the most common circumstances. The contents is based on a mix of practice experiences, scientific insight and design knowledge of components. It also informs about the differences to be aware of applying diagnostics for medium- and high voltage cables, either paper-lead or extruded cable connections or combinations of both.

The article describes a large number of reliable electrical measurements and tests that can be applied for the condition assessment of medium and high voltage cables. It describes both diagnostics that are completely developed and practiced and those still in development. The goal is to support the understanding of the present offer of diagnostics in order to realise a responsible maintenance program for medium and high voltage cables. A description of the application possibilities of the different diagnostics gives insight under which circumstances and for which cable types these diagnostics can be applied. They can be subdivided into the categories voltage tests, dielectric measurements and partial discharge measurements.

It is concluded that the technological development offer growing possibilities to measure and guard the quality of older and newer medium- and high voltage cable systems. A well considered maintenance program will, to a growing extend, be controlled by diagnostic condition measurements. An overview of the applicability of the different diagnostics is given in the table.

<table>
<thead>
<tr>
<th>Medium- or High Voltage:</th>
<th>PLC</th>
<th>XLPE</th>
<th>XLPE/PLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC test main insulation</td>
<td>AT</td>
<td>AT</td>
<td>AT</td>
</tr>
<tr>
<td>AC test main insulation</td>
<td>AT</td>
<td>AT</td>
<td>AT</td>
</tr>
<tr>
<td>Oscillating Voltage test</td>
<td>AT</td>
<td>AT</td>
<td>AT</td>
</tr>
<tr>
<td>DC synthetic mantle test</td>
<td>AT</td>
<td>AT</td>
<td>AT</td>
</tr>
<tr>
<td>Dielectric measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tan δ measurement at 50 Hz</td>
<td>PQ</td>
<td>PQ</td>
<td>PQ</td>
</tr>
<tr>
<td>Tan δ measurement at 0.1 Hz</td>
<td>n/a</td>
<td>PQ</td>
<td>n/a</td>
</tr>
<tr>
<td>Oil analysis</td>
<td>n/a</td>
<td>PQ</td>
<td>n/a</td>
</tr>
<tr>
<td>Partial discharge measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At 25-200 Hz test voltage</td>
<td>AT/PQ</td>
<td>AT/PQ</td>
<td>AT/PQ</td>
</tr>
<tr>
<td>At 0.1 Hz test voltage(VLF)</td>
<td>AT/PQ</td>
<td>*2</td>
<td>*5</td>
</tr>
<tr>
<td>At oscillating test voltage (OWTS)</td>
<td>AT/PQ</td>
<td>*2</td>
<td>AT/PQ</td>
</tr>
</tbody>
</table>

AT after laying test
PM periodical quality measurement
*1 only at extruded insulation
*2 Not yet developed
*4 Only if water treeing is suspected
*5 Due to frequency dependency

Table: Applicability of cable diagnostics

A special remark is made to the knowledge needed for the careful design and execution of the diagnostic measurements. Both execution and interpretation of the information demands experienced experts. Both knowledge as the resulting maintenance program will be continuously subject of evaluation based on a growing amount of experience data.
TOOLS FOR QUALITY ASSESSMENT OF DISTRIBUTION CABLE NETWORKS

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Nuon InfraCore 1  Delft University of Technology 2  NUON 3  Pirelli Cables and Systems 4

THE NETHERLANDS

Abstract

Asset owners and system managers of distribution networks are increasingly aware of the necessity to be able to demonstrate the condition of their network. A combination of, at the one hand, a strong growth of the demand to be able to prove the condition of network components and at the other hand the technical possibilities led to a strong growth in the development of applicable diagnostics for condition assessment.

This article is an initiative of the NUON utility, Pirelli Cable systems and the Delft University of Technology. It is aimed at giving directives for the application of diagnostics for the different cable-types in the most common circumstances.

The contents of this article is based on a mix of practice experiences, scientific insight and design knowledge of components. It also informs about the differences to be aware of applying diagnostics for medium- and high (>36kV) voltage cables either paper-lead or extruded cable connections or combinations of both.

DIAGNOSTICS

This article describes a large number of reliable electrical measurements and tests that can be applied for the condition assessment of medium and high voltage cables. It describes both diagnostics that are completely developed and used in practice and those that are in development.

The article’s goal is to support the understanding of the present offer of diagnostics in order to realise a responsible maintenance program for medium and high voltage cables.

A description of the application possibilities of the different diagnostics gives insight under which circumstances and for which cable types these diagnostics can be optimally applied. They can be subdivided into the following three categories:

1. Voltage tests
   1.1. DC test of the main insulation
   1.2. AC test of the main insulation
   1.3. Oscillating Voltage test of the main insulation
   1.4. DC test of the synthetic mantle

2. Dielectric measurements
   2.1. Tan δ at 50 Hz test voltage
   2.2. Tan δ at 0.1 Hz test voltage
   2.3. Oil analysis
   2.4. RVM (recovery voltage measurement)

3. Partial Discharge measurements
   3.1. At 25-200 Hz test voltage (off-line)
   3.2. At 0.1 Hz test voltage (VLF method)
   3.3. At oscillating test voltage (OWTS method)
   3.4. High frequency partial discharge measurement at 50Hz service voltage (on-line)

figure 1: Flash-over in cable terminal as a consequence of internal partial discharges

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1. VOLTAGE TESTS

A voltage test is meant to test of the cable dielectric and only gives an indication of the quality. Due to the absence of a quantity for the degree of ageing this test is not useful for trend measurement analysis.

1.1 DC test of the main insulation

According to the standard NEN 3172 [1] for MV cables the cable insulation is tested during 10 minutes by applying the test voltage to each phase accordingly earthing the two other phases and the earth-screen. A breakdown is not permitted. An after laying and/or repair test of 24kV during 10 minutes is recommended.

DC testing of cable systems which (partly) consists of XLPE (extruded) insulation is strongly advised against. Due to the polarisation phenomenon trapped space charge effects may occur caused in the extruded insulation material. Consequently there is an increased possibility of a breakdown at the moment the AC nominal voltage is applied.

In case of paper-lead insulation DC testing has no harmful side effects and is as such soundly applicable. In situations where “Nekaldiet” joints are applied (in the past frequently applied in Dutch networks) it is recommended to apply a 10 minutes DC test with 24kV prior to application of other diagnostics.

The DC test of the main insulation is not recommended as a periodical quality test of the main insulation but as a discriminating after laying test method for paper-lead insulated cable systems.

![Figure 2: Exploded mass-cable joint caused by water-intrusion](image)

1.2 AC test of main insulation

According to NEN 3620 [2], AC tests are applied with an external voltage source with a frequency between 25 to 200 Hz. The cable connection is only accepted if no breakdowns occurred during the testing sequence. An AC test is technically accepted for both medium- as high voltage cable systems. A disapproval level of 2.5xUo is applied [2,26]. If an AC test of low frequency (0.1 Hz) is applied a disapproval level of 3xUo, during 15 minutes is required.

For existing cable connections an AC test of 80% of the original test value is advised.

The AC test is recommended as after laying test.

1.3 Oscillating-voltage test of the main insulation

The oscillating voltage test method charges the cable applying a damping AC voltage during a number of periods. The frequency of these oscillating waves strongly depends on the applied external impedance and the capacity of the cable. It can vary between 50Hz and some kHz [17]. Depended on the applied switching technique the shape of the oscillating wave can be slightly of stronger damped. In case of the application of a spark-gap or a mechanical switch a strong damping factor will occur.

An electronic switch however will show a slowly decaying oscillation [18,19]. Compared to the AC tests the oscillating wave (OS) tests show the following effectiveness with regard to breakdown voltages [17,18]:

1. for MV cable connections the OS/AC breakdown voltage factor is ~ 1
2. for HV cable connections the OS/AC breakdown factor is considerably higher: 1.2 tot 1.9

1.4 DC test of synthetic mantle

Synthetic mantles are tested by applying a DC voltage of 5 kV (10 kV for HV cables) during 5 minutes between the temporarily disconnected earth-screen (lead or copper) and earth. A leakage current of some mAmps is an indication of a possible damage to the cable mantle. The exact failure place is found by a bridge measurement followed by a pulsed 30mAmps injection.

The mantle test is recommended as a method to track down small cable defects in extruded cables before breakdown of the main insulation will occur. Besides it is used to control a correct functioning of cross bonding systems. High voltage cable systems are recommended to test once per year. Medium voltage cables should be checked once per year only for the important connections.

2. DIELECTRIC MEASUREMENTS

Unlike voltage testing, measurements of the dielectric do give an absolute value for the quality level of the cable insulation. The results of these measurements have a direct relation to the average qualitative level of the insulation at the moment of measurement and can thus be applied as a trend- or fingerprint measurement

2.1 Tan δ at 50 Hz test voltage

The tan δ measurement is meant for the determination of the loss factor of the insulation material. This factor increases during the ageing process of the cable. The 50 Hz tan δ measurement should be regarded as a diagnostic and/or supporting measurement.

The tan δ value of a cable is strongly influenced by the composition of the connection, the trace, the deviations in joints and the actual cable temperature. The tan δ measurement is only applicable as trend measurement if composition circumstances of the trace and thermal conditions of successive measurements are virtually identical.

At this moment Pirelli investigates the relation between tan δ, temperature and nominal current. If certain relations
are demonstrable the trend analysis of tan δ measurements will be simplified.

The tan δ measurement is not applicable for XLPE cables due to the very low tan δ value. For HV paper insulated cables the tan δ can be an important indicator of possible thermal breakdowns [21,22]. Testing is recommended at t=0 and after 12 years because ageing phenomena will not occur clearly prior to this period. After the 12th year the measurement can be repeated with a time interval of app. 5 years.

2.2 Tan δ at 0.1 Hz test voltage
Like the 50Hz tan δ measurement, the tan δ measurement at 0.1 Hz test voltage is applied to measure the loss factor of the insulation material and can be regarded as diagnostic or supporting measurement. At this moment however, the measurement is only useful for XLPE cables as an indicator for the presence of water treeing. Due to the lack of fundamental verification this measurement is not to recommend for paper-lead cables [5]. Like the 50Hz tan δ measurement it is recommended to apply the measurement at t=0, after 12 years resp. each 5 years following that moment.

2.3 Oil analysis
An oil analysis determines the gas amount, the type of break down voltage and tan δ [20,21] of the insulating oil applied in pressured oil of cables and joints. From these data aging phenomena, thermal overload and partial discharges can be detected. The oil analysis is the standard test with which the quality of oil insulated cables is checked. Important for the judgement of the results are the configuration and age of cable/joints, the historical and present load pattern of the connection and the amount of oil added in the past. These factors have an important influence on the results of the oil analysis.

2.4 RVM (Recovery Voltage Measurement)
This method uses the fact that the polarisation of the insulating material changes as a consequence of the ageing of the cable insulating material. At this moment the RVM bridge measurement is in development for paper-lead and XLPE cable types. With the application of an RVM measurement the occurrence of water treeing in extruded insulating material can be established. An RVM measurement can be applied as a periodical measurement for determining the thermal ageing of paper-lead cables. At this moment however the runtime of the measurement and the practical applicability are still bottlenecks in the development [5,14].

3. PARTIAL DISCHARGE (PD) MEASUREMENTS
Partial discharges are an indication for weak spots in a cable connection (figures 1-3). In order to run the measurement partial discharges are ignited in the cable insulation or joints by the application of a test voltage. Subsequently a discharge detection system measures the PD level, phase-resolved patterns and location of the discharges as a function of the applied voltage. Two principles are applied for the discharge detection process:
1. An IEC 60270 [3] discharge detection with discharge activity measured in pC or nC by application of a defined band-pass integrator. The signal propagation in the cable is calculated according to the standard IEC 885 [15].
2. HF discharge detection with which the discharge activity is registered in mV by means of a broad band amplifier. Through the oscillating wave theory location of discharges in cables up to a length of 6 kms can be estimated.

The different discharge measurement methods distinguish themselves also by the different frequencies of the test voltage applied. Besides there is a difference between on-line and off-line measurements. In case of off-line measurements the cable is taken out of service and electrically stresses by means of external power supplies: 50Hz, 0,1 Hz or oscillating waves (50Hz-500Hz).
In case of on-line PD measurements the cable is in service and the measurement system is detecting the high frequency (HF) discharge activity in the cable system concerned. If and when an absolute value of the discharge level must be determined in pC or nC, a calibration procedure according to the IEC 60270 standard [3] has to be applied.

3.1 PD measurement at 25 - 200 Hz test voltage
In case of a 25 - 200 Hz discharge measurement an external power supply is connected to the cable connection. The frequency is practically in the order of the nominal frequency of the connection. Consequently this measurement is applicable in any circumstances and is applied for both medium and high voltage cables.

3.2 PD measurement at 0.1 Hz test voltage (VLF)
In case of a 0,1 Hz discharge measurement an external 0,1 Hz power supply is connected to the cable system [4]. At this moment the applicability of this measurement for XLPE cables is subject of a scientific discussion. The discussion is directed at the frequency dependency of discharge processes in extruded cables [6]. Paper-lead
cables are less sensitive at this point, which means that these cable types can be measured with the 0.1Hz method.

3.3 PD measurement at 50-500 Hz oscillating voltage (OWTS method)
With the OWTS discharge measurement the cable system is charged with a period of less than 3 seconds with a defined voltage. The oscillating voltage wave (50-500 Hz), subsequently originating by discharging an external coil, lasts for app. 0.3 seconds during which period a number of slightly damped oscillating waves generate a alternating field in the cable [7-13]. The OWTS method has been shown to stimulate the stress of normal power, which means, OWTS generates in the cable sample AC stress only. As a result OWTS stress of XLPE and PILC insulation produces PD behaviour similar to 50Hz: PDIV/PDEV, PD magnitudes [11,16]. Consequently the OWTS measurement is suitable for both after laying tests as diagnostic trend analysis test for all types of MV cables. The OWTS system for HV cables is not developed yet.

3.4 High frequency PD measurement at 50 Hz voltage (on-line)
PD level measurement by means of high frequency (HF bandwidth<10MHz) or very high frequencies (VHF bandwidth<200MHz) is executed on line. This type of PD measurement is often influenced by noise disturbance signals originating from the network. In addition to an efficient noise suppression and filtering three items are of importance:
1. Due to the impossibility of calibrating the measurement (IEC 60270) it is not possible to measure the absolute value of the discharges in pC or nC but only in µV of mV.
2. Detection of discharges by means of HF or VHF sensors is restricted to the direct environment of the sensor. Only discharges in cable joints and cable terminals will be detected by this system.
3. Discharge detection at nominal voltage (on-line) only informs about the existence of PD. Information about the PD as a function of the voltage is not given (very important information due to the inception/extinction characteristics for discharges in XLPE insulation).

On-line discharge measurements are strongly influenced by the actual HF disturbances in the grid. Consequently the cable system the next measurements and tests are recommended:
- Voltage test according to NEN 3620 (XLPE) or NEN 3172 (PLC)
- Partial discharge measurement
- Tangent delta measurement
- DC test of synthetic mantle

As a periodical quality measurement of important MV cables the following program is recommended to execute each 5 years (respectively 10 years for other MV cables):
- Partial discharge measurement
- Tangent delta measurement
- (DC test of synthetic mantles only for important connections)

In practice however external factors can cause a different disturbance behaviour which can give cause for other intervals. At this moment only the 0.1Hz measurement for XLPE cables is under discussion due to the frequency dependency of the igniting mechanism of discharge sources in XLPE cables. Besides a tan δ measurement at 0.1Hz is only recommended for XLPE cables that are suspected of water treeing.

5. MAINTENANCE PROGRAM HV CABLES
The recommended maintenance program for HV cables strongly depends on the type, age and load history of the cable involved. Moreover the maintenance measurement of pressured oil and gas insulated cable systems is very complex. A responsible diagnostic maintenance program demands a thorough inventory of the connection. Table 1 shows a selection of diagnostics that could be part of a maintenance program. Depending on the status of the system (from A to E: from young to old) diagnostics should be applied at different time intervals.
A remark should be made to the knowledge needed for the careful design and execution of the diagnostic measurements. Both execution and interpretation of the information demands experienced experts. Both knowledge as the resulting maintenance program will be continuously subject of evaluation based on a growing amount of experience data.

### Table 1: Program of diagnostics for HV cables

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check oil pressures (existence of gas)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Measure saturation factor</td>
<td>0.2</td>
<td>1</td>
<td>1*</td>
<td>1*</td>
<td>1*</td>
</tr>
<tr>
<td>Oil measurement (dissolved gas, breakdown voltage, tan δ)</td>
<td>0.2</td>
<td>0.5</td>
<td>1*</td>
<td>1*</td>
<td>1*</td>
</tr>
<tr>
<td>Check hydraulic system (leakage)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Visual inspection cable terminals</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>On-site tan δ and PD</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2-1</td>
<td>0.2-1</td>
<td>0.2-1</td>
</tr>
<tr>
<td>Inspection lead mantle</td>
<td>-</td>
<td>-</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Paper quality</td>
<td>-</td>
<td>-</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

* special circumstances can lead to higher frequencies. ** destructive research in case of diversions or disturbances.

### Table 2: Applicability of cable diagnostics

<table>
<thead>
<tr>
<th>Voltage test</th>
<th>PLC (MV)</th>
<th>XLPE (MV)</th>
<th>XLPE/PLC (MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC test main insulation</td>
<td>AT/PQ</td>
<td>AT/PQ</td>
<td>AT/PQ</td>
</tr>
<tr>
<td>AC test main insulation</td>
<td>AT</td>
<td>AT</td>
<td>AT</td>
</tr>
<tr>
<td>Oscillating Voltage test</td>
<td>AT</td>
<td>AT</td>
<td>AT</td>
</tr>
<tr>
<td>DC synthetic mantle test</td>
<td>AT/PQ</td>
<td>AT/PQ</td>
<td>AT/PQ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dielectric measurements</th>
<th>PLC (MV)</th>
<th>XLPE (MV)</th>
<th>XLPE/PLC (MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tan δ measurement at 50 Hz</td>
<td>PQ</td>
<td>PQ</td>
<td>PQ</td>
</tr>
<tr>
<td>Tan δ measurement at 0.1 Hz</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Oil analysis</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>RVM</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Partial discharge measurements</th>
<th>PLC (MV)</th>
<th>XLPE (MV)</th>
<th>XLPE/PLC (MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 25-200 Hz test voltage</td>
<td>A1/PQ</td>
<td>A1/PQ</td>
<td>A1/PQ</td>
</tr>
<tr>
<td>At 0.1 Hz test voltage(VLF)</td>
<td>A1/PQ</td>
<td>A1/PQ</td>
<td>A1/PQ</td>
</tr>
<tr>
<td>At oscillating test voltage (OWTS)</td>
<td>A1/PQ</td>
<td>A1/PQ</td>
<td>A1/PQ</td>
</tr>
<tr>
<td>AT after laying test</td>
<td>Positive advice</td>
<td>Under discussion</td>
<td>Negative advice</td>
</tr>
<tr>
<td>PM periodical quality measurement</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### 6. CONCLUSION

Technological developments offer growing possibilities to measure and guard the quality of older and newer medium- and high voltage cable systems. A well considered maintenance program will, to a growing extend, be controlled by diagnostic condition measurements. An overview of the applicability of the different diagnostics is given in table 2.

### 7. LITERATURE

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