Modern on-site testing and diagnosis of power cables up to 230 kV consists of voltage testing, partial discharge detection, and dissipation factor measurements. Since the last 10 years in addition to continuous ac or VLF energizing, the use of damped ac energizing is getting more and more worldwide attention. Having in mind the forthcoming IEEE 400.4 guide for the use of damped ac testing in this paper the application of damped ac voltages for on-site testing and diagnosis of underground power cables up to 230 kV will be presented.

Insulation failure of a power cable can occur as a result of the normal operational voltage or during a transient voltage due to lightning or switching surges. Examples of failures are shown in Figure 1.

Most failures occur as a result of localized electrical stresses that are higher than the dielectric strength of the dielectric materials in the area of the localized stress or if the bulk dielectric material degrades to the point where it cannot withstand the applied voltage. To find

![Figure 1: Examples of Insulation Defects in Power Cables:](image)

Distribution cables: (a) bad positioning of field grading; (b) large crack in the center of an epoxy resin joint; (c) interfacial problems in a termination; (d) connector sharp edges inside mass insulated cable termination

Transmission cables: (e) termination of 132 kV XLPE cable with unsealed bottom resulting in contamination and moisture ingress in side insulator; (f, h) cable movement due to expansion of oil due to high temperatures, directly resulting in cracks and voids in joint insulation with final breakdown; (g) electrical treeing in 150 kV gas pressure cables resulting in long term insulation degradation and finally cable breakdown
these defects prior to a failure, on-site tests, as shown in Figure 2, are applied to assess the quality and cable system integrity as well as the availability and reliability of the cable circuit.

In relation to the applied damped ac testing procedures, the IEEE 400.4: Guide for Field-Testing of Shielded Power Cable Systems Rated 5 kV and above with Damped Alternating Current Voltage (Damped ac), document is under balloting. This guide includes practical considerations, based on user experience during the last 10 years in relation to several IEC standards. Examples of such considerations include the number of damped ac excitations applied during testing and the minimum recommended test voltage level. User feedback has confirmed the following test parameters:

(a) Maximum damped ac test voltage levels:
   a. For MV cables (6-35 kV) up to 2.0 \( U_0 \) (\( U_0 \) is the rated phase to ground voltage)
   b. For HV cables (36-150 kV) up to 1.73 – 2.0 \( U_0 \)
   c. For EHV cables (150-230 kV) up to 1.4 – 1.7 \( U_0 \)

(b) Number of damped ac excitations at maximum applied damped ac voltage withstand level: 50.

In this paper, the use of damped sinusoidal ac voltages (damped ac) for monitored testing of power cables will be discussed based on general considerations and practical examples.

**ON-SITE ENERGIZING METHOD AT DAMPED AC VOLTAGES**

Damped ac testing can be used as a simple withstand test or in combination with partial discharge (PD) and dissipation factor (DF) measurements for new installed and service-aged cables, Figure 3. The use of damped ac voltages for testing power cables is in compliance with relevant IEC, IEEE, and Cigre international standards and guidelines.

![Figure 3: General Overview of Damped ac (DAC) Field Test Possibilities for Different Testing Goals of Cable Systems [IEEE 400.4/D8 under balloting]](image)

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**Figure 2: Example of On-site Testing Using Sinusoidal Damped ac Voltages (a) diagnostic testing by damped ac system 30 kV of a 3 km long 10 kV XLPE insulated cable; (b) after-laying testing by a damped ac 190 kV system of a 12 km long 110 kV XLPE cable; (c) after-laying testing by a damped ac 270 kV system of a 6 km long 150 kV XLPE cable**
To generate damped ac voltages with durations of a few tens of cycles of ac voltage at frequencies up to a few hundreds of Hz, a test system has been developed. This method is used to energize and to test on-site power cables with sinusoidal ac frequencies. The system consists of a digitally controlled high voltage power supply to energize capacitive load of power cables with large capacitance (e.g., 10 µF), Figure 6. With this method, the cable under test is energized during a time \( t_{\text{charge}} = \frac{U_{\text{max}} C_{\text{cable}}}{I_{\text{load}}} \) with continuously increasing voltage, see Figure 4. During this phase the test object is stressed with an increasing unipolar voltage. The energizing time depends on the maximum available load current of the voltage supply, the test voltage, and the capacitance of the test object. As a result, due to ac field distribution, dc stress, steady-state condition, and space charges are not applied to the test object, and the damped ac stress as applied to the test object can be considered as similar to factory testing conditions.

At maximum selected test voltage, a specially designed solid-state switch connects an air-core inductor to the cable sample in a closing time of <1 µs. Due to relatively low cable inductance, no transient overvoltages will occur in the test object. At this moment, the series of ac voltage cycles starts with the resonance frequency of the circuit \( f_{\text{damped ac}} = \frac{1}{2\pi\sqrt{L \cdot C_{\text{cable}}}} \) where \( L \) represents the fixed inductance of the air core and \( C_{\text{cable}} \) represents the capacitance of the cable sample, Figure 6. The air core inductor has a low loss factor and design, resulting in a slowly decaying ac waveform of test voltage 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. This procedure can be repeated for multiple excitations followed after each other to perform a voltage withstand test as shown in Figure 5.

The DF can be measured with the decay characteristics of the damped ac voltage wave and the evaluation of the DF can be

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**Figure 4:** Schematic Overview of One Damped ac Excitation. The maximum damped ac voltage level is determined by the voltage peak values \( V_{\text{damped,ac}} \) and respective RMS-values \( V_{\text{damped,ac}/\sqrt{2}} \) of the 1st damped ac cycle.

**Figure 5:** Schematic overview of withstand test by damped sinusoidal ac voltage excitations. The duration of the test is determined by the number of damped ac excitations which are applied to the power cable at a selected damped ac test voltage. The maximum damped ac withstand voltage level is determined by the voltage peak values \( V_{\text{damped,ac}} \) and respective rms-values \( V_{\text{damped,ac}/\sqrt{2}} \) of the first damped cycle.

**Figure 6:** Schematic Diagram of Damped ac (DAC) Systems for On-site Testing and PD Detection of Distribution and Transmission Power Cables.
especially valuable for finding insulation ageing development in paper-oil insulated cables.

**DAMPED AC VOLTAGE WITHSTAND TESTING**

The application of withstand tests can be divided into two classes:

1. Unmonitored damped ac hold test: a number of damped ac excitations is applied and the ability to hold the maximum damped ac voltage (i.e., no breakdown occurs) is recorded as seen by the black dotted lines in Figures 7a and 7b. The intent of a simple damped ac withstand test is to cause weak points in the cable insulation to fail during voltage application (with minimal fault current) at a time when the impact of the failure is low (no systems or customers affected) and repairs can be made more cost effectively. If a failure occurs during the test, see the vertical dotted line in Figure 7c breakdown, then the failure should be located through a fault location process and repaired and the circuit retested. The results of these tests are described as either pass or fail.

2. Monitored damped ac hold test: a number of damped ac excitations are applied and one or more additional attributes are measured and used to determine whether the cable passes or fails the damped ac test. In the graphs in Figure 7, the black dotted lines represent the applied damped ac voltage and the grey dotted lines represent the PD detection. Due to additional information as provided by PD detection, the monitoring insulation properties during a damped ac withstand test, and the effect of the test voltage during its application can improve the evaluation of the insulation condition.

The applied maximum test voltage levels for voltage withstand testing of newly installed cables are given in Table 1.

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**Figure 7:** Schematic Overview of Three Different Situations of Damped ac (DAC) Voltage Withstand Test: (a, b) during selected number of \( N_{\text{DAC}} \) excitations (black dotted lines) no breakdown has occurred and alternatively above the PD background noise PD has been observed or not (grey dotted lines); (c) before the selected number of \( N_{\text{DAC}} \) excitations for the damped ac withstand test has been applied breakdown has occurred, and above the PD background noise PD has been observed.
PRACTICAL EXAMPLES

The application of damped ac voltages for testing and diagnosis of transmission power cables up to 230 kV has a history of more than 10 years. In this section, examples are presented and discussed to highlight the importance of monitored testing.

Example 1: A newly installed 2.1 km long, 10 kV XLPE insulated underground cable circuit has been tested in accordance with the IEC 60502 Standard which recommends voltage withstand testing using sinusoidal ac voltage up to 2 \( U_0 \). Monitored withstand testing was performed by using a damped ac resonant circuit with damped sinusoidal ac voltages at 224 Hz for 50 damped ac excitation at 2.0 \( U_0 \). For the duration of the withstand test, standardized PD detection was applied. During the application of damped ac over-voltage, no breakdown was observed. It follows from Figures 8 and 9 that internal PD activity was registered in a joint in phase L3. The joint was investigated and the PD source

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**Table 1:** Damped ac test voltages levels (20 Hz–500 Hz) as used for damped ac testing (50 damped ac excitations) of recently installed power cables [IEC 60502, IEC 60840, IEC 62067].

<table>
<thead>
<tr>
<th>Power cable rated voltage ( U ) [kV] phase-to-phase</th>
<th>( U_0 ) [kV]</th>
<th>DAC test voltage level ( V_T ) [kV(_{peak}) phase-to-ground]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
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</tr>
<tr>
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<tr>
<td>30</td>
<td>18</td>
<td>51</td>
</tr>
<tr>
<td>35</td>
<td>21</td>
<td>60</td>
</tr>
<tr>
<td>45-47</td>
<td>26</td>
<td>74</td>
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<td>60-69</td>
<td>35</td>
<td>99</td>
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<td>64</td>
<td>181</td>
</tr>
<tr>
<td>132-138</td>
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<td>187</td>
</tr>
<tr>
<td>150-161</td>
<td>87</td>
<td>212</td>
</tr>
<tr>
<td>220-230</td>
<td>127</td>
<td>254</td>
</tr>
</tbody>
</table>

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**Figure 8:** PD Results of an After-laying Testing of a 10 kV 2.1 km Long XLPE Cable Section

<table>
<thead>
<tr>
<th>PD level:</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDIV L3 = 1.7 ( U_0 )</td>
</tr>
<tr>
<td>PD level L3 = 200pC @ PDIV</td>
</tr>
<tr>
<td>PD level L3 = 800pC @ 2x( U_0 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PD location:</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3: 1 joint at 955 meter</td>
</tr>
</tbody>
</table>

**Figure 9:** Investigation of the Joint at 955 m Location Having PD up to 800 pC at 2 \( U_0 \)
was identified in the crimping tube. After the repair, the complete cable system was free of PD and the test was considered successful.

**Example 2:** Maintenance testing was performed on a service-aged 2.0 km long 30 kV XLPE insulated underground circuit. Starting from 0.6\(U_0\), PD activity up to 9000 pC was registered in one of the joints. Increasing the damped ac test voltage up to 1.7 \(U_0\) resulted in concentrated PD activity in this particular joint (Figure 10). Due to the fact that the PD inception voltage is below \(U_0\), increased network stresses may result in inception of, and an increase in PD activity during normal operation. Recommended replacement of the joint was accomplished, and the investigation confirmed a PD source (Figure 11).

**Example 3:** A newly installed 13.3 km long, 220 kV XLPE insulated underground cable circuit was tested using a damped ac resonance system at 49 Hz, applying up to 1.3 \(U_0\), (Figures 12-14). Monitored withstand testing was performed. As the damped ac test voltage was increased starting from 0.2 \(U_0\), PD activity was observed in phase L1. An increase in the test voltage resulted in an increase of PD activity. At 0.4 \(U_0\) test voltage, a breakdown at the discharging site occurred. PD mapping revealed the PD concentration at 5.3 km indicated the breakdown position in the cable. The defect produced PD before an actual breakdown occurred, and with TDR analysis, the PD defect location could be determined. The other two phases fulfilled the after laying conditions and successfully passed the test. No internal PD activity in the cable insulation and accessories and no breakdown occurred during the tests of the other phases. The measurement was repeated from the other end of the L1 cable. The PD activity occurring before the breakdown could be localized at 8 km, which is the same location seen from the original tests (13.3 – 8 = 5.3 km).

**Example 4:** Maintenance testing (damped ac frequency 62 Hz) was performed on a service-aged 35-year old 2.2 km long 66 kV XLPE insulated underground circuit: see Figures
Starting from 1.1 \( U_0 \), PD activity of up to 100 pC was registered in one of the joints. Increasing the damped ac test voltage up to 1.5 \( U_0 \) resulted in concentrated PD activity in three joints. Based on this test, it was concluded that if this cable section were energized for network operation, there was a possible risk of failure during operation. Due to the fact that PDIV was very close to \( U_0 \) and increased network stresses could result in an inception and increase of PD activity, the risk of a failure depends on the overvoltage stresses during operation. Replacement of the joint or performing the next maintenance tests within approximately six months was recommended in order to evaluate the progress of the degradation at the above mentioned locations by comparing the change of PD activity over time.
CONCLUSIONS
The following conclusions may be drawn:

1. Monitored voltage withstand testing is becoming more and more common practice. PD measurement, including PD-pattern information and time domain reflectometry (PD localization), helps detect and locate discharging defects in the insulation and accessories of power cables.

2. The combination of damped ac voltage measurements and PD detection are an alternative to continuous ac test voltage testing of distribution and transmission power cables.

3. In the context of detecting and locating discharging defects in cable accessories, monitored testing using damped ac voltages can be less destructive and more sensitive than unmonitored continuous ac voltage testing.

4. Damped ac voltage measurements are useful for after-laying testing of newly installed cables, maintenance testing of repaired cables, and diagnosis and condition assessment of service-aged cables.

5. The upcoming IEEE 400.4 guide will support users around the world with the application of the damped ac technology for diagnosing and testing underground power cables.

Figure 15: PD Patterns as Observed at 1.5 UF during Maintenance Testing of a 30-year Old 66 kV XLPE Insulated 2.2 km Long Underground Circuit

Figure 16: PD Mapping as Made up to 1.5 U₀ During Maintenance Testing of a 30-year Old 66 kV XLPE Insulated 2.2 km Long Underground Circuit
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