On-site Testing and PD Diagnosis of High Voltage Power Cables

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ABSTRACT

In addition to after-laying of new-installed high voltage (HV) power cables the use of on-site non-destructive on-site testing and diagnosis of service aged power cables is becoming an important issue to determine the actual condition of the cable systems and to determine the future performances. In this paper based on field experience an overview is presented on on-site testing and partial discharge diagnosis of HV power cables with regard to on-site testing methods: energizing, diagnostic aspects, possibilities and implications for new and service aged power cables.

Index Terms — **High voltage power cables, on-site testing, ac over-voltages, partial discharges, diagnosis, condition assessment.**

1 GENERAL

DUE to the fact that transmission power cables are distributed insulation systems up to multiple kilometers the knowledge about local condition mostly within few millimeters along the whole length of the cable may be very important to determine the reliability of a particular cable circuit. In particular, detection and localization of discharging insulation defects in high voltage (HV) power cables are very relevant to qualify high-risk systems in the cable network [1-5].

Due to the great impact of an insulation failure in the service life of HV transmission power cables, extensive voltage withstand tests combined with partial discharges (PD) detection are applied during the factory acceptance testing. Moreover, after installing the cable system on-site, different types of voltage withstand tests are applied [6-9] which can or cannot be applied in combination with PD detection [10].

In general, the on-site PD detection in HV power cables is performed off-line. For this purpose the power cable to be measured is taken out of service and an external power supply is used to energize the cable circuit and to ignite the discharging defects. For this purpose different on-site energizing methods are in use (Table 1).

This paper is focused on off-line testing of new and service aged transmission power cables (voltage range from 50kV up to 380 kV) and the application of off-line testing to new and service aged HV power cables. In particular, referring to existing methods of on-site energizing and available advanced diagnostics an overview of experiences will be presented with regard to different aspects of on-site testing and the importance of PD detection.

2 INTRODUCTION

It is known, that HV insulation failure of a HV cable can occur as a result of the normally applied operational voltage or during a transient voltages, such as lightning or switching surges. The failure can occur if localized electrical stresses are greater than the dielectric strength of dielectric materials in the area of the localized stress or the bulk dielectric material degrades to the point where it cannot withstand the applied voltage. Therefore additional to factory type and routine tests the reliability of HV power cables may further

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Table 1. On-site testing voltages.

VOLATGE	DESCRIPTION
Alternating current voltage (AC)	AC voltage testing uses alternating current at frequencies between 20Hz and 300Hz is an effective method to energize on-site all types of cable systems. As compared to AC voltage stresses during factory testing and service operation it is recommended for withstand testing. HVAC withstand test: the cable section can be accepted if after application of a selected HVAC voltage stress for a recommended duration no breakdown has occurred. Diagnosis: at certain voltage levels partial discharges, dielectric losses can be measured in function of time/voltage and used for diagnostic purposes.
Damped alternating current voltage (DAC)	Damped AC voltage testing uses damped alternating current at frequencies between 20Hz and 500Hz. In combination with partial discharge measurement it is an effective method in testing on-site all types of cable systems. Due to similarity in partial discharges occurrence at AC voltage stresses during factory testing and service operation it is recommended for on-site testing and PD measurements. DAC withstand test: the cable section can be stressed with a selected DAC voltage stress for selected time duration and the cable section can be rejected if a breakdown has occurred. Diagnosis: at certain voltage levels partial discharges, dielectric losses can be measured in function of time/voltage and used for diagnostic purposes.
Very low frequency voltage (VLF)	Very low frequency (VLF) voltage testing uses frequencies down to 0.01Hz to test on-site the all types of cable insulation. Due to much lower frequency range as compared to AC voltage stresses, VLF testing is based on the fact that insulation defects have to breakdown during time of testing. VLF withstand test: the cable section can be rejected if after application of a selected VLF voltage stress for a recommended duration breakdown has occurred. Diagnosis: at certain voltage levels partial discharges, dielectric losses can be measured in function of time/voltage and used for diagnostic purposes.
Direct current voltage (DC)	DC voltage testing was introduced in the past as an on-site method to test laminated dielectric cable systems. In general testing with DC voltages has due to less or no (XLPE insulation) representative character as compared to AC voltage stresses. HVDC withstand test: the cable section can be accepted if after application of a selected HVDC voltage stress for a recommended duration no breakdown has occurred. Diagnosis: at certain voltage level total leakage output current can be measured in function of time whereas the differences in function of time are used for diagnostic purposes.

be improved by on-site testing and PD diagnosis. In particular, the on-site tests are applied to prove two characteristics of a cable circuit.

1. Quality and cable system integrity of the cable circuit
    a. As part of commissioning on-site: check possible damages after completed factory test due to transportation, storage and installation.
    b. To demonstrate that the transport from manufacture to site and erection on-site have not caused any new and dangerous defects in the insulation. In fact, the power cable is tested in the factory as well as the main parts of prefabricated cable accessories (i.e. stress cones and joint bodies). However the effect of transportation and the correctness of the final assembling can only be tested after completing the installation in the field.
    c. After on-site repair: to spot bad workmanship during complete installation of the cable (including joints and terminations). To demonstrate that the equipment has been successfully repaired and that all dangerous defects in the insulation have been eliminated.
2. Availability /reliability of the cable circuit
    a. For diagnostic purposes: to estimate actual condition of the service aged cable system by checking the insulation degradation after a period of service operation e.g. 40 or 50 years.
    b. By providing reference values of diagnostic tools (voltage test including partial discharges and dielectric losses) for later tests to demonstrate whether the insulation is still free from dangerous defects and that the life-time expectation is sufficient high.

3 TYPICAL INSULATION DEFECTS

As comparing to distribution power cables, with regard to recognition of insulation defects in transmission power cables less investigation has been done till now. As shown in [1] by analyzing the visual inspections of distribution power cables the typical defects in the different elements of cable network are listed in [1] (see Tables 2.4 and 2-5) which are assigned to several defect introducing stresses involved. It follows that visual inspection of the disturbed components may provide insight in the different types of defects resulting in breakdown. From the forensic investigations [1] during many years repetitive fault have been found. Some of the defect descriptions are hypotheses, obtained from the practical insight from forensic investigations.

In general, taking into account the effect of significantly higher electrical design field strengths as they occur in HV power cables and accessories, such systematic of insulation defects as shown in [1] (see Tables 2-4, 2-5, 2-6 and 2-7) can also be used in discussion of insulation defects in HV power cables.

The different defects described in [1] (see Tables 2.4 and 2-5) are actually degrading according to different mechanisms. In many cases the breakdown of the insulation will be preceded by discharge activity. It has been shown that evaluating the typical insulation defects and their introducing factors in combination with PD activity may be involved in the degradation process. In [1] the Table 2-6 shows an overview of the degradation processes for the different defects, which may occur in cable insulation. This overview shows that partial discharges are responsible for the intermediate or final stage of the deterioration processes (e.g. in the form of electrical treeing). From the described deterioration processes, partial discharges can be indicated as important symptoms to determine the presence of degradation processes in cable insulation. Moreover, defects may be accompanied by PD activity, where the partial discharges are not responsible for the deterioration, but are just indicators for defects. E.g. cracking of insulating material (due to tension) may result in increasing fissure sizes, which will involve PD activity. PD phenomena are for the described reasons a sensitive detection parameter to recognize and localize the presence of the major part of the defects in the different cable components.

As a result with regard to typical defects that occur in the cable insulation and the resulting insulation deterioration the following is of importance.

a) The defect introducing factors for power cables are the operational stresses, the environmental stresses and the human influences. The latter stress is mainly involved at the start of the lifetime of a cable component during the on-site assembly. The operational and environmental stresses occur during the lifetime of the cable component during the operation. Some of the above-mentioned stresses cannot be prevented.

b) Investigations on disturbed components by visual inspections over the years have revealed the typical defects that occur in the power cable network. Table 5 shows an overview of the typical defects for the applied cable insulation and accessories.

c) The insulation degradation mechanisms related to the various defects can be reduced to four different types; degradation in cavities or fissures, degradation on surfaces, degradation by treeing and degradation by discharges in oil.

d) Insulation deterioration symptoms of the typical defects are identified by discharge activity, in the intermediate stages or final stages. As a result, partial discharges are characteristic diagnostic property to detect, which recognizes the presence of these defects.

Due to significantly higher electric field strengths in the insulation and the accessories of HV power cables the degradation processes of discharging defects are much faster than those in MV power cables. Nevertheless it is possible that in certain type of insulation e.g. mass-impregnated insulation or certain type of HV cables accessories the PD may occur during service life. But in general the HV cables are supposed to be PD free during operation [20]. Therefore to detect the presence of discharging insulation defects in service aged HV power cables during on-site testing voltages higher than U_0 (over-voltages) have to be used. In combination with PD detection information can be provided about the PD occurrence: PD inception voltage, PD extinction voltages, PD level. In the next two paragraphs aspects of testing and PD detection will be discussed.

4 VOLTAGES FOR ON-SITE TESTING

According to [6-10] several voltages have been defined for on-site testing. Based on field experiences a number of test voltage types are in use for testing and diagnosis. It follows from Table 1 that depending on particular voltage type different application effectiveness's can be given [19, 21, 22]. The application of dc voltages has the longest history in testing laminated cable insulation. This method is applicable for failures related to insulation conductivity/thermal problems. The test systems are simple, lightweight, cost effective equipment with low input power requirements. dc stresses do not reflect ac operational electrical stresses and sensitive to thermal condition. Moreover, dc voltage stress is not sensitivity to ac related insulation problems e.g. partial discharges.

The VLF testing is since several years an accepted method for voltage withstands tests for all types of distribution cables. Different to dc voltages no space charge formation in polymeric insulation occurs due to continuous 0.1 Hz polarity reversals. As compared to ac voltage withstand stresses higher voltage levels are required and as compared to ac operational stresses in polymeric insulation different PD behavior (PD inception, PD magnitudes) have been observed.

In particular applying ac voltages has long history in laboratory testing of all types of cable insulation. Moreover,

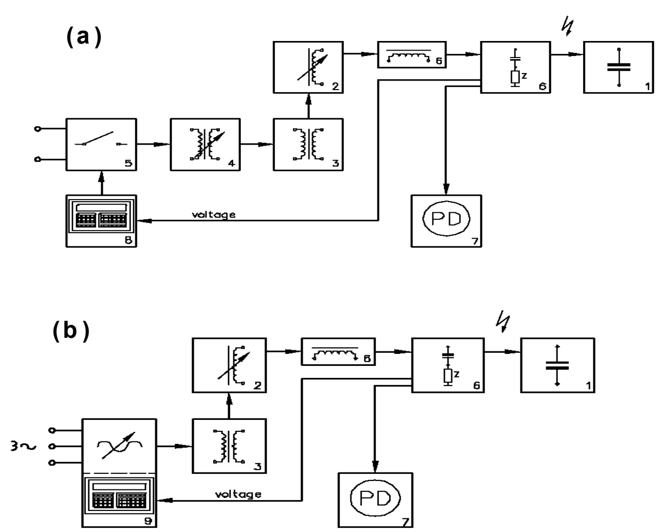

Figure 1. Schematic view of ac series resonant test systems [16].

(a) Inductively Tuned Resonance Circuit (ITRC)

(b) Frequency Tuned Resonant Circuit (FTRC);

1 – cable system under test; 2 – test reactor; 3 – exciter transformers; 4 – regulating transformer; 5 – switching cubicle; 6 – voltage divider, PD coupler including blocking impedance; 7 – PD instrument; 8 – control rack including peak voltmeter; 9 – control and feeding unit including peak voltmeter. (for more details of this type of test see type 2 in Table 2).

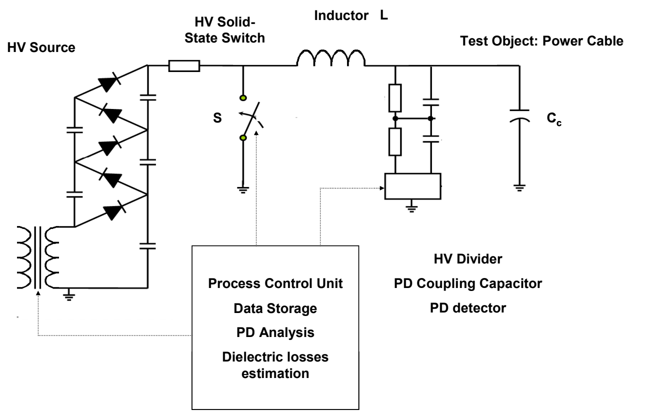

Figure 2. Schematic view of damped AC test system [16], (for more details of this type of test see type 3 in Table 2).

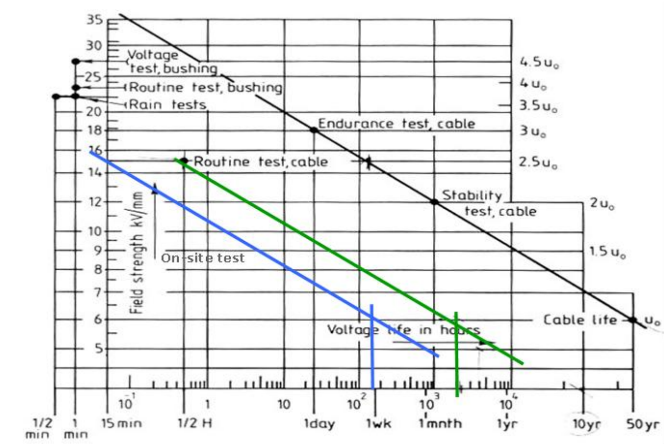

Figure 3. Example of a life curve of a 220kV cable with indication of the life time consumption effects of a) routine test (green line) 1/2hrs at 2.5 U_0, b) an on-site test (blue line) at 15min at 2.5U_0.

more than 10 years long history in on-site testing of all types of cable systems has confirmed that applying on-site similar ac electrical stresses as during factory testing and service operation is applicable for the recognition of all types failures related to insulation and it can be also combined with diagnostics e.g. PD, dielectric measurements (see Figure 1).

As a consequence of experience in on-site ac testing on the one hand and the technological progress in power electronics and advanced signal processing on the other hand, damped ac (DAC) voltage have become accepted since several years for on-site testing and PD measurements [8-10], (see Figure 2). In particular the DAC testing is suitable for all types and length of MV power cables and since few years it is in use for all types and all lengths of HV power cables [11-13, 20, 21].

The on-site use of ac voltages is mostly based on the concept of an over-voltage test. As a result the following aspects have to be considered:

a) Routine HV tests are the most fundamental of all electric tests on cable insulation.
b) Since the test voltage is higher than the rated voltage it is considered as an over-voltage test.
c) It has been introduced many years ago because the over-voltage test was the only available electrical test.
d) A breakdown of the insulation may occur on the insulation weak-spot and it can be sometimes accompanied by pre-breakdown phenomena (in-homogeneity with locally enhanced electric field).
e) Regarding electrical over-stress a balance is important between detecting serious defects and avoiding insulation damage.

5 RELEVANCE AND IMPACT OF ON-SITE TESTING

From the point of view of a HV power cable quality and reliability four aspects are important for on-site AC over-voltage tests and results evaluation.

a) A healthy (defect-free and/or non-aged) insulation can withstand a high voltage stress level, whereas insulation which is aged and/or consists of insulation defects should have lower level of withstand voltage, see Figure 3.
b) An over-voltage test shall be designed in such a way that the life time consumption due to the on-site test of a healthy insulation is negligible, whereas the impact on that of a defective insulation is high enough to cause a breakdown.
c) Due to test voltage stresses higher than the operational stresses, the test may be destructive even if no failure has occurred.
d) Due to the fact that the duration of the over-voltage is arbitrarily selected e.g. 10 minutes it can not be excluded that after 11 minutes a failure will occur.

In general applying enhanced voltage after-laying testing e.g. up to 2.5U_0 to a defect-free and not aged insulation does not have significant influence on the service life of the component. It follows from Figure 3 that in this case the life-time consumption will be in the range of one week.

In the case that defects are present in the cable insulation the effects of ac over-voltage are more complex. It follows from Figure 4 that different aspects are important and have to be taken into consideration. Moreover, several interactions are possible between the defect type/location, breakdown and pre-breakdown possibilities and the test voltages applied.

The type and design stress level of accessories are in direct interaction with the type of defect and the local electric field

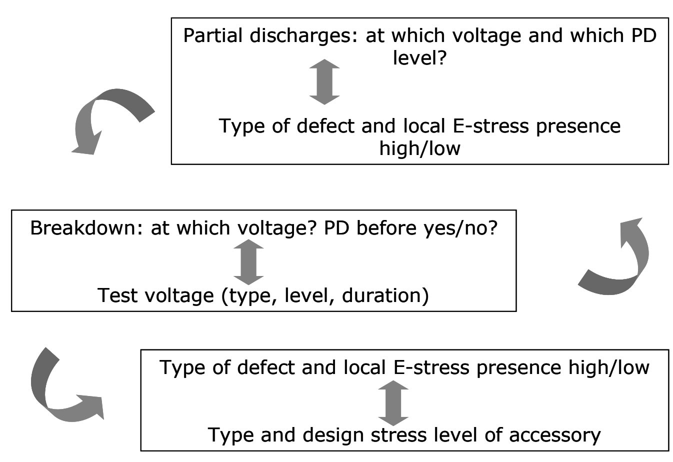

Figure 4. Important issues and the complexity of on-site testing of power cables with ac over-voltages in the presence of insulation defects.

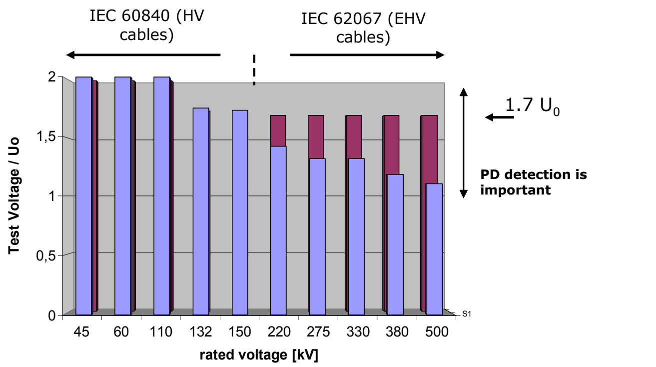

Figure 5. Relevance of test voltage levels for testing HV and EHV power cables as indicated in the IEC 60840/62067 Standards.

enhancement. E.g. presence of internal cavities on the outer conductor in MV cables design has lower breakdown impact for the same cavity which is close to inner cable conductor. In both cases a breakdown is not guaranteed during the on-site testing with ac over-voltages, due to lower design field strength of MV power cables. But the presence of the same cavities in the insulation of a HV cable will probably result in a breakdown. Moreover in that case prior breakdown in the cavities significant PD activity will be present.

The interaction between the applied ac over-voltage stress and the breakdown depends also on the type of defect. If pre-breakdown phenomena e.g. partial discharges will appear, it depends also strongly on the type of defect. It is known that high non-homogeneities like sharp edges, cavities, impurities are mostly accompanied by the inception of partial discharges. It is also important to understand that in the case of PD presence the duration and the level of the voltage application are crucial to produce the breakdown.

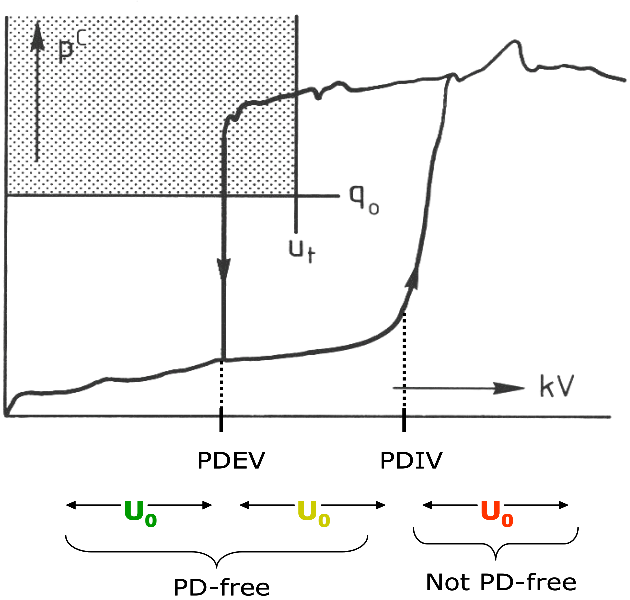

Figure 6. Schematic evaluation of PD measurement in function of the AC over-voltage test. According to cable specific acceptance values: q_0 and U_t any particular discharge larger than q_0 measured below selected test voltage U_t leads to rejection of the object under test, see shaded area. PD inception voltage PDIV and PD extinction voltage PDEV referred to U_0 are important indicators of PD presence during network operation. Based on the PDIV and PDEV information the PD-free condition of a cable can be determined.

In the case of homogeneous defects e.g. local insulation degradation by moisture or other rough defects like missing field grading may result in a breakdown without any PD occurrences. As a result in Figure 5 the importance of selecting the most optimal test voltage levels for HV and EHV power cables is shown. In particular the need of decreasing the ratio U_{test}/U_0 for EHV cables is important due to:

a) the limitations in on-site availability of test voltages/test energies,
b) in case of immediate insulation breakdown making visible the pre-breakdown phenomena (PD),
c) the design field strengths limitations of EHV cable accessories.

As indicated in Figure 5 by lowering the ratio U_{test}/U_0 for EHV power cables increases the relevance of using PD detection as additional information source about the discharging defects.

It is known, that comparing HV and EHV cable designs, the design stress level of EHV cables is much higher than those of HV cables. As a result, for EHV cables high testing stresses are obtained even with a "reduced" test over-voltage. For HV cables (V<=150kV) the design stress level is lower which means that although the U_{test}/U_0 ratio is rather high, the stress during testing may result to be the same or even lower than the testing stress of EHV cables.

As a result of this discussion, it can be concluded that combining ac over-voltage stresses e.g. up to $1.7U_0$ for new installed cables and up to 80% of $1.7U_0$ for service aged cables, with sensitive PD detection can be useful to demonstrate that the cable system is PD-free. In the case that discharging defects are present the PD behavior (PD inception voltage, PD level) and the location (mostly accessories) can be determined and evaluated form the point of view of degradation stage.

6 PARTIAL DISCHARGES

The partial discharge diagnosis may indicate weak spots in a cable connection. In order to run the measurement, partial discharges are ignited in the cable insulation or joints by the application of a test voltage [8-10]. The occurrence of partial discharges has physical character and it is described by such important parameters as PD inception voltage, PD pulse

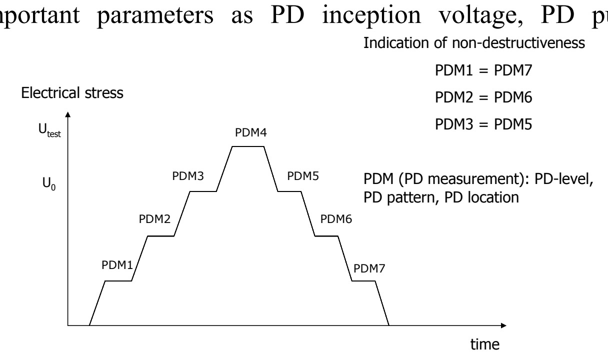

Figure 7. Schematic application of PD measurements to confirm the non-destructiveness of an on-site ac over-voltage test. Performing PD measurements during over-voltage tests and comparing the PD measurement results PDM can be vary valuable to evaluate the effect of an over-voltage stress on discharging insulation defects.

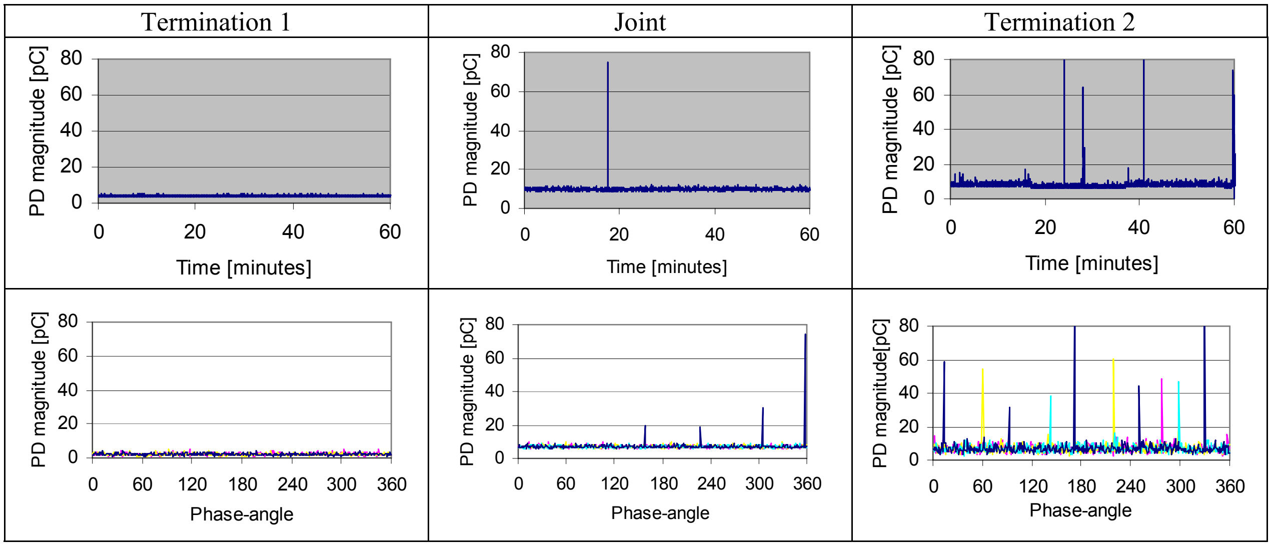

Figure 8. Example of measuring results simultaneously obtained at the three cable accessories during the acceptance test of one cable: the PD magnitude versus time for one hour testing and examples of phase-resolved patterns obtained during several cycles of the test [18].

Table 2. On-site testing and PD measurements methods.

TEST TYPE	DESCRIPTION
1) AC voltage test	a) AC test voltage 20-300 Hz substantially sinusoidal b) Test @ 1.7 U_0 / 1 h (but lower values are also allowed) c) As alternative, a test @ U_0 / 24 h may be applied
2) AC voltage test and not standardized (non-conventional) PD measurement (Figure 1)	a) RF (up to 500 MHz) PD measurement in [µV] b) detection of PD in cable accessories
3) AC voltage test and PD measurement in accordance to IEC60270/ IEC885-3 (Figure 2) Note: IEC60270 High-Voltage Test Techniques - Partial Discharge Measurements is a general standard for PD detection in [pC] and does not cover distributed systems such as installed cable systems.	a) PD level measurement in [pC] b) localization of PD in cable insulation c) localization of PD in cable accessories

magnitudes, PD patterns and PD site location in a power cable. Also performing on-site PD measurements at test voltages higher than the normal network voltage stresses ($1.0U_0$) up to highest system voltages ($1.7U_0$) is important for several reasons (Figures 6 and 7).

a) To see and to evaluate if there are discharging insulation defects with PD inception voltage (PDIV) > U_0. Such defects may initiate insulation failure in the case of temporary ac over-voltages.

b) to conclude in similar way as after successful after-laying test, that there are no PD detected up to $1.7U_0$ and that during the service operation the power cable insulation is free of discharging defects.

c) That the on-site test has not initiated any discharging processes in the insulation which information is important to confirm the non-destructives of the diagnostic on-site test itself.

Moreover, for utilities, which are interested in applying PD diagnostics for condition assessment of their power cable networks, all these parameters are of importance. In particular, analyzing PD parameters for different types of cable insulation and cable accessories can result in developing experience norms [14]. Such norms would be very helpful in developing knowledge rules to support asset management decisions.

7 APPLICATION EXAMPLES

Based on the field experiences the following three types of ac on-site testing can be defined, see Table 2. Depending on the type of test as applied, differences may occur in the information which can be obtained. In particular the 3rd type of test, where in addition to selected over-voltage also the presence of discharging defects in the whole cable system (insulation and accessories) can be investigated, will provide complete information with regard to PD occurrence.

To illustrate the specific character of the different types of testing where PD detection is combined two practical examples are discussed below.

7.1 EXAMPLE OF AFTER-LAYING TEST

In this section an example of HV cable tested by continuous ac voltages with non-conventional PD measurement will be shown (test type 2, Table 2).

After the installation of two 380 kV cable connection an ac voltage test with non-conventional PD measurements was performed. The 380 kV cable connections consist of two 2200 m long XLPE cable circuits [15]. Each circuit is divided into two sections by means of joints and it is terminated by composite outdoor sealing ends. Each phase of the two circuits was tested for 1 hour at 374 kV ac voltage (phase to ground), according to the IEC62067 standard [7].

The voltage was applied by means of an ACRF system [16]. The ac voltage frequency during the test was 43 Hz. At this frequency value the resonance condition is fulfilled for the cable capacitance and for the fixed inductance of the ACRF system reactor [16].

During the ac voltage test, partial discharge measurement was performed at the cable accessories. For this purpose three autonomous PD measuring units were installed at the two sealing ends and at the joint of each cable phase.

A measuring unit consists of a VHF/UHF PD sensor integrated in the cable, a pre-amplifier and a PC-controlled spectrum analyzer [17, 18]. In addition, a trigger unit was adopted to synchronize the ac voltage and the PD signal. Finally, a wireless network was used for the communication between the three stand-alone measuring systems. In [18] the PD detection system is described.

Before starting the PD measurement, the sensitivity check as described in [18] was performed. This was done in order to convert the measured voltage signal in μV's into a PD signal in pC's. Using a fast impulse generator which was calibrated in the laboratory, artificial PD pulses were injected into each cable termination.

To achieve optimal performances of the measuring system, the spectrum of each PD detection unit was tuned to maximize the signal-to-noise ratio. For the specific spectrum range used for the PD detection, the noise level was lower 10 pC. However, due to the fact that the terminations itself act as large antennas, some external noise activity was observed.

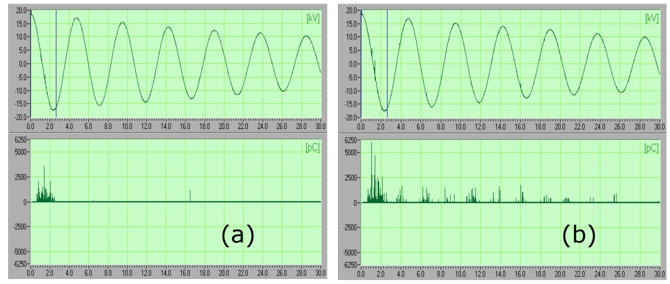

Figure 9. Typical phase-resolved PD patterns as observed at damped AC stresses of:
a) a discharging insulation defect (delamination) in oil filled system
b) a discharging insulation defect (cavity) in epoxy insulation or dry area of PILC insulation.

In order to separate these external disturbances from eventual partial discharge signals, the phase-resolved PD patterns were displayed in real time and stored during the PD measurements. In this way it was possible to establish that all accessories employed in the cable connection were PD-free at voltage of 374kV.

In Figure 8, some of the results of the PD measurements are shown. Thanks to the real-time phase-resolved PD plotting, random disturbances could be discriminated, as shown Figure 9, at termination 2.

7.2 EXAMPLE OF CONDITION ASSESMENT TEST

In this section an example of service aged HV cables tested by damped ac voltages with conventional PD measurement (test type 3, Table 2) is presented.

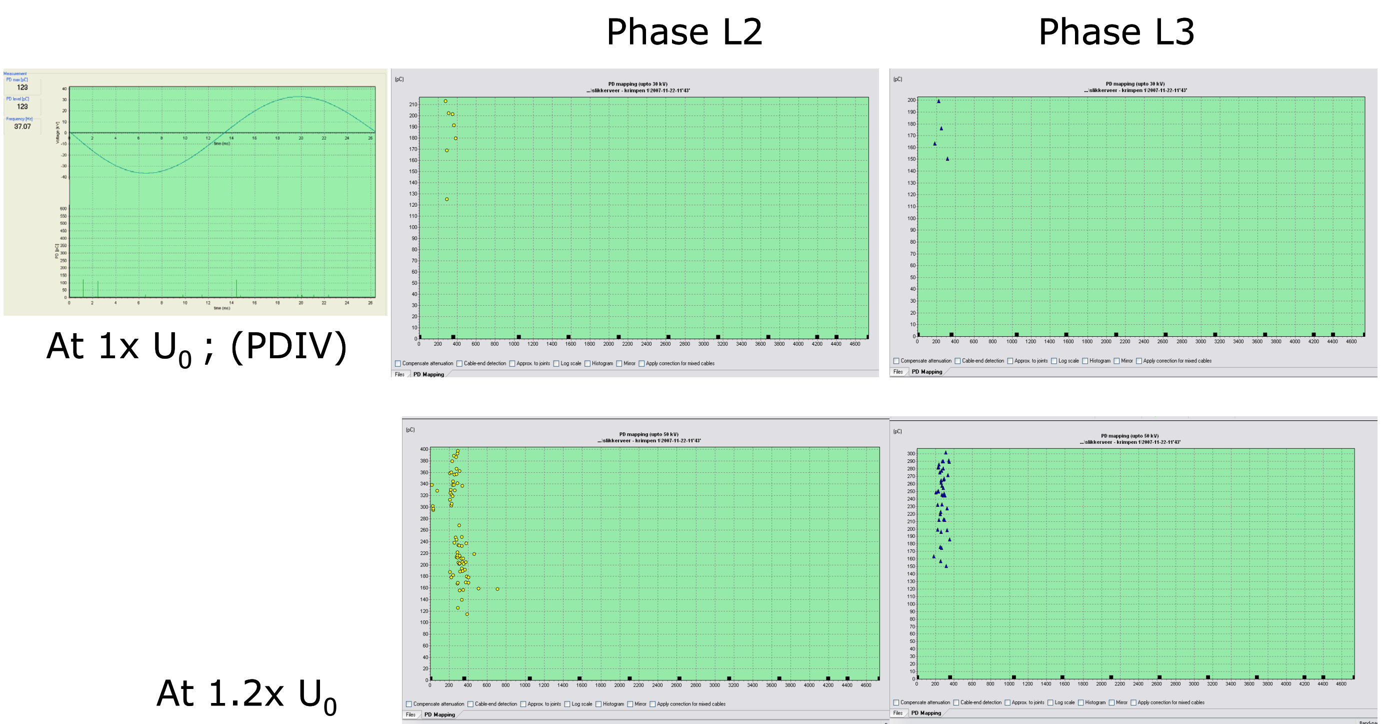

Figure 10. Example of phase-resolved PD patterns as observed during on-site testing of a 50 kV, oil-filled, 4.8 km long HV cable section: Upper row at 1.0 U_0 shows the PD phase resolved pattern with PD inception of discharges up to 200 pC (left picture), PD mapping indication that in a joint at 380m position (phases L2 and L3) PD activity has been observed (middle, right picture), Lower row show at 1.2 U_0 the PD mapping with indication of PD activity up to 440 pC in a joint at 380m position (phases L2 and L3) (left, right picture)

To evaluate correctly the test results of service aged cable systems and in particular the PD measurements knowledge about the test object is required. Type of cable insulation, length of cable sections, position and the information about type of joints are necessary to conclude from the PD parameters PDIV, PDEV, PD level at PDIV and at voltages up to $2.0U_0$ on the severity of PD defects.

With regard to HV power cables it is important to maintain on-site low as possible background noise level e.g. lower than 10pC. To be able to evaluate the PD measurement in [pC] PD calibration of a measuring circuit has to be done. PD calibration means the reading adjustment of the diagnostic system to particular parameters of the test circuit [16]. This calibration consists of a process where two calibrations procedures are automatically performed:

a) Calibration of the PD reading; in accordance to IEC60270 recommendation a PD pulse calibrator as defined in the IEC 60270 has to be used.
b) Calibration of the PD pulse propagation velocity reading: for this purpose the same as in a) mentioned PD pulse calibrator can be used.

Analyzing phase-resolved PD patterns provides the recognition of the type of PD defect in PILC and in typical constellations of joint or termination failures in XLPE cables. Typical patterns from PD in oil filled joint (Figure 9) can clearly distinguished from PD in voids, gaps or for example from PD between paper layers in a dry area of PILC cables.

Stressing the cable insulation with DAC voltages and applying time domain reflectometry (TDR) to PD signals in HF range (up to 50 MHz) provides the PD site location in cable insulation. In particular a PD mapping can be generated (see examples in figure 10 and 12) where the whole cable length is shown (black dots indicate cable joints) and where the PD activity can be pointed out in function of the cable length. As a result a PD mapping of a cable indicates the location and statistics of magnitude and intensity of PD occurrences (Figure 10).

With the knowledge about type of components in the circuit, the PD parameter, the information from the mapping about concentrated PD activities, the operational history and importance of the circuit an evaluation of PD defects and clear recommendations for maintenance or replacement can be concluded.

In general HV power cables (starting from 50kV voltage system ratting) suppose to be PD free. This status has to be confirmed during after-laying tests of new or repaired HV cables, or during condition assessment tests of service aged power cables (Figure 11a). Therefore, with regard to HV power cables it is important to maintain on-site low as possible background noise level e.g. lower 10 pC.

Also performing on-site of PD measurements at test voltages higher than the normal network voltage stresses (1.0 U_0) up to highest system voltages (1.73 U_0) is important for several reasons.

a) To see and to evaluate if there are discharging insulation defects with PD inception voltage (PDIV) > U_0. Such defects may initiate insulation failure in the case of temporary AC over-voltages.
b) To conclude in similar way as after successful after-laying test, that there are no PD detected up to 1.73 U_0 and that during the service operation the power cable insulation is free of discharging defects.

That the on-site test has not initiated any discharging processes in the insulation which information is important to confirm the non-destructives of the diagnostic on-site test itself.

In Figures 11 and 12 an example is shown of a 55 year's old cable section which is not PD- free. In particular due to PDIV

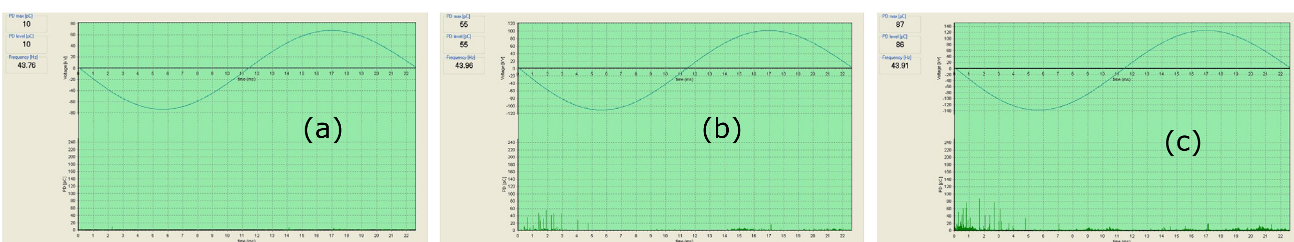

Figure 11. Example of phase-resolved PD patterns as observed during on-site testing of a 150 kV, oil-filled, 55 years old, and 6.2 km long HV cable section: a) at 0.7 U_0: background noise is < 10 pC, the cable section is PD-free, b) at 1.0 U_0: PD activity up to 40 pC starting at $0.9U_0$ has been observed in phase L1, c) at 1.2 U_0: PD activity up to 90 pC starting at $0.9U_0$ has been observed in phase L1

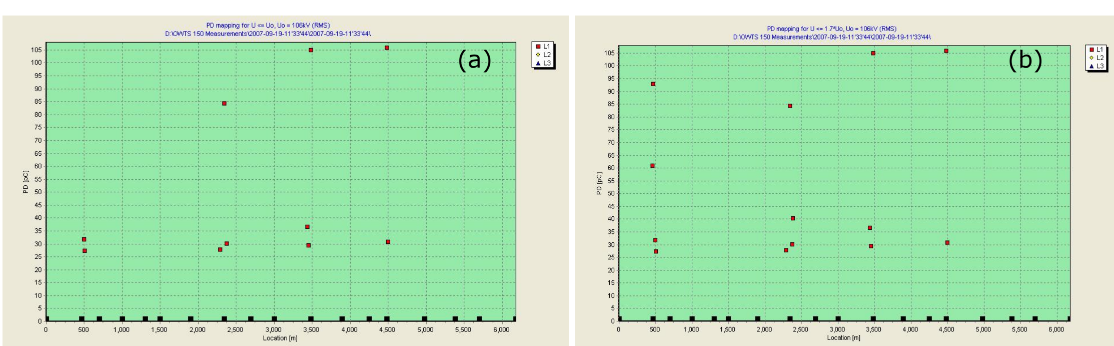

Figure 12. Examples of PD mappings as made during on-site testing of a 150 kV, oil-filled, 6.2km long, and 55 years old HV cable section: a) up to $1U_0$: PD activity between up to 100 pC has been observed in four joints (phase L1), b) up to $1.2U_0$: as compared to $1U_0$ no significant change of PD behaviour.

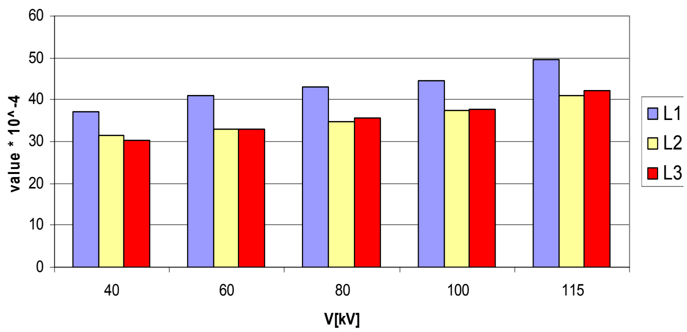

Figure 13. Example of dielectric losses (tan ∂) measurement between $0.3U_0$ and U_0 on a 150 kV, oil filled, 6.2 km long and 55 years old HV cable section.

lower than $1.0U_0$ it was of importance to localize the PD activity in the cable. It follows from the PD mappings (Figure 6) that all discharges as observed in phase L1 are localized in cable joints. Also it was observed that an increasing the test voltage up to 1.2 U_0 did not changed significantly the PD magnitudes. Additional measurements of dielectric losses (tan ∂) in function of the test voltage have confirmed that comparing to phases L2 and L3 the phase L1 shows higher values of dielectric losses (Figure 13).
Finally the information of PD presence in one of the phases of the 150 kV cable section as well as the deviating behavior of dielectric losses are valuable inputs for further decisions about the maintenance and the operation of this particular HV cable section.

8 CONCLUSIONS

Based on the discussion of this paper the following can be concluded:

1. Electrical testing on-site is an important step of quality insurance of new/repaired and service aged cable systems. Actual knowledge of the condition of HV cable systems may support the network managers
   a. to obtain a finger print of new installed cable section,
   b. to evaluate overall condition of the power network condition,
   c. to be able to estimate the reliability of the power network,
   d. to set up maintenance/replacement schedule, diagnostic data may provide important information for conditions assessment.
2. There are several methods of on-site ac voltage generation which can be applied for withstand testing and for voltage testing in combination with PD measurements.
3. Enhanced ac voltage testing up to e.g. $1{,}7U_0$ or even $2.5U_0$ of defect-free /non aged insulation does not have destructive influence on the service life of the component.
4. Due to service life time consumption of installed HV circuits for on-site testing (for after-repair or diagnostics purposes) lower ac over-voltages e.g. 80% should be used.
5. Enhanced ac voltage testing higher than $1.0U_0$ of defective/aged insulation may have destructive influence on the service life of the component in service. Even if no breakdown has occurred.
6. Combining ac voltage on-site testing with PD detection provides information about discharging insulation defects. Moreover it can be assessed, if the on-site test had a destructive impact on the insulation system.
7. Based on field experiences and using diagnostic data (partial discharges, dielectric losses) for different types of insulation and accessories experience norms can be estimated.
8. Such experience norms can be used to support the Asset Management decision processes of HV power cable networks.

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