Die Anwendung von gedämpften Wechselspannungen für Vor-Ort Prüfungen und Zustandsbestimmung von Hochspannungskabeln The application of damped AC voltages in onsite testing and conditioning of high voltage cable

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Kurzfassung

Für die Inbetriebnahmeprüfung nach Erstmontage einer neuen Hochspannungskabelanlage oder für die Qualitätskontrolle nach einer Reparatur stehen heute verschiedene Arten von Vor-Ort-Prüfungen zur Verfügung. Eine besondere Herausforderung an die Prüftechnik stellt dabei die Prüfung von Kabelanlagen mit großen Kabellängen bei Nennspannungen von zum Beispiel 220 kV oder höher dar.
Gleichzeitig wird die Möglichkeit zusätzlicher Aussagen, beispielsweise hinsichtlich der Diagnose des Alterungszustandes (tan δ) oder der Kontrolle einer Muffenmontage (TE-Messung), vor Ort für Betreiber, Kabelhersteller und Montageunternehmen immer wichtiger.
Der vorliegende Beitrag berichtet über Aspekte der Vor-Ort-Prüfung und Diagnosemessungen die heute für Hochspannungskabelanlagen verfügbar sind. Basierend auf Untersuchungen in unterschiedlichen Stromnetzen, an Kabeln unterschiedlicher Hersteller und den Erkenntnissen aus der Arbeit von Cigre, IEEE gibt dieser Beitrag grundlegende Hinweise und Anwendungsaspekte für die Vor-Ort-Prüfung und Diagnose von Hochspannungskabelanlagen mit Hilfe von gedämpften Wechselspannungen.

Abstract

For after-laying tests of new high voltage cable systems and maintenance tests after repairing, there are different kinds of onsite test methods available. A special challenge for the test equipment is the test of long length cable systems with nominal voltages of 220 kV or higher.
Also the possibility of observing additional conclusions onsite get more and more important for the operating company, cable manufacturer and installation company. In example the diagnosis of the ageing (tan δ), or the test of a joint installation (PD-measurement) gives important information.
This contribution reports about the aspects of onsite tests and diagnostic measurements which are available nowadays for high voltage cable systems. Based on investigations in different power networks, cables of different manufacturer and the knowledge of the activity in Cigre, IEEE this contribution gives basic information and application aspects for the onsite test and diagnostic in high voltage cable systems by use of damped oscillating voltages.

1 Introduction

High voltage power cables are distributed insulation systems up to several kilometers. It is known, that small damages and/or bad installation practices on power cables may deteriorate and lead to failures which can occur in the cable insulation and/or accessories as a result of the normally applied operational stresses or during transient voltage stresses, such as lightning or switching overvoltages [1-9], **figure 1**.
As a result in addition to factory routine tests the reliability of power cables may further be improved by on-site after-laying testing and service diagnosis. In general the on-site testing can be applied for three main reasons: as a part of commissioning on-site, after repairing, or as a diagnostic test for service aged cables.

In general as on-site acceptance test for newly installed or repaired circuits one of the two approaches is in use:

1) Withstand test by over-voltage stresses applied, e.g. $2xU_0$ for 1 hour to the test object.
2) Withstand tests with “operational voltage level” of $1xU_0$ applied for 24 hours.

The first approach is based on the assumption that a healthy (defect-free and/or non-aged) insulation can withstand high level of voltage stresses and all insulation which is aged and/or consists of insulation defects should have lower level of withstand voltage and should produce a breakdown during the designated test time.
It is known that the above described so called non-monitored voltage withstand testing methods only, are not always sufficient to identify all manufacturing and installation problems. Moreover it has to be considered that due to test voltage stresses higher than the operational voltage,

the test may be destructive even if no failure has occurred, or because of that the duration of the over-voltage is arbitrarily selected e.g. 1 hour. It cannot be excluded that after 1 hour and 10 minutes a failure will occur which might be initiated during the test.

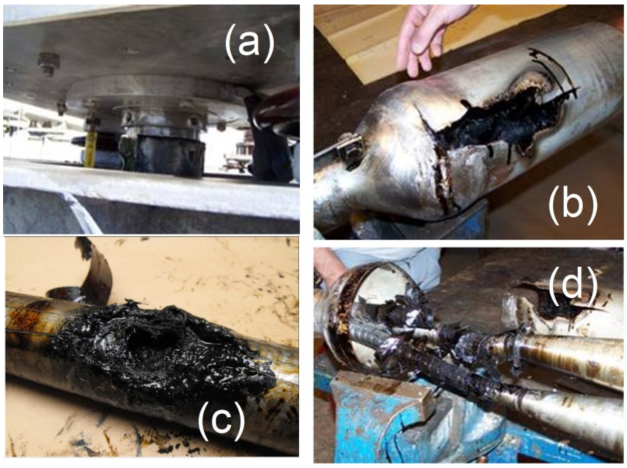

Figure 1 Examples of insulation defects in power cables: (a) termination of 132 kV XLPE cable with unsealed bottom resulting in contamination and moisture ingress inside insulator, (b) (c) cable movement due to expansion of oil due to high temperatures. Directly resulting in cracks and voids in joint insulation with final breakdown, (d) electrical treeing in 150 kV gas pressure cables resulting in long term insulation degradation and finally cable breakdown [10].

Figure 2 Modern monitored on-site testing and diagnosis with damped AC voltages on a 220 kV cable circuit.

Therefore to detect during after-installation or after-repair testing all weak points in the cable insulation and cable accessories monitored testing is becoming nowadays more and more the common practice. It is known that monitored testing consists of a voltage withstand test combined with a diagnostic test, e.g. partial discharge measurement.

Practical realization of such on-site tests becomes more attractive if the modern on-site test system performs:

- high level of mobility and lightweight
- compactness versus output voltage
- easy assembling and low supply voltage
- low power demand also for long cable lengths
- possibility of sensitive standardized PD detection and dissipation factor measurement

In this paper, based on general consideration and practical examples, the use of damped sinusoidal AC voltages (DAC) for monitored testing of new installed and service aged power cables will be discussed, **figure 2**.

2 Necessity and effect of on-site testing for high voltage cable systems

It was already mentioned that the on-site test for after-laying and repaired cable systems is a useful practice to determine the defect freeness and correct installation of the parts of the whole cable system. But not only the test results are important information, also the effect and influence of the on-site test to the cable installation is an important issue. The lifetime shortening by stressing the cable parts by overvoltage should also be considered. In that case the electrical stress for the installation should be compatible with the lifetime consideration.

In general applying enhanced voltage in after-laying testing e.g. up to $2xU_0$ to a defect-free and not aged cable insulation does not have significant influence on the service life of the component. It follows from [9] that in this case the life-time consumption can 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 and several interactions are possible between the defect type/location, breakdown and pre-breakdown possibilities and the test voltages applied [9].

The stress level for accessories is in direct interaction with the type of defect and the local electric field enhancement. E.g. presence of internal cavities on the outer conductor in cables insulation has lower breakdown impact for the same cavity which is close to inner cable conductor. During the on-site testing with ac over-voltages in the 1st case a breakdown is less probable as compared to the 2nd case. In both cases depending on the local field enhancement in kV/mm in the cavities significant PD activity can be detected. 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, see **figure 3**.

3 Consideration of the monitored DAC withstand test

In the following part the advantages of monitored DAC withstand test due to the non-monitored DAC withstand test will be pointed out. Therefore the two classes of test can be described in the following way:

The non-monitored DAC withstand test applies only a defined number of DAC excitations with a specified maximum DAC voltage. The aim of this test is to check if the test object could withstand the maximum defined DAC voltage (i.e. no breakdown occurs), see the dotted lines in figures 3a and 3b. The intent of a simple DAC withstand test is to cause weak points in the circuit to fail during voltage application (with minimal fault current) at a time when the impact of the failure is low (no system or customers affected) and repairs can be made more cost effectively. If a failure occurs during the test, see the dotted lines in figures 3c and 3d, the failure should be located through a fault location process, repaired and the circuit retested. The results of these tests are described as either Pass or Fail.

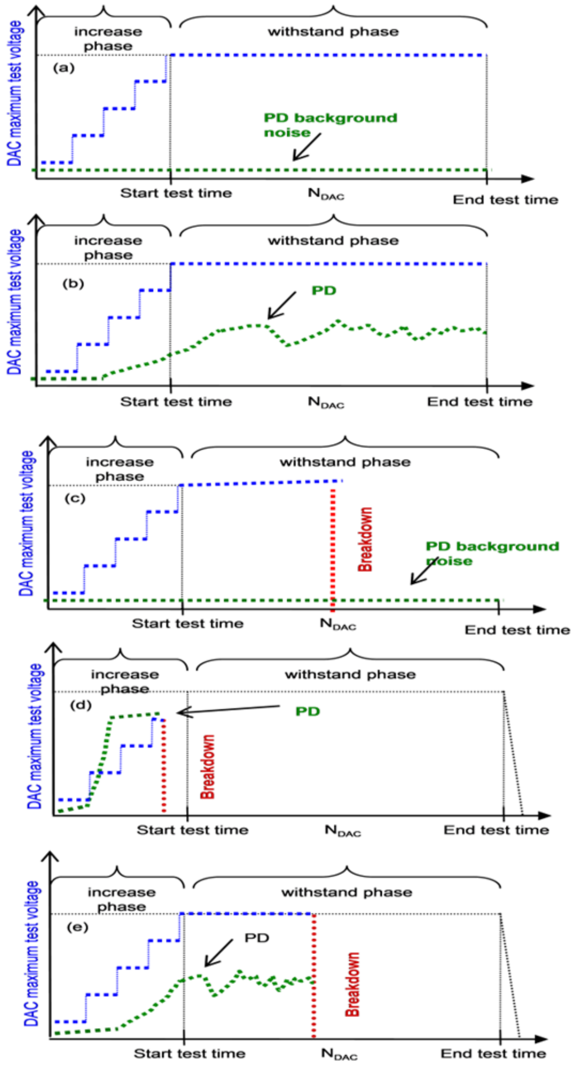

Figure 3 Schematic overview of different situations of DAC voltage withstand test: (a), (b) no breakdown during selected number of DAC excitations (dotted lines) and alternatively above the PD background noise PD has been observed or not; (c) breakdown during DAC withstand test without any PD presence; (d), (e) breakdown before the for the DAC withstand test selected number of DAC excitations has been applied during voltage increase phase respectively during voltage withstand phase and above the PD background noise PD has been observed.

The monitored DAC withstand test – a number of DAC excitations are applied and one or more additional attributes are measured and used to determine whether the cable passes or fails the DAC test, see in figures 3 dotted lines for DAC voltage and dashed lines for PD measurement. These additional attributes are advanced diagnostic properties such as partial discharge detection.
Due to this additional information as provided by PD detection the monitoring insulation properties during a DAC withstand test and the effect of the test voltage during its application can improve the evaluation of the insulation condition.

4 General aspects of on-site testing

According to [1, 6, 9] several voltages and test procedures have been defined for on-site testing. Based on field experiences a number of test voltage types are in use for testing and diagnosis. Moreover depending on the particular voltage type different application effectiveness can be given. In particular applying sinusoidal AC voltages has long history in laboratory testing of all types of cable insulation and more than 10 years long history in on-site testing of all types of cable systems. Experiences have confirmed that applying on-site AC electrical stresses is applicable for the recognition of all types of failures related to insulation and it can also be combined with diagnostics e.g. PD, dielectric measurements [9]. According to [1] the sinusoidal damped AC voltages have been proposed 20 years ago as a complementary and/or alternative method to sinusoidal continuous AC voltages and in the last years DAC has become accepted for on-site testing and PD measurements of all types and lengths of power cables [3, 5, 7]. Moreover as compared to conventional continuous AC testing DAC systems fulfill the above mentioned characteristics of modern on-site testing methods, figures 2, 4.
As a result of expectations of modern monitored testing for on-site the use of DAC testing includes several parameters which can be measured as a function of the applied test voltage. Extending the voltage testing by PD measurements provides information about changes in the test voltage and or test duration and the presence of discharging insulation defects. Moreover the increase of PD activity up to e.g. $1.3xU_0$ (generally accepted test voltage level for PDIV to set the PD-free status of a component) is an important indicator about the PD activity at voltages higher than the operational stress which may occur during the service life [8]. The estimation of the dissipation factor at operational stresses, e.g. up to $2xU_0$ and at one of the equivalent power frequencies, e.g. 20-300Hz is an important parameter of oil-impregnated cable.

5 On-site testing with damped ac voltages

Damped alternating voltages are generated by the coupling of the charged test object capacitance with a suitable inductance. The test circuit basically consists of a unipolar HV voltage source, an HV inductor, a capacitor represented by the test object and a suitable HV switch. When the preselected maximum test voltage level is reached, the HV switch is closed. This is generating a damped alternating voltage at the test object, see **figure 4**.

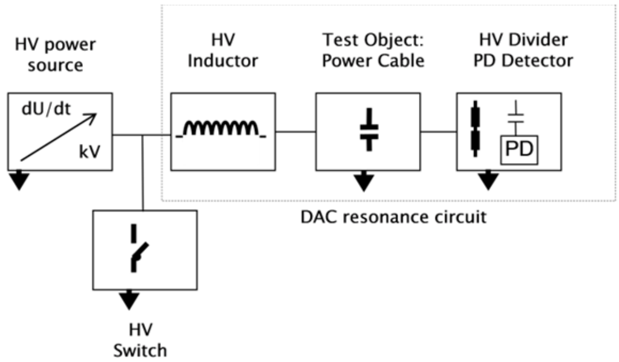

Figure 4 Schematic block diagram of a DAC system with PD detection unit.

DAC testing can be used as simple withstand test or in combination with partial discharges (PD) and dissipation factor (DF) measurements. For the voltage withstand test, a predetermined number of DAC excitation is applied. Due to shorter duration of the excitation and decaying characteristic of the voltage, test results obtained by DAC testing can be different from those obtained by continuous AC withstand voltage testing.

To generate damped AC (DAC) voltages with duration of a few tens of cycles of AC voltage at frequencies up to a few hundreds of Hz a system has been developed [1, 2]. This method is used to energize and to test on-site power cables with sinusoidal AC frequencies in the frequency range of 20 Hz up to 500 Hz. In addition this method can easily be used to measure and to locate on-site partial discharges in power cables in accordance with IEC 60270 recommendations, figure 4. The system consists of a digitally controlled power supply to charge capacitive load of power cables with capacitive values of e.g. 10 µF. With this method, the cable under test is charged during $t_{charge}=U_{max}\cdot C_{cable}/I_{load}$ with increasing voltage over a period of a number of seconds to the selected maximum test voltage level. Then a specially designed solid-state switch connects an air-core inductor to the cable sample in a closing time of <1 µs. Now a series of AC voltage cycles starts with the resonant frequency of the circuit $f_{DAC} = 1/(2\Pi\sqrt{(L \cdot C_{cable})})$ where L represents the fixed inductance of the air core and C_{cable} represents the capacitance of the cable sample, see **figure 5**. The test frequency of the damped AC voltage is the resonant frequency of the circuit. The air core inductor has a low loss factor design, so a slowly decaying AC waveform of test voltage is applied to the cable sample. During a number of AC voltage cycles the PD signals are initiated in a way similar to 50(60) Hz inception conditions [12]. By usage of digital signal processing of the PD signals, single PD pulses can be obtained and their origins can be localized in the cable. With this advantage also different fault locations can be found simultaneously, see **figure 6**. This method is the so called time domain reflectometry. After localization of the PD origin the cable system could be repaired at the specific position. It could be seen, that the PD origins are localized at different positions. E.g. here phase one and two have clusters at the beginning of the cable and also at the far end. On phase three we see clustering at two positions inside the cable, which were at two joint locations.

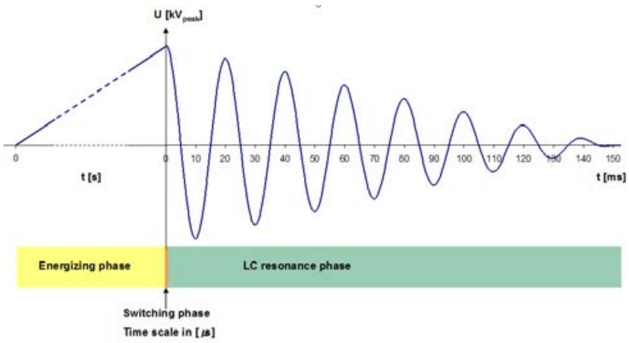

Figure 5 Typical DAC voltage shape. The RMS-value of the voltage is determined by $V_{DAC}/\sqrt{2}$ *of the 1st cycle.*

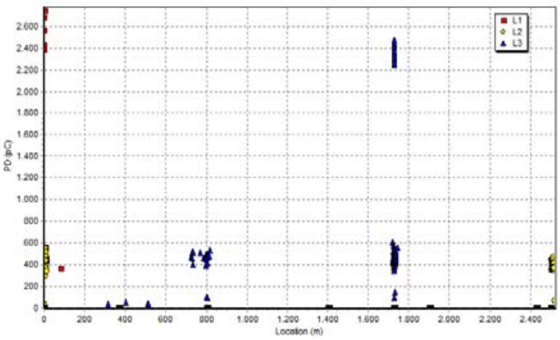

Figure 6 Example for a PD mapping. The clusters of dots show a concentration of PD from the same origin.

In particular the IEC 60840 and IEC 62067 recommend that the test voltage must have a sinusoidal shape, and it should have the frequency in the range 20-300 Hz. As a result damped sinusoidal AC fulfills both recommendations and it can be used for on-site testing. It has to be remarked that comparing to continuous AC test voltages in case of strong inhomogeneous defects (PD presence) the destructiveness of DAC testing can be lower. Therefore it is recommended to perform DAC testing as monitored testing where PD measurement is used to identify the upcoming defects [3-5]. Referring to IEEE 400 and 400.3 and the 400.4 the DAC testing is fully recommended for testing and PD detection. PD measurement in combination with DAC also provides the possibility of localization of the PD-initiating defects.

6 Practical Examples

Application of damped AC voltages for testing and diagnosis of transmission power cables up to 230 kV has a history of more than 6 years [4, 7]. Following with regard to the discussion about the importance of monitored testing two examples will be discussed.

Example 1: A newly installed 12 km long, 50 kV XLPE insulated power cable circuit has been tested in accordance to the Dutch NEN 3630 recommendation. This norm recommends voltage withstands testing using AC resonance system 25-200 Hz applied at $2.5xU_0$. It has been decided to perform monitored withstand testing by using DAC resonant circuit with damped sinusoidal AC voltages (25-200 Hz) for 1 hour testing at $2.5U_0$. During the whole time of withstand test standardized PD detection has been applied. As a result of 1 hour DAC over-voltage no breakdown has been observed, **figure 7**. Also no internal PD activity has been detected (except external corona). It has been concluded that up to 1.7Uo the complete cable system was PD–free (background noise level < 10 pC) and the test has been considered as successful.

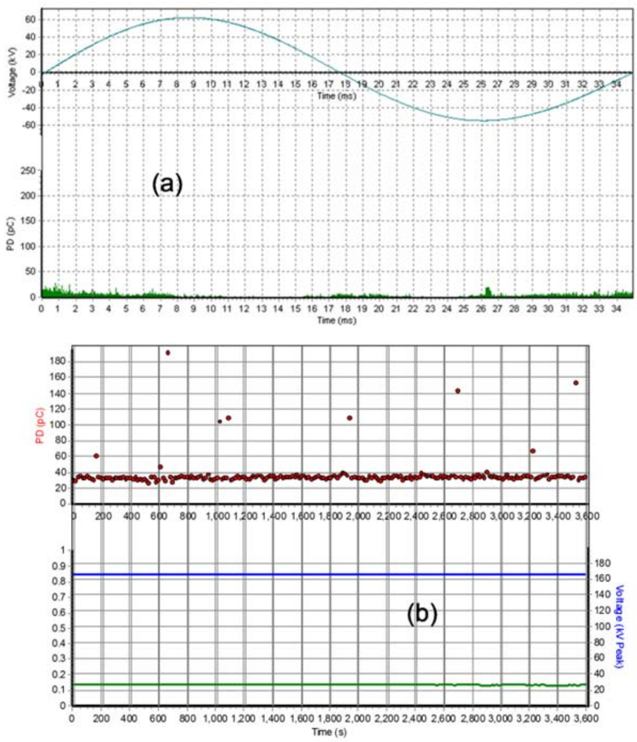

Figure 7 Monitored voltages withstand testing of a 50 kV XLPE cable underground circuit (12 km). (a): Example of PD pattern at $1.7U_0$; (b) DAC voltage withstand test 1hrs $2.5U_0$.

Example 2: A newly installed, 4.0 km long, 110 kV XLPE insulated underground circuit has been energized after a successful after-laying test by 1xUo as applied for 24 hours. After 4 years of operation maintenance test has been performed at 1.3Uo, **figure 8**. At nominal voltage 1xUo no PD has been observed.

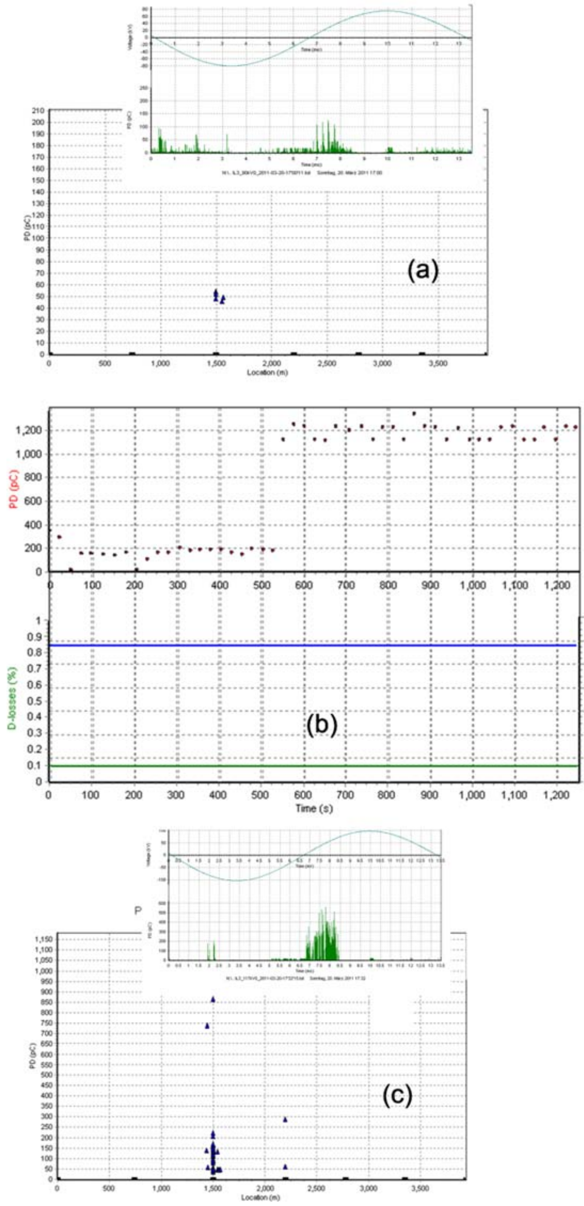

Figure 8 Monitored voltages withstand testing of a 110 kV XLPE cable underground circuit (4 km): a) example of PD pattern and PD mapping at $1.4U_0$ before DAC voltage withstand test, b) DAC voltage withstand test 50 excitations at $1.4U_0$, c) example of PD pattern and PD mapping after DAC voltage withstand test.

Starting from $1.2U_0$ PD activity up to 200 pC has been registered in one of the joints. During DAC voltage withstand test with 50 excitations (IEEE 400) at $1.3U_0$ and after 20 DAC excitations significant increase of PD activity up to 1000 pC has been observed in the particular joint at 1.5 km location. Based on this test it has been concluded that this cable section can be energized for network operation with a possible risk of a failure during operation. Due to the fact that PDIV in the joint at 1.5 km was very close to U_0 and increased network stresses may result in an inception and increase of PD activity the risk of a failure depends on the over-voltage stresses during operation. Replacement of the joint has been recommended or to conclude the progress of degradation at above mentioned locations by comparing PD activity the next maintenance tests have to be done within approximately period of 6 months.

7 Conclusions

Based on the results above the following can be concluded:

- According to newest developments the monitored voltage withstand testing is becoming more and more a common practice. The use of the PD measurement helps to detect and to localize partial discharge defects in the insulation and in accessories.
- For testing power cables damped AC voltages can be applied as an alternative to continuous AC test voltages. DAC Testing is also according to the standards (e.g. IEEE, IEC)
- Regarding breakdown and as compared to non-monitored continuous AC voltage testing in case of inhomogeneous defects (PD occurrence) monitored testing using damped AC voltages can be less destructive and more sensitive (in case there is no breakdown observed) to detect and to localize discharging defects in accessories.
- Application of dissipation factor estimation at power frequencies close to operational conditions provide useful information about the insulation degradation of oil-impregnated power cable circuits.

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