

IEEE Guide for Field Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current (DAC) Voltage

IEEE Power and Energy Society

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Insulated Conductors Committee

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**Insulated Conductors Committee
of the
IEEE Power and Energy Society**

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Abstract: The application of Damped AC (DAC) for field testing of power cables is described in this guide. DAC voltage withstand testing and diagnostic tests and measurements that are performed in combination with DAC voltage application in the field on shielded power cable systems are discussed. Whenever possible, cable systems are treated in a similar manner to individual cables. Tables and figures are included to show the effectiveness of the DAC ac voltage test, the diagnostic evaluation and the user experiences in the past years for field testing of different medium and (extra) high voltage cable system.

Keywords: after-laying testing, asset management, cable fault locating, cable system testing, cable testing, condition assessment, condition monitoring, damped ac voltage testing, diagnostic testing, dielectric losses, electric breakdown, grounding, high-voltage testing, IEEE 400.4™, IEEE Power and Energy Society, nondestructive testing, oil-filled cables, partial discharge measurement, power cable insulation, safety, tangent delta testing.

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Introduction

This introduction is not part of IEEE Std 400.4™-2015, IEEE Guide for Field Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current (DAC) Voltage.

This new guide provides an overview of an available method for performing electrical tests in the field on shielded power cable systems using damped alternating current (DAC) voltages. It is intended to help the reader select a test that is appropriate for a specific situation of interest. It provides a brief description of the use of DAC voltage sources to perform field tests with a short discussion of specific tests. The material presented is descriptive and tutorial. Based on the current state of the art using this testing method, the guide addresses the evaluation of test results, the specification of test voltage levels and time of application.

If applicable, additional details are provided in the omnibus standard, IEEE Std 400™¹, IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above, or in “point” documents, such as IEEE 400.1™, IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above with High Direct Current Voltage; IEEE 400.2™, IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF); and IEEE 400.3™, IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment.

¹ Information on references can be found in Clause 2.

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1. Overview

1.1 Background

This guide provides a description of the methods and practices to be used in the application of damped alternating current (DAC) voltages for field testing of shielded power cable systems.

DAC voltage testing is one of the alternative methods of ac voltage testing and is applicable for a broad range of medium-voltage (MV), high-voltage (HV), and extra-high-voltage (EHV) cable types. As the DAC test procedure has been used for several years for diagnostic, maintenance and acceptance (commissioning) tests, it provides a method of evaluation of the insulation condition and helps to fill the need for more complete information on the condition of cable systems.

This guide addresses DAC voltage testing in the frequency range from 20 Hz to 500 Hz [B12], [B14], [B16], [B31], [B45], [B78]¹.

The information contained in this guide is intended to provide the methodology, the voltage levels, and test procedures as well as other factors to be considered when utilizing DAC voltages, whether for withstand or

¹ The numbers in brackets correspond to those of the bibliography in Annex F.

diagnostic tests. For general information regarding other field testing methods, reference is made to the omnibus standard, IEEE Std 400™².

1.2 Scope

This guide presents the practices and procedures for testing and diagnosis of shielded power cable systems rated 5 kV and above using DAC voltages. It applies to all types of power cable systems that are intended for the transmission or distribution of electric power. The tabulated test levels assume that the cable systems have an effectively grounded neutral system or a grounded metallic shield.

1.3 Purpose

The purpose of this guide is to provide uniform practices and procedures for performing (DAC) voltage off-line tests on installed shielded power cable systems in the field and to provide guidelines for evaluation of the test results. As at present certain test parameters and procedures require further study and clarification, this guide provides a starting point that can be grown and improved with time as more experience is gathered from the field and analyzed.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Accredited Standards Committee, C2-2012, National Electrical Safety Code® (NESC®).^{3,4}

ASTM D150-11, Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation.⁵

IEC 60060-3, High Voltage Test Techniques—Part 3: Definitions and requirements for on-site testing.⁶

IEC 60270, High-voltage test techniques—Partial discharges measurements.

IEC 60885-3, Electrical test methods for electric cables;—Part 3: Test methods for partial discharge measurements on lengths of extruded power cables.

IEC 61230 Live working—Portable equipment for earthing or earthing and short-circuiting.

IEEE Std 4™, IEEE Standard for High Voltage Testing Techniques.

² Information on references can be found in Clause 2.

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⁵ ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, USA (<http://www.astm.org/>).

⁶ IEC publications are available from the Sales Department of the International Electrotechnical Commission, 3 rue de Varembe, PO Box 131, CH-1211, Geneva 20, Switzerland (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org>).

IEEE Std 400.3™, IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment.

IEEE Std 510™, IEEE Recommended Practices for Safety in High Voltage and High Power Testing.

NFPA 70E, Standard for Electrical Safety in the Workplace.⁷

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁸

breakdown: Disruptive discharge through or along the insulation causing a breakdown of the applied voltage.

cable system: One or more lengths of shielded power cable joined together, 5 kV and above, including cable accessories (joints and terminations).

charging time t_c in [s]: equals to the necessary time at given maximum current $I_{C\max}$ to charge the test object capacitance C_{TO} up to selected test voltage level V_{DAC} .

circuit natural frequency f_r in hertz: equals to reciprocal of the time between two successive peaks of same polarity and it is determined by the C_{TO} and L_C , and in most cases the $f_r = 1/2\pi\sqrt{(L_C \cdot C_{TO})}$.

DAC excitation: complete process of stressing the power cable under test with Part 1, continuously increasing test voltage up to selected maximum test voltage level, and Part 2, a damped-(co)sinusoidal oscillation with circuit natural frequency and a given damping factor.

DAC voltage PD test: a field test in which the focus of the test is to obtain information about the presence and behavior of partial discharge (PD) in the cable section under the test.

DAC voltage withstand test procedure: is the whole procedure of DAC voltage step phase (by performing DAC excitations with increasing voltage level) followed by a DAC voltage hold phase consisting of series of DAC voltage excitations as applied consecutively at selected voltage levels to the power cable under test.

damped alternating voltage DAC: starting from a (negative or positive) maximum voltage level and having damped sinusoidal oscillations around the zero level. It is characterized by the peak value V_{DAC} , the circuit natural frequency f_r and the damping factor D_f .

damping factor D_f percentage: equals the voltage difference between the first and second peak of same polarity divided by the voltage value of the first peak.

⁷ NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (<http://www.nfpa.org/>).

⁸ *IEEE Standards Dictionary Online* subscription is available at: <http://dictionary.ieee.org/>.

electrical tree: Tree-like growths, consisting of non-solid or carbonized micro-channels that can occur at stress enhancements such as protrusions, contaminants, voids or water tree/dry insulation interfaces subjected to electrical stress for extended time periods. At the site of an electrical tree, the insulation is damaged irreversibly. If the voltage stress on the electrical tree is above the inception voltage, partial discharge will be present, the tree will grow, and a failure can occur in only a matter of time.

hybrid cable system: A cable system consisting of cables with very different dielectric or construction characteristics, for example, extruded dielectric insulation cable and laminated insulation cable or cables with filled and unfilled insulations.

(insulation) weak spot: A part of the cable insulation system where, due to one or more factors such as mechanical, chemical, or thermal stresses, the insulation medium breaks down before the rest of the system under certain applied voltage. An insulation weak spot that leads to a breakdown at operating voltage is sometimes called a gross defect.

laminated dielectrics: Insulation formed in layers typically from fluid-impregnated tapes of either cellulose paper or polypropylene or a combination of the two. Examples include paper-insulated, lead-covered (PILC) cable designs, mass-impregnated, non-draining (MIND) cable designs, high pressure pipe type cable designs, and self-contained cable systems.

partial discharge (PD): localized electrical discharge that only partially bridges the insulation between conductors.

partial discharge (PD) pulse: A high-frequency current pulse that results from a PD. In a shielded power cable, the pulse propagates away from the PD source in both directions along the cable.

shielded cable: A cable in which an insulated conductor is enclosed in a grounded conducting envelope.

tests: For the purpose of this guide, several test categories are considered:

- a) **off-line testing:** The cable system under test is disconnected from the service power source and energized from a separate field-test power supply.

From the application point of view, there are three categories of tests:

- 1) **installation test:** A field test conducted after cable installation but before the application of joints or terminations.
- 2) **acceptance test:** A field test made after cable system installation, including terminations and joints, but before the cable system is put into normal service.
- 3) **maintenance test:** A field test made during the operating life of a cable system.

- b) From the technical point of view, there are three broad sets of tests:

- 1) **diagnostic test:** A field test made during the operating life of a cable system to assess the condition of the cable system and, in some cases, locate degraded regions that can result in a failure.
- 2) **monitored withstand test:** a diagnostic test in which a voltage of a predetermined magnitude is applied according to a withstand test procedure of voltage step and hold phase. During the test, other properties of the test object are monitored to help determine its condition and also evaluate if the test duration needs to be extended or may be reduced.
- 3) **non-monitored or simple withstand test:** a diagnostic test in which a voltage of a predetermined magnitude is applied according to a withstand test procedure of voltage step and hold phase. If the test object withstands the test it is deemed to have passed the test.

voltage level V_{DAC} in peak kilovolts: this is the actual test voltage level of the DAC voltage which is equal to the actual selected test voltage level V_T as it has to be generated by a DAC system.

NOTE—From a practical point of view and due to the fact that cable test specifications are given in kVrms, the V_{DAC} can also be determined as the value $V_T / \sqrt{2}$ in kVrms.⁹

3.2 Acronyms and abbreviations

DAC	damped ac voltage (for the purpose of this guide: 20 Hz to 500 Hz)
D_f	DAC damping factor
EVH	extra-high-voltage
f_r	DAC natural frequency
DF	dissipation factor, also referred to as tan delta ($\tan \delta$)
HV	high-voltage
MIND	mass-impregnated, non-draining
MV	medium-voltage
N_{DAC}	number of DAC excitations
OF	oil-filled
PD	partial discharge
PDEV	partial discharge extinction voltage, V_e
PDIV	partial discharge inception voltage, V_i
PILC	paper-insulated lead-covered
TDR	time domain reflectometry
U_n	power cable rms rated voltage, phase-to-phase
U_0	nominal rms operating voltage, phase-to-ground
V_T	peak test voltage, phase-to-ground

⁹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

4. Safety awareness

WARNING

For all tests involving hazardous voltage levels, special attention must be paid to improve the safety of personnel. Personnel safety is of utmost importance during all testing procedures. All cable and equipment tests shall be performed on de-energized and isolated systems except where otherwise specifically required and properly authorized. Appropriate safety practices must be followed. Where applicable, the safety practices shall include, but not be limited to, the following requirements:

- a) Applicable user safety operating procedures
- b) IEEE Std 510, IEEE Recommended Practices for Safety in High Voltage and High Power Testing
- c) Accredited Standards Committee, C2-2012, National Electrical Safety Code® (NESC®)
- d) NFPA 70E, Standard for Electrical Safety in the Workplace
- e) Applicable national, state and local safety operating procedures
- f) Protection of utility and customer property

High-voltage field testing of cable systems involves all of the factors normally associated with working on energized circuits, as well as several unique situations that must be addressed.

Cable circuits will normally have one or more ends remote from the location of the test equipment and the test operator. These ends must be cleared and guarded to protect the safety of personnel. Reliable voice communication should be established between all such locations and the test operator.

The use of an energized circuit indicator or other suitable device may be used to indicate that the circuit is completely de-energized before application of safety grounds.

Precautions shall be taken to allow adequate voltage clearance when testing conductors in close proximity to other energized conductors. Failure to maintain safe clearances may lead to flashover between the test conductor and other live conductors, particularly when test voltages above the rated operating voltage are used. When spacing is marginal, special precautions may be required to prevent flashover.

WARNING

Particular attention shall be directed to the special techniques required for discharging cables after testing to eliminate personnel hazards. Cables have high capacitance and dielectric absorption characteristics. Cables subjected to high-voltage testing that are not grounded for sufficiently long periods of time after such tests can experience dangerous charge buildups as a consequence of the very long time constant associated with dielectric absorption currents. For this reason, the grounding procedures recommended in the appropriate work rules should be followed.

Personnel safety is of utmost importance during all testing procedures. All cable and equipment tests shall be performed on de-energized and isolated systems except where otherwise specifically recommended and properly authorized. The safety practices shall include, but not be limited to, the above-mentioned requirements.

Prior to testing, determination of particular safe clearances must consider both the test voltage and voltage of nearby energized equipment:

When a switch or disconnect type device is used to isolate the cable circuit from the rest of the system, the ability of the device to sustain the DAC test voltage and maintain safe voltage isolation while the other end is under normal operating voltage shall be checked with the manufacturer.

- Care should be taken to carefully monitor the discharging (earthing) of the cable, particularly on long cables that may take tens of seconds to fully discharge.
- When isolation of the cable from the energized source is via an air gap, such as when a cable terminator connection is removed, the clearance distance must be sufficient to maintain isolation with the cable system at the DAC test voltage and the surrounding equipment at normal line voltage.
- Proper Blocking/Lock-out/Tag-out procedures must be followed to make sure that the isolation device cannot be operated nor the isolation distance violated without proper authorization.
- Appropriate personnel protective equipment (PPE) should be worn.

While testing, one or more cable ends will be remote from the manned testing site, therefore, before testing begins:

- Cable ends under test must be cleared and cordoned off
- Cables that are de-energized should be grounded when not being tested.
- Remote cable ends must be marked to indicate that a high-voltage test is in progress.

At the conclusion of high voltage testing, attention should be given to:

- Discharging cables and cable systems including test equipment.
- Grounding requirements for cables and test equipment to eliminate the after effects of recharging the cables due to dielectric absorption and capacitance characteristics.

Cable systems can be considered de-energized and grounded when conductor and metallic shield are connected to system ground at the test site and, if possible, at the far end of the cable.

When testing, a *single system ground at the test site* is recommended (See Figure 1). The shield or sheath of the cable to be tested is connected to system ground. If this connection is missing, deteriorated, or has been removed, it must be replaced at this time. *A safety ground cable must connect all test instrument casings with system ground.* All exposed conductive parts of the test system must be bonded to the common ground point. As a DAC test instrument is a high-voltage device, an external safety ground cable should be used to safely ground the cable to be tested. This cable should be able to accommodate the fault current of the system. Once the test lead from the DAC test equipment is connected to the cable to be tested, this safety ground can be removed so that testing can commence.

Should a local ground be advisable or recommended for the test equipment, case ground must remain connected to system ground in order to maintain an acceptable single ground potential.

Care should be taken to verify that all ground connections cannot be disconnected accidentally. Grounding connections, which can be securely tightened, are recommended. Portable ground clamps and grounding assemblies built and tested per IEC 61230 are recommended.

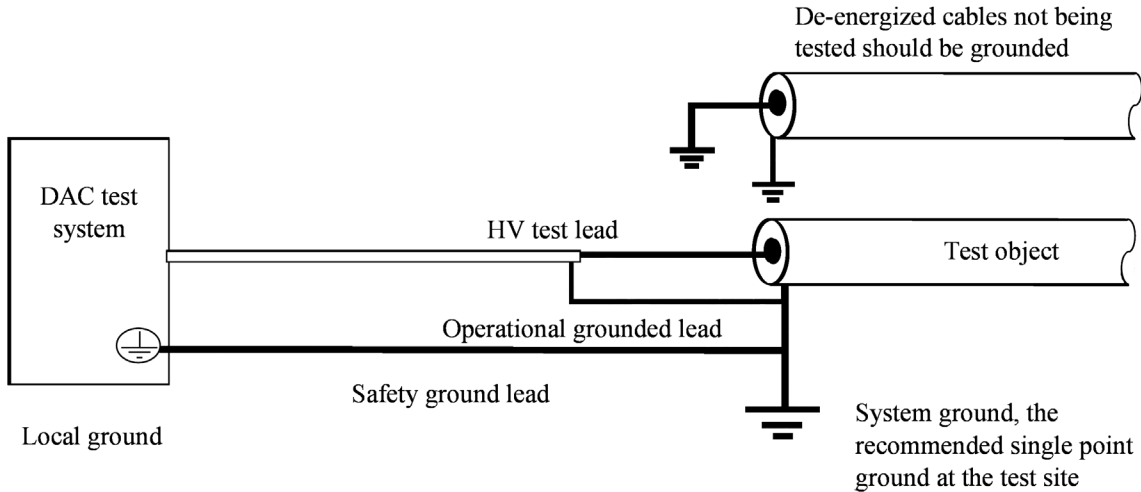


Figure 1—Recommended DAC safety connection diagram

5. Damped ac testing

5.1 General

Sinusoidal damped ac (DAC) voltage testing, also known as oscillating wave testing, was introduced at the end of the 1980's as an alternative to DC test voltages [B3], [B4], [B5], [B6], [B12], [B13], [B15], [B19], [B23], [B25], [B28], [B31], [B45], [B56], [B58], [B59], [B60], [B65], [B66], [B67], [B70], [B71], [B79], [B82], [B83]. As a consequence of experiences in onsite AC testing on one hand and the technological progress in power electronics and advanced signal processing on the other hand, DAC testing has been used since the end of 1990s. Some countries are currently using DAC for onsite testing with PD measurements and dissipation factor (DF) estimation for condition assessment of all types of power cable systems [B9], [B31], [B73], [B76], Annex E.

DAC voltages are generated by charging of the test object to a predetermined voltage level and then discharging the test object's capacitance through a suitable inductance. During the charging stage, the capacitance of the test object is subjected to a continuously increasing voltage at a rate dependent on the test object capacitance and the current rating of the power supply. During the discharging stage, a DAC at a frequency dependent on the test object capacitance and the inductance is present (See Figure 2).

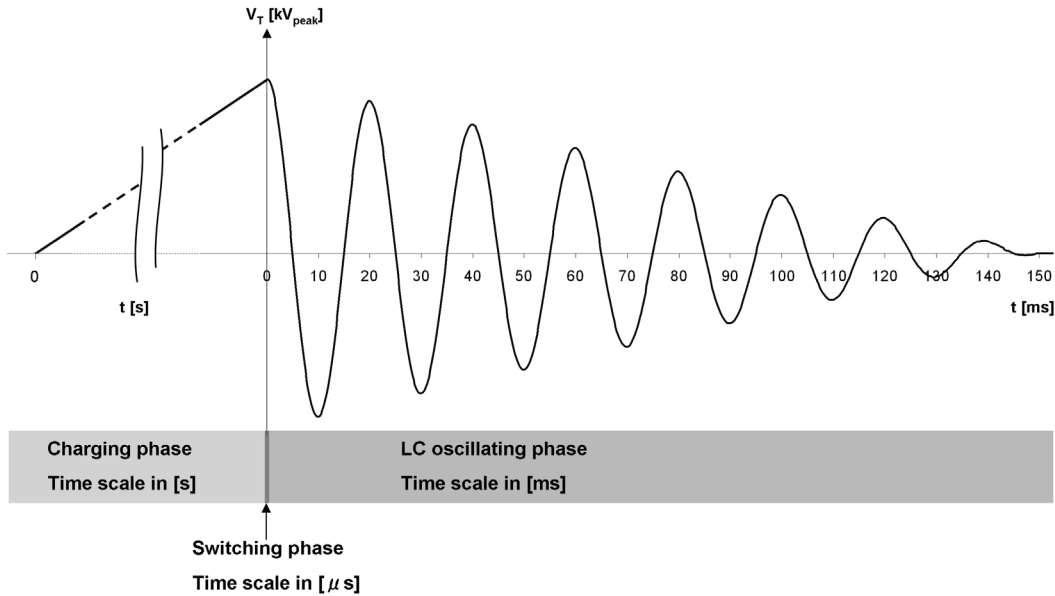


Figure 2—Schematic overview of the three stages of one DAC excitation.
The maximum DAC voltage level is determined by the voltage peak value V_T respectively the value $V_T/\sqrt{2}$ in root-mean-square kilovolts

Most applications for DAC so far are based on the combination of voltage withstand and advanced diagnostic measurements [e.g., partial discharges (PDs) and DF]. For a voltage withstand test, a predetermined number of DAC excitations is applied [B9], [B14], [B16], [B52], [B72], (See Figure 3)

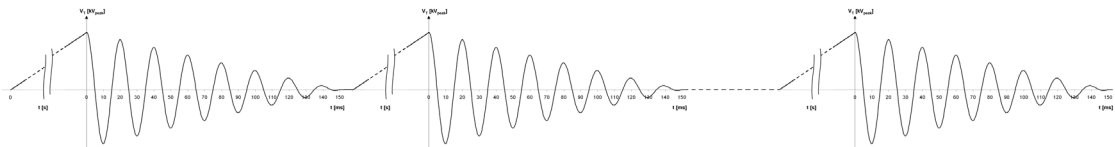


Figure 3—Schematic overview of a withstand test by damped sinusoidal ac voltage excitations. The duration of the test is determined by the number of DAC excitations which have been applied to the power cable under test at a selected DAC test voltage. The maximum DAC withstand voltage level is determined by the voltage peak values V_T respectively the value $V_T/\sqrt{2}$ in root-mean-square kilovolts of the first DAC cycle.

According to [B3], [B4], [B5], [B6], [B9] [B12], [B14], [B15], [B16], [B31], [B45], [B69], [B71], [B72], [B78], [B79], and [B87], the major advantages and disadvantages of DAC testing can be summarized as follows:

Advantages:

- The DAC voltage withstand test by applying a defined number of DAC excitations gives the possibility to produce a breakdown or to initiate PD occurrences in insulation defects [B4], [B5].
- Can give the possibility to detect various defects in the insulation that will be detrimental to the cable system under service conditions, without creating new defects or causing any significant aging of healthy insulation [B18], [B20], [B69], [B81].
- Gives PD patterns and parameters similarity between the results of DAC tests and continuous power frequency (50/60 Hz) factory tests [B3] [B4], [B15], [B86], [B87].
- Has low system complexity, is lightweight, and is easy to handle and operate.
- Requires relatively low input power of the DAC test equipment for testing long lengths of cable.

Disadvantages:

- Due to the charging and decaying characteristic of the voltage, withstand and breakdown DAC test results can be different from those obtained by continuous ac withstand voltage testing, especially in the case of presence of PD activity (typical for inhomogeneous insulation defects) [B32].
- The use of fixed inductors with different cable capacitances results in variation of DAC frequency.
- To keep the DAC frequency in the range of 20 Hz – 500 Hz for the case of very short cable lengths, an additional capacitive load is necessary.
- Due to the fact that the recommended test voltages and durations for tests (given in this document for DAC testing, see Annex A) are based on field-experiences as obtained by different users of the DAC technology further data collection and evaluation are necessary and should be part of the next revision process of this document.
- The decay of the DAC voltage depends on the actual dielectric loss behavior of a particular cable section.
- The charging time varies as it is dependent on the cable capacitance, the test voltage level V_T and the charging current of the power supply.

5.2 Types of DAC testing

In Figure 4, an overview of DAC field test possibilities of different cable systems is shown. It follows that depending on the objectives for testing a number of options can be considered.

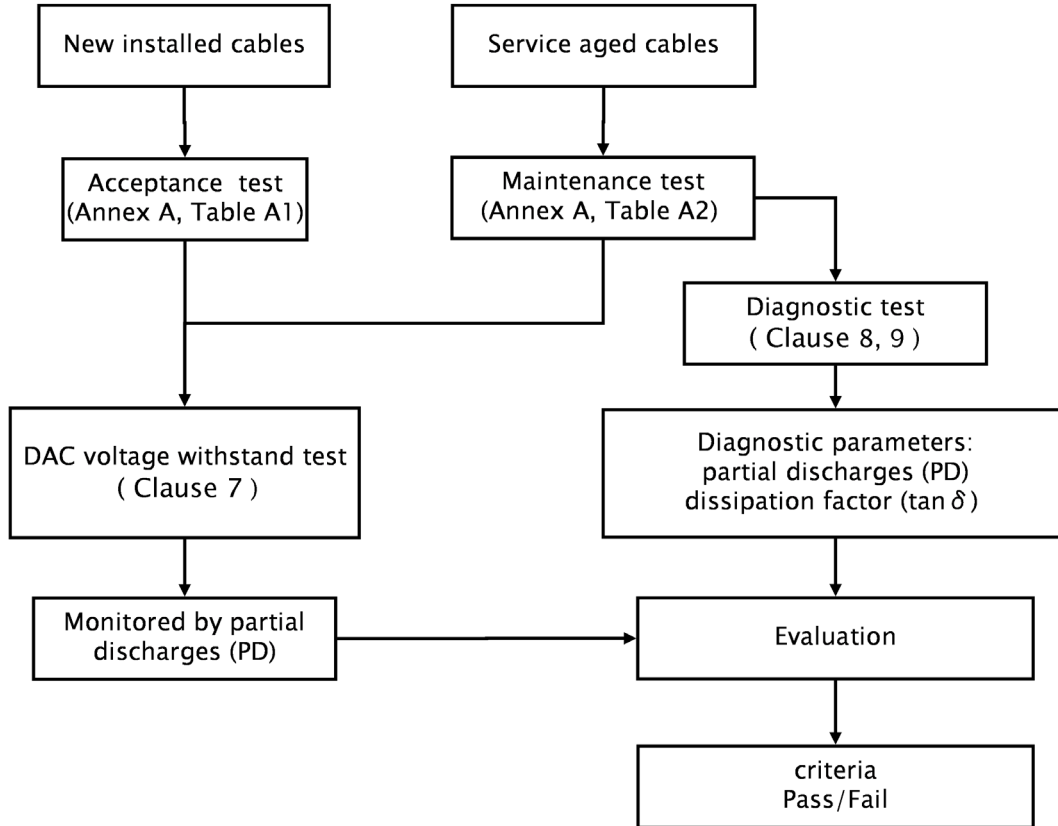


Figure 4—General overview of DAC field test possibilities for different testing goals of cable systems.

- *DAC acceptance test:* According to the test voltage levels as given in Table A.1 newly installed cable systems can be tested with 50 DAC excitations in monitored and/or non-monitored ways. The actual practice in the recent years indicates that most DAC acceptance tests are monitored by PD detection. Due to the fact that this application is under development, the effectiveness and verification of the DAC voltage withstand test is based on the following references [B4], [B15], [B75], [B81]. The actual practice of last ten years of use is of value, but further data collection, evaluation and basic considerations [B32] are necessary to mature the technique. This experience should be part of the next revision of this document.

Prior to the DAC acceptance test, based on user requirements, installation testing can be performed on new cable sections, to verify the quality of installation. Once a cable has been terminated or jointed to the overall cable system, which can be taken into service, an installation test should be replaced by acceptance or maintenance tests.

- *DAC maintenance test:* According to the test voltage levels as given in Table A.2, cable systems in service or after repair or refurbishment, can be tested with 50 DAC excitations in a monitored and/or non-monitored way. The actual practice of the recent years indicates that most DAC maintenance tests are monitored by PD detection and/or DF measurements.
- *DAC diagnostic testing:* According to the test voltage levels as given in Table A.1 and Table A.2 as well as user's own test procedures, cable systems in service can be tested periodically for condition assessment purposes e.g. by using PDs and/or DF measurements.

6. Damped ac test circuit and parameters

6.1 Overview

To generate DAC voltages, different types of test circuits can be applied [B5], [B9], [B16], [B21], [B29], [B30], [B51], [B73], [B78], [B86]. In this document, the basic circuit shown in Figure 5 will be used to explain the principles of DAC voltage generation. The DAC test circuit basically consists of a HV voltage source generating an increasing unipolar voltage (See Figure 2,) a HV inductor in the range of several [H], a capacitive test object and a suitable HV switch (See Figure 5.) The capacitive test object can consist of one or more capacitive test objects, such as power cables or generators. Even though a cable has distributed parameters, for simplification a lumped capacitor model is used. When the unipolar charging voltage has reached the maximum value V_T the HV switch is closed, generating a damped alternating voltage on the capacitive test object. The damping factor depends on the loss characteristics of the test circuit and the test object. The DAC natural frequency (f_r) is determined by the values of the HV inductor and the capacitance of the test object. Below a certain capacitance value of the test object, the natural frequency of the oscillation will exceed acceptable values. For these cases an additional HV storage capacitor can be connected in parallel to the circuit.

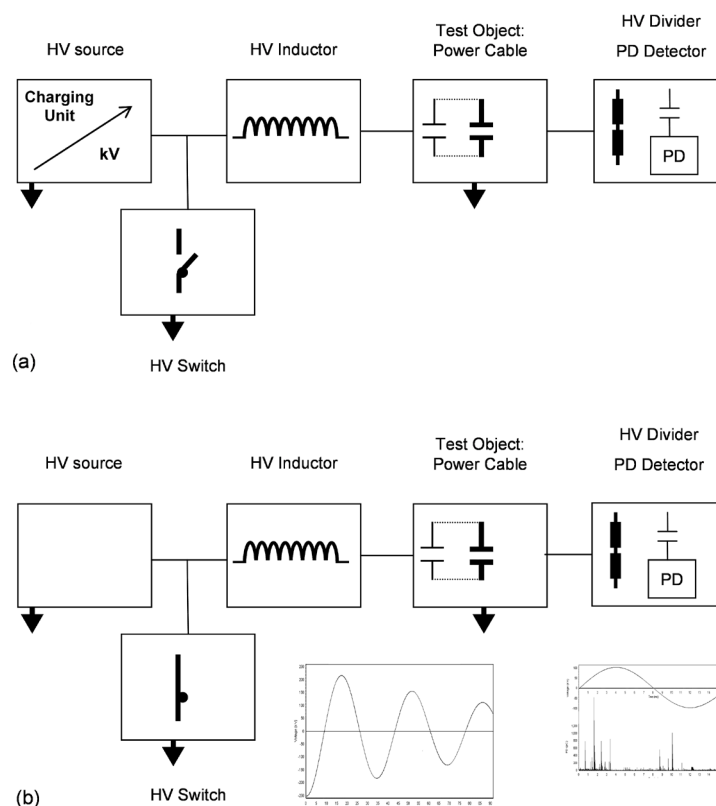


Figure 5—Schematic overview of a basic DAC test circuit with monitoring:
(a) circuit-charging phase and (b) LC-oscillation phase. In case of monitored test, such parameters as PDs and DF can be measured.

6.2 DAC test voltage circuit

6.2.1 Overview

Basic principles of DAC test circuits are shown in Figure 5 and in 6.3 the parameters relevant for characterizing a DAC test circuit are defined. The complete process of a DAC excitation generation consists of three phases (See also Figure 2)

6.2.1.1 Charging phase:

During this phase the test object is stressed with increasing unipolar (negative or positive) voltage. The charging time depends on the maximum available load current of the voltage supply, the test voltage, and the capacitance of the test object.

According to Kreuger, 1995 [B53], no dc stresses and steady-state condition occur in the cable under test if the voltage is continuously increasing up till the time of triggering the HV switch. As a result, space charges are less likely to form in the cable insulation unless the frequency is less than 0.01 Hz and the electric stress is more than 10 kV/mm [B80]. Referring to Dissado, et al. [B13] and Takada [B80], the amount of space charge trapped is a function of frequency and occurs below 0.01 Hz for an applied electric field [B47]. For example, in contrast when applying pure HVDC stress compared to DAC to insulation and according to Kreuger, 1995 [B53], the initial voltage distribution will be capacitive and slowly relaxes to a resistive distribution with the time constant of typical XLPE insulation (permittivity $\epsilon_r \epsilon_0$ times volume resistivity ρ).

$$2.3 \times 8.85 \times 10^{-12} \text{ F/m} \times 10^{14} \text{ } \Omega \cdot \text{m} = 2035 \text{ s}.$$

As a result, in a hypothetical case of pure HVDC stress (constant voltage level only), the time constant needed for this transition would be over 33 min. As the duration of the charging phase of DAC is significant below this time with the test voltage levels as mentioned in Table A.1 and Table A.2 (See Annex A), the E-fields will stay below critical values [B13], [B80], not only for one DAC excitation but also for several excitations as typically applied during a DAC withstand test. The result is to produce only ac field stresses in the cable. To avoid the side effects of a unipolar excitation time and possible space charge development, it is recommended to stay with an excitation time of less than 100 s. If this value cannot be met, the charging supply current has to be increased to reduce the charging time. Alternatively a bipolar charging procedure (charging with positive and negative voltage) with a suitable HV source can be used.

6.2.1.2 Switching phase:

After the unipolar charging voltage with a given voltage ramp rate of dU/dt , has reached the selected maximum DAC test voltage V_T (charging voltage), the HV switch closes instantaneously, with very fast turn on time, e.g., less than 1 μs . This fast switching time is necessary to avoid switching over-voltages and disturbances of PD measurements. The cable capacitance and the system HV inductance then form an LC oscillating circuit. The maximum resulting DAC current flowing in the LC circuit is a function of the actual capacitive load, system inductance and the maximum test voltage.

6.2.1.3 LC damped oscillating phase:

The frequency of the DAC test voltage equals the natural frequency of the circuit.

The DAC attenuation depends on the quality factor of the total resonant circuit. The quality factor is inversely proportional to the losses of the circuit which includes the HV switch, the losses in the cable system, and the losses in the test set inductor.

Due to the symmetrical bipolar ac discharging process, no remaining charges will be introduced to the cable insulation during the oscillating phase.

As a result of the relatively low cable inductance and no occurrence of transient over-voltages due to reflections at joints and cable terminations, the DAC stress applied to the cable capacitance regarding PD inception represents the normal ac stress conditions. This means that the PD inception voltage (PDIV), the PD amplitudes, and the PD behavior are comparable to factory testing conditions, and the following references show that a DAC stress is similar for inhomogeneous insulation defects [B54], [B69], [B86], [B87].

In the case of PD-free insulation, the application of DAC stress will have the similar effect as at factory testing conditions on the pass/fail outcome of the test [B54].

The DF can be estimated with the decay characteristics of the DAC wave, as shown in Houtepen, et al. [B34], IEEE Std 386™ [B44], and described in Annex B.

The measurement of the test voltage should be made with an approved measuring system as described in IEEE Std 4 and IEC 60060-3. The peak value of the test voltage should be measured with an overall uncertainty of $\pm 5\%$, and the response time of the measuring system should not be greater than 0.5 s.

6.3 DAC parameters

For a DAC test of a power cable circuit, a number of parameters that are related to the test circuit, the test procedure, the data acquisition and the data analysis have to be considered. The knowledge of these parameters is relevant for the definition of the test conditions and to provide proper evaluation of the test data as obtained for a particular test object.

- *Test circuit parameters:* Depending on the type of DAC test circuit, the total test circuit can be described by a number of parameters. Annex C describes the parameters which are of importance to determine a specific configuration of the test circuit.
- *Voltage parameters:* Based on the selected test circuit, the type and voltage rating of the test object, as well as the test procedures to be applied and the basic parameters which can be used to characterize the DAC voltage are described in Annex C.
- *Test parameters:* Performing a DAC test in accordance with the recommended test parameters can be used to describe the test process (See Annex C).
- *Evaluation parameters:* Performing a DAC test provides a number of parameters that can be used to evaluate the test results. Depending on the type of test, for example withstand test, monitoring test or diagnostic test, these parameters can provide information about the test outcome (Annex C).

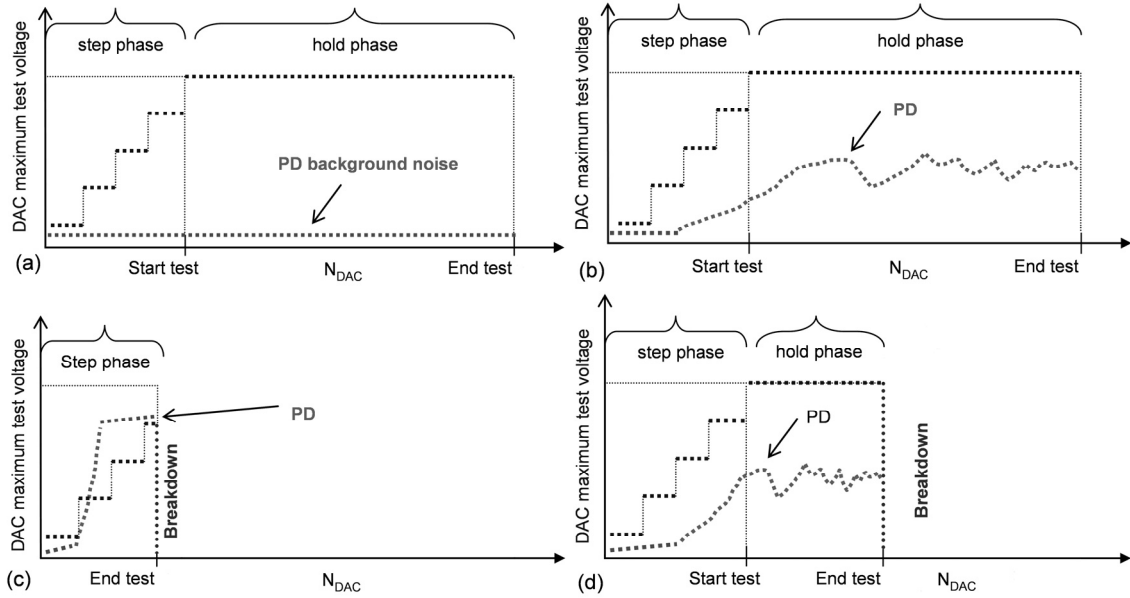


Figure 6—Schematic overview of four different situations of DAC voltage withstand tests:
(a) during selected number of NDAC excitations (dotted lines), no breakdown occurred;
(b) during selected number of NDAC excitations (dotted lines), no breakdown occurred, but there is PD above the PD background noise level; (c) PD and breakdown occurred before the DAC withstand test level had been reached; and (d) PD and breakdown occurred before the DAC withstand test number of NDAC excitations had been applied.

7. DAC voltage withstand testing

7.1 General

A withstand test using DAC voltage is based on the application of a defined number of DAC excitations at a selected voltage level that is generally higher than the rated voltage. DAC testing can be applied to all cable and accessory types, and it is based on the insulation breakdown/no breakdown outcome. In conducting a non-monitored withstand test, no information is gained about the test's effects on the insulation system.

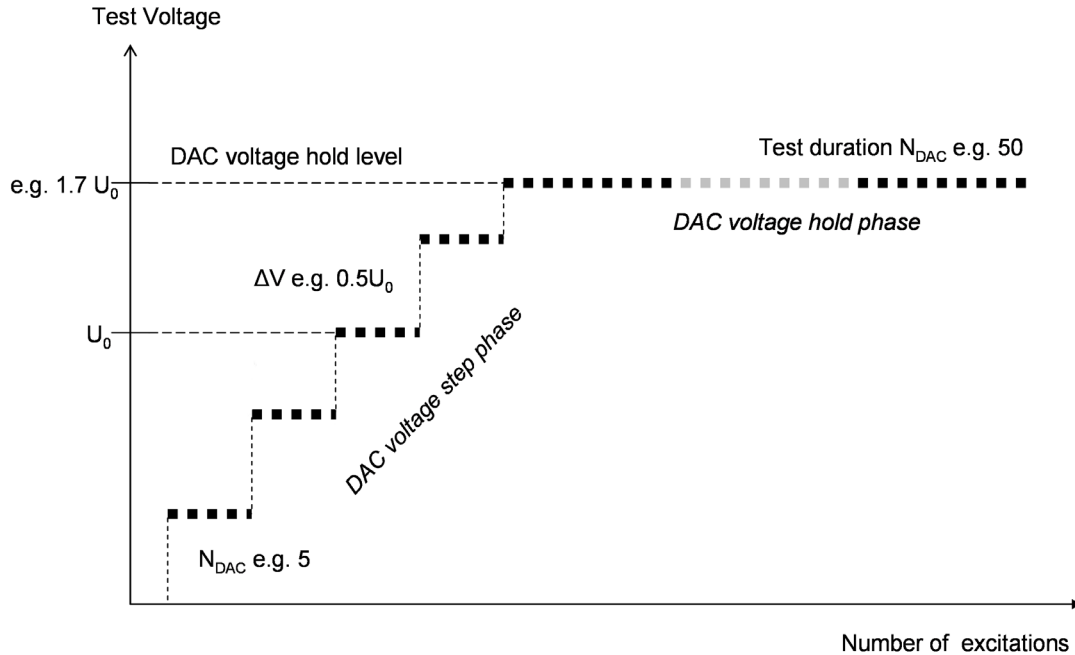


Figure 7—Schematic overview of DAC voltage application procedure, PD detection can be performed during step-an-hold phase (monitored withstand test)

The tests can be further subdivided into two classes:

- *Non-monitored DAC withstand test:* A number of DAC excitations is applied and the ability to hold the maximum DAC voltage (i.e., no breakdown occurs) is recorded, see the dotted lines in Figures 6a and 6b. The intent of a withstand test is to extend existing dangerous defects to breakdown 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 Figure 6) then 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.” As this test is an alternative method to a continuous voltage ac withstand test there is no direct correlation to selected number of DAC excitations at selected voltage level. As a result, it cannot be excluded that a fixed number of DAC excitations at a selected voltage level may or may not be sufficient to cause a defect to breakdown in a cable.
- *Monitored DAC withstand test:* A number of DAC excitations is applied and one or more additional attributes are measured and used to determine whether the cable passes or fails the DAC test. (See the black dotted lines for DAC voltage and gray dotted lines for PD measurement in Figure 6.) These additional attributes are advanced diagnostic properties, such as PD detection. Temporal stability of the measured property can also be used to monitor the effect of the test on the cable system during voltage application.

Although some users perform simple non-monitored withstand testing (see the survey in Annex E), the recommendation is to perform testing monitored by PD detection and recording (see Figure 5).

Additional information provided by PD detection in monitoring insulation properties and the effect of the test voltage on diagnostic parameters during a DAC withstand test can improve the evaluation of the insulation condition.

For all types of tests, voltage levels and the number of DAC excitations should be consistent with the purpose of the test. From the point of view of a shielded power cable system's quality and reliability, two aspects are important for field tests and results evaluation:

- The DAC test parameters should be chosen in such a way so as to prevent or reduce the reduction of the service lifetime due to the field test. In the case of a withstand test, the impact on defective insulation needs to be high enough to cause a breakdown or to exceed a critical level of a monitored property but not so high as to cause degradation.
- Voltage level and the number of DAC excitations and the duration of the excitations are important and inseparable elements for the under-test and after-test performance of the cable circuit. The recommended test voltages and number of excitations for tests (See Annex A) are based on field-experiences obtained by different users of the DAC technology. Arbitrarily increasing voltage or extending the number of excitations from the recommended values could increase the probability of an early failure in service.
- For quality acceptance tests on new cable systems, the required withstand voltage for routine tests in factory shall be considered adequate.

7.2 DAC test parameters and procedures

For the DAC voltage testing, five test parameters are considered:

- a) The maximum DAC test voltage level $V_T[\text{kV}_{peak}]$ (see Annex A)
- b) The number of DAC excitations to be applied at selected DAC voltage levels during the test
- c) The DAC frequency in hertz
- d) The DAC damping percentage
- e) The DAC charging time in seconds

Depending on the test objective, a DAC test may consist of two phases (Figure 6 and Figure 7):

- During the DAC voltage step phase, voltage is increased to a selected maximum test voltage in selected steps of ΔV , e.g. $0.2 U_0$, with a selected number of DAC excitations, $N_{DAC} - \text{Step}$, per voltage level (a minimum of $N = 5$). ([B14], [B16], [B45], [B58]) See Annex A.
- During the DAC voltage hold phase, a selected test voltage $V_T[\text{kV}_{peak}]$, for a number of DAC excitations, $N_{DAC} - \text{Hold}$, e.g. $N = 50$, is applied to the test object. ([B14], [B16], [B45], [B58]) See Annex A.

DAC frequency is determined by a given HV inductor, L_C , of the test system and the capacitance of the test object, C_{TO} . In most cases the DAC frequency can be calculated as $f_r = 1/2\pi\sqrt{L_C \cdot C_{TO}}$, in conformance with IEC 60060-3.

DAC damping factor (D_f) is determined by the voltage difference between the first and second peak of same polarity, divided by the voltage value of the first peak.

7.3 DAC evaluation criteria

When applying DAC testing for acceptance and/or maintenance testing there are two possible outcomes:

- The complete installation and/or repair have been successfully done, and the cable section is approved and can be used for network operation
- The complete installation and/or repair have not been successfully done and the cable section has to be repaired or needs further investigations

For the case of non-monitored DAC voltage withstand test, the evaluation is based on two outcomes:

- Pass, in the case of no breakdown during the test,
- Fail, in the case of a breakdown during the test.

For the case of monitored DAC voltage withstand test the evaluation is based on four outcomes (see Annex A).

For the case of a diagnostic test, the evaluation is based on an application of the knowledge rules (if available) and the asset management (frequently the user's) expectations.

8. PD measurement using DAC

8.1 General

Regarding PD detection, refer to IEEE Std 400.3 for more information about test application. Regarding PD detection by applying DAC testing, the principal methods are described in IEC 60270, IEC 60885-3 and in Agoris, [B1], Cigré, 2010 [B17], IEC 62478 [B42], and Meijer, et al. [B64], which should be considered for detection of onsite PDs in external energized power cables. In general, one or more PD detection units can be connected to at least one of the cable terminations and/or cable joints. Due to the fact that DAC testing is not continuous but based on voltage excitations as applied to the power cable, a proper triggering/synchronization between the DAC voltage source and the PD detection unit has to be provided.

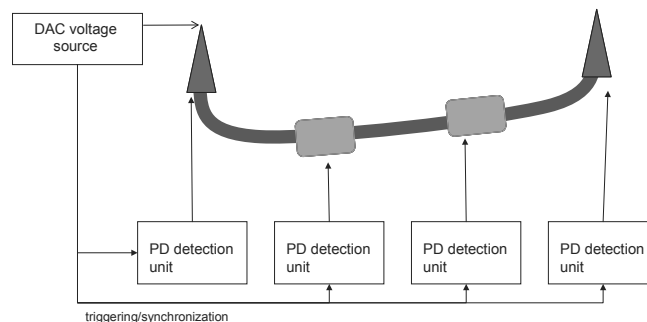


Figure 8—Principles of offline PD detection methods as connected to a power cable and its accessories during DAC testing

By applying PD detection during DAC, discharging activity can be detected in both cable insulation and cable accessories (see Figure 8).

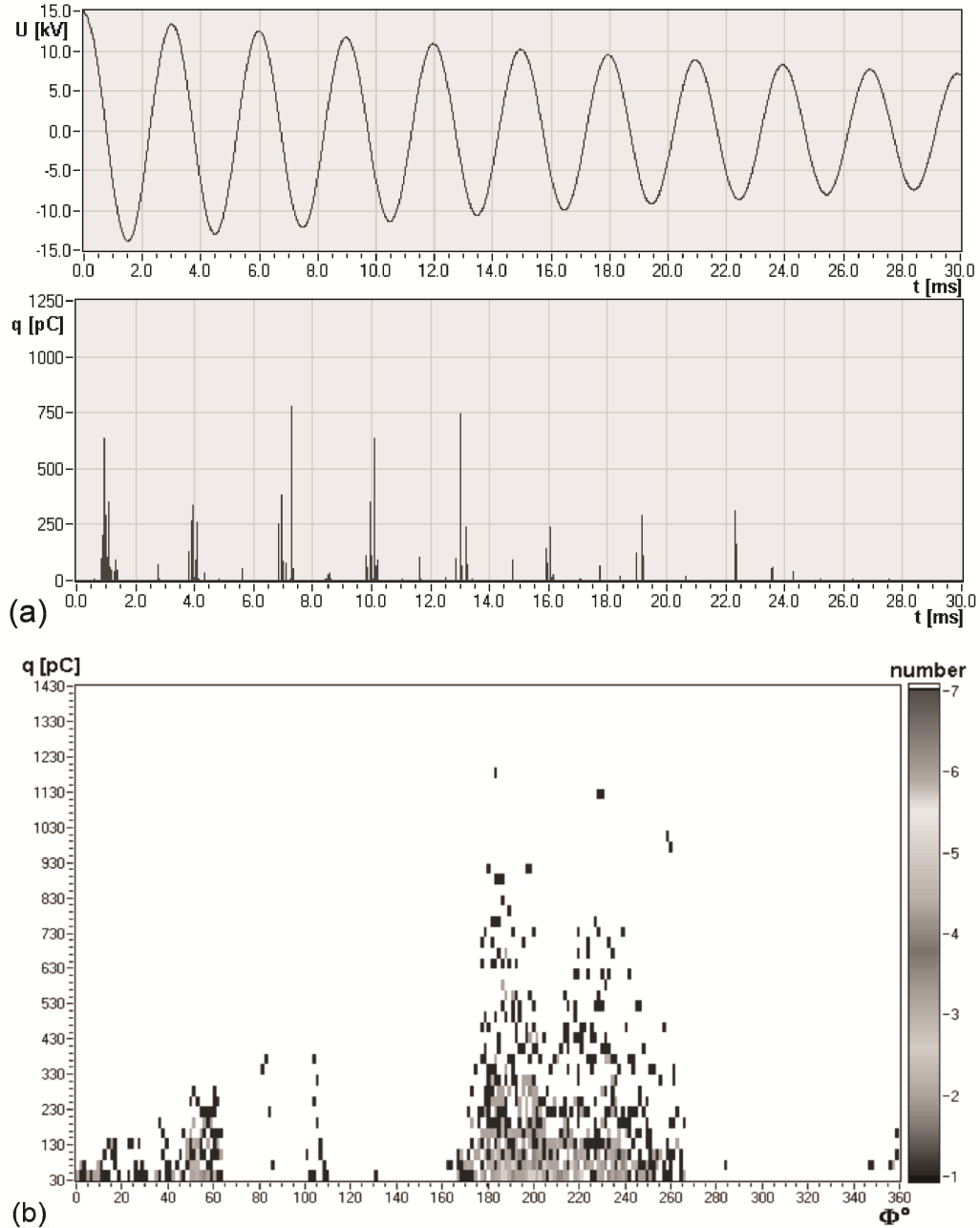


Figure 9—Example of PD patterns at DAC test voltages [B86]: (a) 2D pattern with the PD occurrence q versus the test voltage U on identical time base and (b) 3D pattern with the PD occurrence represented in discharge magnitude, phase angle, and number of PDs (by grey scale) as generated up to a selected maximum test voltage level for a number of DAC excitations.

8.2 PD characteristics

DAC testing is based on single voltage excitations. As a result, the PD pattern as generated during one such DAC excitation consists of information about (see Figure 9):

- a) Maximum PD amplitude
- b) Phase-related PD pattern
- c) PD changes as a function of the decaying voltage
- d) PD extinction voltage (PDEV)

Due to the fact that DAC testing is based on the application of single voltage excitations, the determination of the PDIV and PDEV is based on the stored and recorded PD pattern analysis (see Figure 10).

For all other PD parameters suitable for onsite PD detection, the references IEC 60270, IEC 60885-3, and IEEE Std 400.3 can be used.

The principles applicable to estimation of the PDIV and PDEV during DAC testing are explained in Figure 10 [B86].

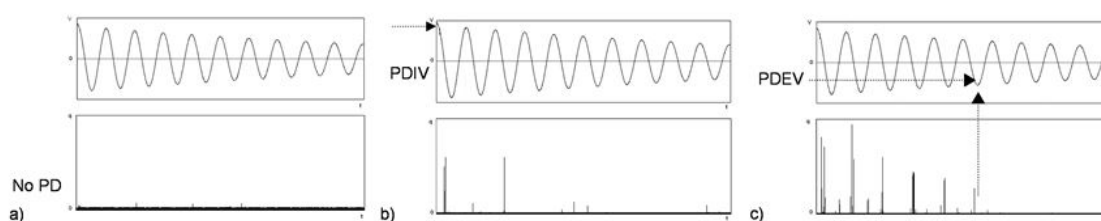


Figure 10—Principles of the determination of PDIV and PDEV voltages during DAC testing [B86]. The PDIV voltage level of the DAC excitation at which the first PD activity has been observed.

8.3 PD Evaluation criteria

Applying DAC testing for PD detection provides DAC-specific PD patterns. For PD detection and PD parameters, the information given in IEEE Std 400.3 and in Annex D is applicable. For more information about PD evaluation see Annex D.

9. DF ($\tan \delta$) estimation using DAC

9.1 General

The DF of the insulation material can be determined during a DAC test based on the recording of the attenuation (derived from the decay characteristic, see Annex B) of the voltage wave applied to the cable,

(see ASTM D 150-2004, IEC 60141-1 [B37], IEC 60141-3 [B38], and IEEE Std 1425™ [B49]). Due to the fact that DF increases during the aging process of the cable, DF measurement can be used for diagnostic purposes. The cable capacitance can also be calculated by performing a DAC test at a given test voltage frequency f_r based on the resulting natural frequency and the known value of the air core inductance. An estimation of the DF ($\tan \delta$) can be derived from the decay characteristics of the damped sinusoidal voltage wave [B27], [B34], [B74], [B78], [B86].

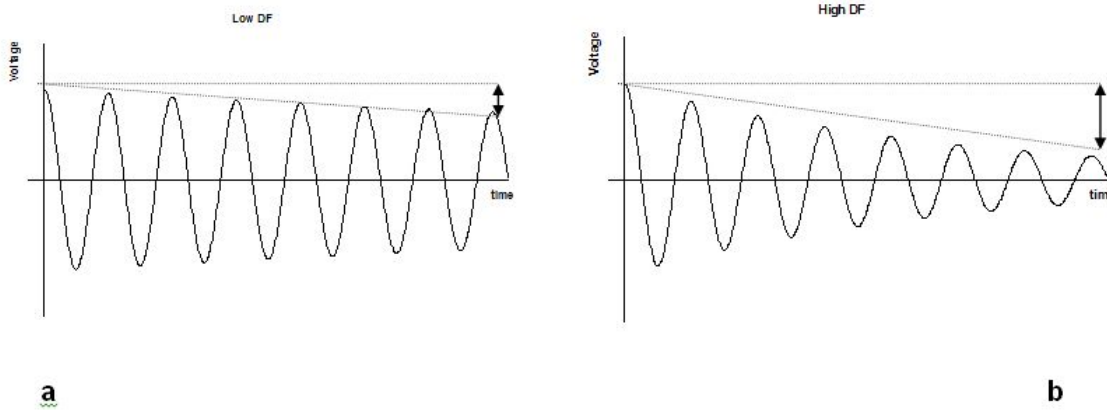


Figure 11 —DF estimation during DAC testing; schematic examples of DAC voltage waves as observed for power cables with (a) low DF and (b) higher DF.

For a better estimation of the losses of the cable from the decay characteristic of the DAC wave, the losses in the test and measuring circuit must be known, i.e., those due to the losses in the air-core inductor and the HV switch. The test object can be represented by a resistance in parallel with a capacitance. Test-object resistance can be estimated using formulas presented in Annex B, and, therefore, the load DF can be calculated.

Figure 11 (a) shows an illustration of a DAC wave taken from a test object with very low dielectric losses, e.g., $< 0.1\%$ as estimated for a newly installed polymeric power cable. Figure 11 (b) shows a DAC voltage wave with high dielectric losses, 0.5% as estimated for a service-aged oil-impregnated power cable. Various DAC voltage waves corresponding to several $\tan \delta$ values can be seen in Annex B.

Table 1—Examples of discrete DF values are shown representing a non-aged condition of oil-filled (OF) cable insulation. Typical accuracy for DF is 0.01%.

Test voltage	DF phase yellow	DF phase red	DF phase blue
$0.5 U_0$	0.15% 15×10^{-4}	0.17% 17×10^{-4}	0.14% 14×10^{-4}
$1.0 U_0$	0.19% 19×10^{-4}	0.2% 20×10^{-4}	0.17% 17×10^{-4}
$1.7 U_0$	0.21% 21×10^{-4}	0.22% 22×10^{-4}	0.19% 19×10^{-4}

9.2 DF Parameters

Performing DF measurement on a cable sample results in a single DF value in percent, expressed as $N_{DF} \times 10^{-4}$ (with N_{DF} a number for the DF) where the relation is $0.1\% = 10 \times 10^{-4}$. According to Houtepen, et al. [B34], the measuring threshold value of the measurable DF at DAC is 0.1%.

Table 1 gives examples of discrete DF values representing a non-aged condition of oil-impregnated cable insulation.

9.3 DF Evaluation Criteria

In general (except in IEC 60141-1 [B37], which recommends maximum allowable DF values for several insulation types), there are no fixed rules for DF interpretation because the cable systems are complex and often contain many components. As a result, for each type of cable insulation, the judgment has to be made regarding how much the dielectric losses differ (see Figure 12 through Figure 14). The evaluation may come from

- Comparison with adjacent phases (A, B, C)
- Comparison with other cables (e.g.: of the same design and vintage within the same location)
- Values when new, or changes as monitored during periodic inspections or under different test conditions, e.g., electrical stresses, different temperatures
- A historic experience library.

Establishing the acceptable DF values for a cable system is complicated by the fact that the values depend not only on the cable system quality but also on the cable and accessory technologies employed. It is clear that the DF is most useful if the specific cable and accessory technologies are known, as this assists in making the appropriate comparisons. Due to the fact that DF depends by definition on the frequency of the test voltage, using DAC voltage for comparison of DF should attempt to use the same order of frequency for each test.

In addition to the absolute value of DF, the increment of DF (Δ DF or tip-up) measured at two designated voltages or the variability (which can be quantified using the standard deviation or the interquartile range) of DF values with time at a constant voltage level, can be used for condition assessment [B27], [B85].

To enhance the effectiveness of the DF test in assessing cable degradation, the DF values should be observed over time whenever the diagnostic test is repeated to observe trends. In general, a significant increase in the DF in comparison to previously measured values may indicate insulation degradation has occurred [B18], [B57].

It is important to recognize that data as obtained using different DAC test voltages at different frequencies between 20 Hz up to 500 Hz can be compared. As shown in Houtepen, et al. [B34], estimations of the DF of DAC system calibration procedure at different DAC frequencies and at different DAC testing voltage levels are made. In those ranges where a DAC system is calibrated, the values can be compared and can be considered similar. As a result, DF limits that are considered acceptable compared to conventional constant voltage (ac) can be used for comparison.

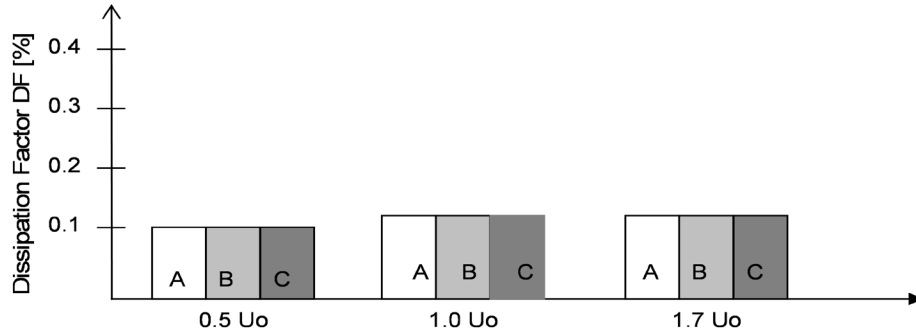


Figure 12—Schematic view of DF measurements at different DAC test voltages using comparison with adjacent phases (A, B, C). Case comparison shows that there is no difference between particular phases. All phases show low DF values and that there is no significant increase of DF in function of the test voltage.

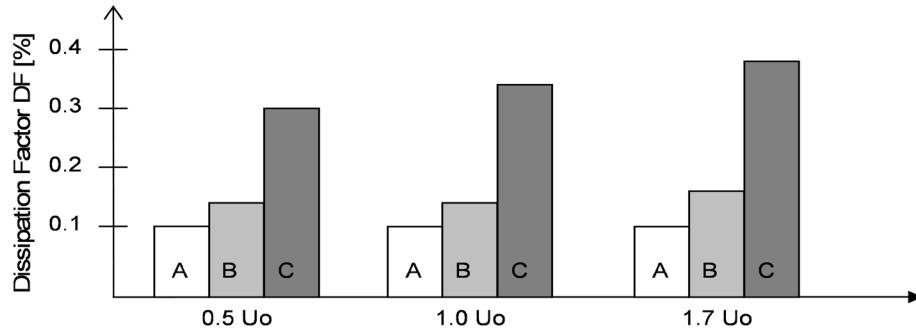


Figure 13—Schematic overview of DF measurements at different DAC test voltages using comparison with adjacent phases (A, B, C). Case comparison shows that there is significant difference between particular phases and that not all phases show low DF values.

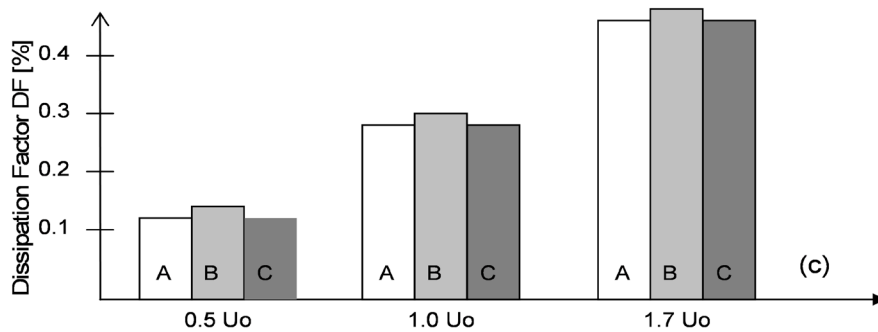


Figure 14—Schematic overview of DF measurements at different DAC test voltages using comparison with adjacent phases (A, B, C). Case comparison shows that there is no difference between particular phases. All phases show increased DF values and that there is significant increase of DF in function of the test voltage.

The DF should only vary slightly between different voltage levels for good cables (See Figure 14.) The DF of oil/paper insulation, which will normally go through a minimum with increasing voltage, is more temperature sensitive than that for extruded insulations. An increase in the DF with increasing voltage can have different physical origins. It can indicate the presence of high intensity of or severe PD in paper-insulated, lead-covered (PILC) cable systems, the presence of water treeing in extruded dielectric cable systems or other defects [B18], [B38], [B44], [B48], [B57], [B77]. The variation of DF with time at constant voltage can also indicate water treeing. A decrease in DF can indicate moisture problems in accessories. Such variation in DF can be on the order of less than 0.1%. Results are reported in terms of the temporal stability of the DF, the increase of loss (“tip-up”) at selected electrical stresses, and/or the absolute DF at a specific voltage (See Figure 13 and Figure 14). The data should be reported to make further analysis possible (e.g., to track trends, compare with adjacent cable lengths, and/or reinterpret data in the light of new knowledge).

New oil-filled (OF) insulation always shows relatively low dielectric losses when measured at power frequencies. The DF should not exceed 2×10^{-3} (0.2 %). In addition, when the test voltage is increased from $0.5 U_0$ to $2.0 U_0$, the DF should not increase by more than 10×10^{-4} . When, as a result of aging, the DF exceeds 50×10^{-4} (0.5%), thermal breakdown of the insulation is likely. Dissipation of energy in the cable insulation is caused by different phenomena occurring when the voltage is applied to the insulation [B20], [B54].

Due to these aging processes, OF insulation is more prone to exhibit high values of DF. Therefore, for OF cables, the DF can possibly be used as degradation indicator, as it increases during aging. Moreover, by the DF measurements performance on OF cables, the degradation assessment of OF insulation can be made [B10], [B21], [B22], [B37], [B49], [B57], [B58], [B61], [B70], [B77]. DF historical information gathered during maintenance testing can be helpful to give operational recommendations to the cable owner.

10. Conclusions

DAC testing is an alternative method for testing and diagnosis of all types of distribution and transmission power cable systems. DAC uses—after charging and short-circuiting the test object via an inductor—the damped free oscillation, presumed the natural frequency is within the 20 Hz to 500 Hz range.

This guide addresses the use of DAC non-monitored (simple) and monitored withstand and other diagnostic field testing of installed shielded power cable systems covering voltage classes from 5 kV up to 230 kV. Non-monitored and monitored [tangent delta (DF), differential tangent delta, and PD] withstand tests at DAC are used as diagnostic tools to assess the condition of cable systems.

Based on actual practice experience, tables of test voltage levels are included in Annex A for acceptance and maintenance tests on cable systems up to 230 kV. The actual practice of recent years in the use of this method indicates that most DAC acceptance tests are monitored by PD detection. Due to the fact that this application is still evolving, and the verification of the effectiveness of DAC voltage withstand testing is based on the last ten years of use, further data collection and evaluation are necessary and should be part of the next revision process of this document.

The advantages, limitations, and open issues with respect to DAC testing of cables and accessories are discussed. DAC voltage testing techniques, along with other test techniques, are continuing to be developed.

Annex A

(informative)

DAC test voltage levels and test procedures

A.1 Test voltage levels

With regard to applied DAC test voltage levels, experience has shown the users have selected the test values to be the same as the international recommendations related to tests with ac alternating voltage of near power frequency IEC 60502-2, IEC 60840 and IEC 62067 and/or in accordance with actual practice feedback ([B14], [B16], [B19], [B23], [B25], [B28], [B29], [B45], [B57], [B58], [B65], [B66], [B67], [B82], see Table A.1 and Table A.2). Regarding the number of DAC excitations, these are selected to be the same as in Aucourt [B4], Farneti, et al, 1989 [B15], and Farneti, et al., 1990 [B16]. Due to limited experience, more verification is needed for cables 150 kV above these values [B32].

**Table A.1—DAC test voltage levels (20 Hz to 500Hz) as used for DAC testing
(50 DAC excitations) of new installed power cables.**

Power cable rated voltage U [kV] phase-to-phase	U_0 [kV]	DAC test voltage level V_T [kV _{peak}] phase-to-ground
3	2	6
5	3	8
6	4	12
8	5	14
10	6	17
15	9	26
20	12	34
25	15	43
30	18	51
35	21	60
45–47	26	74
60–69	35	99
110–115	64	181
132–138	77	187
150–161	87	212
220–230	127	254

**Table A.2—DAC test voltage levels (20 Hz to 500 Hz) as used for maintenance testing
(50 DAC excitations) of repaired/refurbished power cables.**

Power cable rated voltage U [kV] phase-to-phase	U_0 [kV]	DAC test voltage level V_T [kV _{peak}] phase-to-ground
3	2	5
5	3	6
6	4	10
8	5	11
10	6	14
15	9	21
20	12	28
25	15	35
30	18	41
35	21	48
45–47	26	60
60–69	35	80
110–115	64	145
132–138	77	150
150–161	87	170
220–230	127	204
275–287*	159	237
330–345*	191	282
380–400*	220	293

* Test voltage levels given above 230 kV are provisionally and given for study purposes only.

A.2 Acceptance and maintenance tests

The DAC test procedures for acceptance tests and maintenance tests are the following IEC 60060-3, [B3], [B4], [B5], [B6], [B9], [B12], [B14], [B15], [B16], [B31], [B45], [B56], [B58], [B59], [B60], [B69], [B70], [B71], [B72], [B78], [B79], and [B87].

- Step 1. According to the cable voltage rating select the DAC maximum test voltage level V_T in peak kilovolts, see Table A.1 and Table A.2.
- Step 2. For the DAC voltage step phase, fix the test voltage steps ΔV_T in peak kilovolts or in the unit of U_0 , e.g., $0.2 U_0$.
- Step 3. Fix the number of excitations N_{DAC} to be applied for the DAC voltage step phase N_{DAC} , e.g., five per each ΔV_T test voltage step.
- Step 4. Fix the number of excitations N_{DAC} to be applied for the DAC voltage hold phase, e.g., 50. Nevertheless, for maintenance tests on aged cable systems, reduce the number of DAC excitations to a minimum quantity required to get a useful diagnostic result; this may avoid possible initiation of electrical trees. Decisions for any actions may be adopted accordingly before risking incipient failures.
- Step 5. According to the parameters as defined in Step 1 through Step 3, start the test procedure of the DAC voltage step phase (see also Figure 7).
- Step 6. For a PD-monitored test, evaluate the PDIV. In the case of PD occurrence, evaluate the harmfulness of the PD source, e.g., external or internal, and take the appropriate action.

- Step 7. After the DAC maximum test voltage level V_T has been achieved, start the DAC voltage withstand test according to the parameters of Step 1 and Step 4.
- Step 8. For a PD monitored test, evaluate the PD inception. For a PD occurrence, evaluate the harmfulness of the PD source, e.g. external or internal and take the appropriate actions.
- Step 9. Evaluate the results of the test in accordance with Figure A.1 and in 7.3.

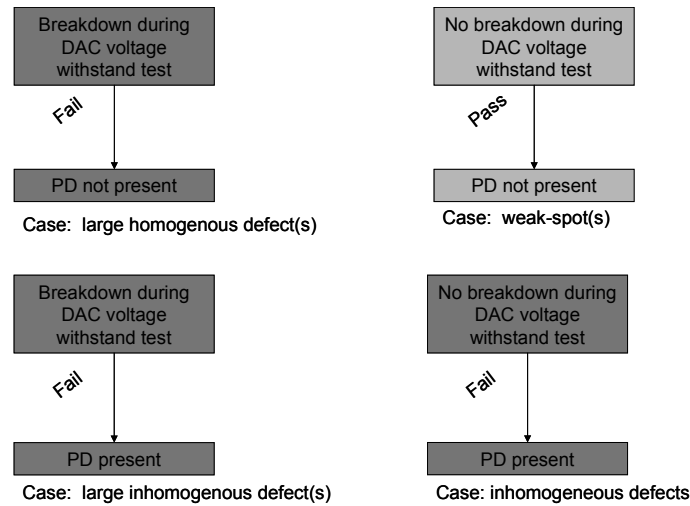


Figure A.1— Schematic overview of evaluation criteria for PD monitored DAC voltage withstand test of (E) HV power cables. Where a new or maintained power cable circuits must to be PD free, even if there was no breakdown observed, the particular cable has to be rejected due to the presence of PD.

A.3 Diagnostic test

The DAC test procedure for a diagnostic test is:

- Step 1. According to the cable voltage rating, select the DAC maximum test voltage level V_T in peak kilovolts (see Table A.2). In accordance with the maintenance and operational history, reduce the maximum test voltage level to a level where no effects of lifetime consumed previously is expected.
- Step 2. For the DAC voltage step phase, fix the test voltage steps ΔV_T in in peak kilovolts or in the unit of U_0 , e.g., $0.2 U_0$.
- Step 3. Fix the number of excitations N_{DAC} to be applied for the DAC voltage step phase N_{DAC} , e.g., five per each ΔV_T test voltage step
- Step 4. According to the parameters as defined in Step 1 through Step 3, start the test procedure of the DAC voltage step phase (see also Figure 7).
- Step 5. For a PD monitored test, evaluate the PDIV. In case of PD occurrence, evaluate the harmfulness of the PD source, e.g., external or internal, and take the necessary actions.

- Step 6. For DF measurement at selected DAC test voltage levels the actual DF values have to be determined.
- Step 7. Evaluate the results in accordance with 7.3, Clause 8, and Clause 9.

Annex B

(informative)

DF estimation for DAC voltages

The DF represented by $\tan \delta$ parameter is an important diagnostic parameter to assess the condition of oil-impregnated paper insulation [B10], [B18], [B20], [B22], [B27], [B37], [B38], [B44], [B48], [B49], [B57], [B61], [B77], [B85]. The most important and recognizable origins are [B54]:

- Conductive losses caused by finite bulk resistance of the insulation and leakage currents
- Friction between dipoles and insulation material (polarization losses)
- Local field enhancement on interfaces between materials characterized by different permeability
- In case of the presence of PD activity, this can also increase the value of DF.

For healthy paper oil insulation at power frequencies of tens of hertz, the DF is characterized by low values, e.g., below 20×10^{-4} (0.2%) and less dependence on the electric stresses, e.g., less than 0.1% as the test voltage is raised from, e.g., $0.5 U_0$ to $2.0 U_0$. Theoretically, values higher than 0.5% DF at nominal voltage in combination with aging effects and temporary and local thermal over-stresses may represent a higher risk of thermal breakdown.

An increase of electric stress above PDIV accompanied with high intensity PD activity, e.g., PD-levels in the range of nano-Coulombs [nC] may also increase dielectric losses.

Figure B.1 shows a circuit model for the DAC system, essentially a series RLC circuit.

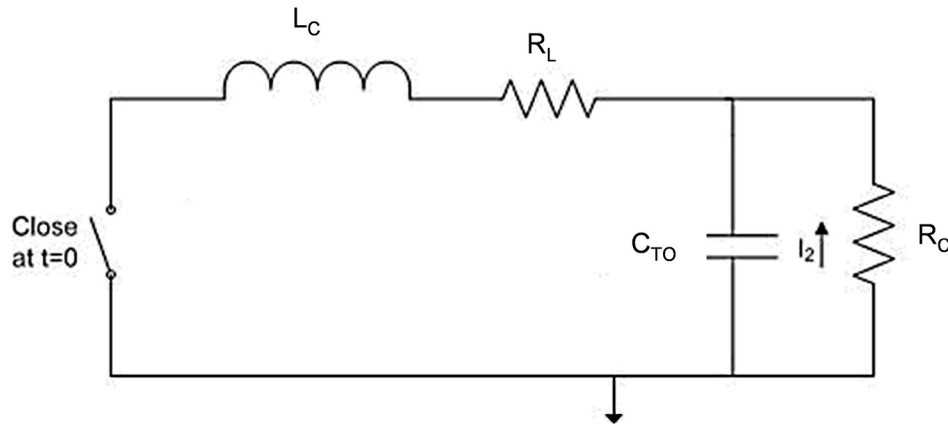


Figure B.1—DAC circuit model that can be used for the DF estimation.

R_L is the total internal resistance of the system, which varies with the amplitude and frequency of the applied voltage, R_C represents the losses in the test object, L_C is the inductance of the air-core inductor, and C_{TO} is the capacitance of the test object. It should be noted that C_{TO} and R_C may also be a function of voltage and frequency.

Based on the resulting oscillating voltage of a DAC test setup, the DF can be measured with the decay characteristics of the DAC voltage wave, as shown in Houtepen, et al. [B34] and Wester, et al, 2007 [B87] (see Figure B.2).

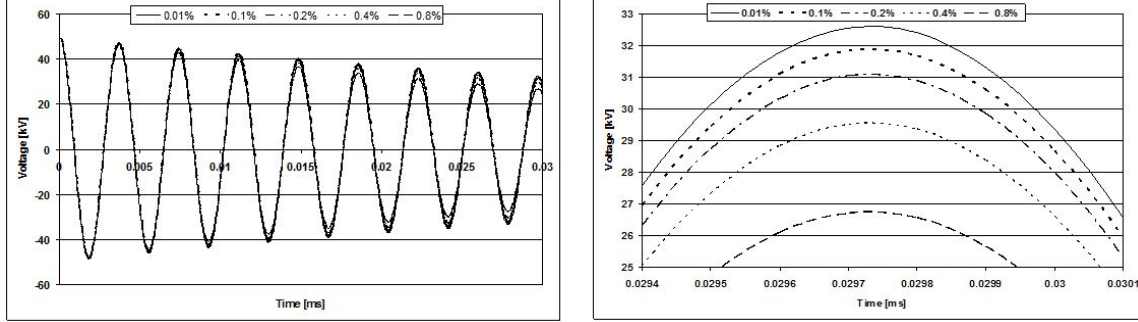


Figure B.2—DAC voltage wave shape for a DAC test system setup with $L = 2$ H and $C = 1$ uF for different dielectric loss factors. The right side is a close up of the eighth DAC cycle to show the difference in damping in higher detail.

A DAC voltage wave can be described by

$$U(t) = U_0 \cdot e^{-\beta \cdot t} \sin(\omega \cdot t + \varphi)$$

Where U_0 is the voltage at the end of the unipolar voltage charging time, β is the attenuation coefficient, φ is the phase shift, and $\omega = 2\pi f$. $\tan \delta$ can be calculated from the decay characteristics of the wave.

To be able to estimate the DF of the test object, the losses of the DAC test setup should be known, e.g., by determination of the losses as a resistance R_L in the whole DAC test circuit without the losses of the test object. The losses of the test object can be represented by a parallel resistance R_C . This R_C can be estimated numerically from the measurement results with the formula presented by Houtepen, et al. [B34] or in Wester, et al, 2007 [B87]:

$$R_C = \frac{L_C}{2\beta_{DAC} L_C C_{TO} - R_L C_{TO}}$$

The unknown factor β_{DAC} can be calculated directly from the damping characteristics of the DAC voltage, using the voltage and time of the voltage peaks of different periods. For example:

$$\frac{U_5}{U_1} = e^{-\beta(t_5 - t_1)} \Rightarrow \beta_{DAC} = -\frac{\ln(U_5/U_1)}{(t_5 - t_1)}$$

Now, the DF equals to DL of the cable sample is given by:

$$DL = \frac{1}{\omega \cdot R_C \cdot C_{TO}}$$

Annex C

(informative)

DAC parameters

C.1 Test circuit parameters

C.1.1 Test object capacitance C_{TO} in microfarads

Depending on the cable type, length, and dimension, this value can vary between a few nanofarads and several microfarads. In the case of a test object with a relative low capacitance of a few nanofarads, the total test object capacitance can be a parallel connection of the test object with an additional HV capacitor. In this case, it is of importance that this capacitor is suitable to withstand the maximum test voltage and in the case of monitored tests, e.g., PD or dielectric loss measurement, it has to be PD-free and its dielectric losses as a function of voltage should be known. In case of PD measurements, a blocking inductance should be placed in series with the additional capacitance to avoid PD signals running through the additional capacitance instead of the measuring system.

C.1.2 System inductance L_C in henry

Next to the test object capacitance, this is the second fundamental part of a DAC system, and depending on the DAC system type, the inductance (one single coil or several coils) of the DAC system can be fixed, e.g. 8 H or it can be variable in dependence on the test voltages and the test object capacitance.

C.1.3 Maximum test voltage $V_{\max}$ in peak kilovolts

This is the maximum test voltage of the first DAC voltage cycle (V_T) which is equal to the pre-selected maximum test voltage as it can be generated by a specific DAC system for the test purpose whereas also the test circuit elements and the test object are designated to be tested.

C.1.4 Maximum charging current $I_{C\max}$ in milliamperes

This is a standard parameter of the DAC system, and depending on the type of system it can vary between a few milliamperes up to tens of milliamperes. It has to be considered that in combination with the C_{TO} and with $V_{\max}$ this parameter determines the DAC charging time.

C.1.5 Maximum switching circuit current $I_{S\max}$ in amperes

This is a standard parameter of the DAC system and depending on the type of system it can vary between few amperes up to several hundred amperes. It has to be considered that this parameter in combination with $V_{\max}$ determines the maximum test object capacitance C_{TO} .

C.1.6 Switching duration t_s in microseconds

This is the time that is needed by a DAC system after the maximum test voltage V_T is reached after the charging to close the oscillation circuit of L_C and C_{TO} and to start the damped oscillation between L_C and C_{TO} . The duration can vary in the range of several microseconds.

C.1.7 Quality factor Q_C

The quality factor Q_C of the oscillating circuit is

$$Q_C = \left(L_C / (C_{TO} \cdot R_A^2) \right)$$

where

R_A is the equivalent circuit resistance.

C.1.8 Maximum cable capacitance $C_{TO \max}$

The maximum cable capacitance $C_{TO \max}$ that can be tested by a DAC test facility can be calculated by

$$C_{TO} = (I_{s \max} / V_{\max})^2 \cdot L_C$$

Where

$V_{\max}$ is the maximum applied test voltage

$I_{s \max}$ is the permissible ac current in the oscillating circuit and the minimum accepted circuit natural frequency f_r .

C.2 Voltage parameters

C.2.1 DAC excitation

DAC excitation completes process of charging the test object capacitance C_{TO} with $I_{C \max}$ to a selected test voltage level V_{DAC} followed by a damped sinusoidal oscillation with circuit natural frequency f_r and a given damping factor D_f . The time duration of a DAC excitation consists of two parts: the charging part (in the range of a number of tens of seconds) and the DAC oscillation part (in the range of hundreds of milliseconds) (see Figure 2).

C.2.2 DAC

Starting from a (negative or positive) excitation voltage level and having damped sinusoidal oscillation around the zero level, DAC is characterized by the peak value V_{DAC} , the circuit natural frequency f_r and the damping factor D_f .

C.2.3 Circuit natural frequency f_r in hertz

Circuit natural frequency f_r equals the reciprocal of the time between two successive peaks of same polarity and it is determined by the C_{TO} and L_C and in most cases it can be calculated as:

$$f_r = \left(1/2\pi\sqrt{L_C \cdot C_{TO}}\right)$$

Requirements (tolerances): e.g. natural frequency: $f_r = 20$ Hz to 500 Hz.

C.2.4 Damping factor D_f percentage

The damping factor D_f percentage is the voltage difference between the first and second peak of same polarity, divided by the voltage value of the first peak. To generate a realistic DAC excitation the D_f factor generally should be less than 15%. Requirements (tolerances): e.g., damping factor $D_f \leq 15\%$.

C.2.4.1 Voltage level V_{DAC} in peak kilovolts

The voltage level V_{DAC} in peak kilovolts is the actual test voltage level of the DAC voltage, which is equal to the actual test voltage as it has to be generated by a DAC system. Requirements (tolerances): e.g., voltage value $V_{DAC} = V_{peak} (1 \pm 0.03)$

C.2.5 Charging time t_c in seconds

The charging time t_c in seconds equals to the necessary time at given, e.g., maximum current I_{Cmax} to charge the test object capacitance C_{TO} up to selected test voltage level V_{DAC} . Requirements (tolerances): e.g., charging time $t_c < 100$ s.

C.3 Test parameters

C.3.1 Test voltage level V_T in peak kilovolts

The test voltage level V_T is the maximum voltage value during the whole DAC excitation (see Figure 2). For test purposes, this value has to be selected in accordance with valid test recommendations. Depending on the test procedure the V_T can be selected for on one or even more test levels.

C.3.2 Test voltage steps ΔV

Test voltage steps ΔV applying DAC excitations for an increasing voltage test the steps in the V_T voltage increase have to be defined. The ΔV_T can be defined in peak kilovolts or in the unit of U_0 , e.g., $0.1 U_0$ or $0.2 U_0$.

C.3.3 Number of excitations N_{DAC}

This parameter describes the number of DAC excitations that will be generated at given test voltage level V_T . The total test procedure can consist of different sequences of N_{DAC} , e.g. during voltage withstand test on a new cable $N_{DAC} = 50$ excitations [B16], [B45] or during diagnostic test where N_{DAC} can be lower.

C.3.4 Duration of the test in minutes

The duration of the test in minutes is the total time at which a selected consecutive number of DAC excitation N_{DAC} at given test voltage level V_T has been applied to the test object.

C.3.5 DAC voltage withstand test

The DAC voltage withstand test is a series of DAC voltage excitations as applied consecutively to the power cable under test. The duration of the test is determined by a number of DAC excitations that have been applied to the power cable under test at a selected DAC test voltage. The maximum DAC withstand voltage level is determined by the voltage peak values V_{DAC} respectively rms values $V_{DAC}/\sqrt{2}$ of the first DAC cycle.

C.4 Evaluation parameters:

C.4.1 DAC voltage withstand test outcome

After applying a number of DAC excitations at a selected voltage level, the result can be described as either “Pass,” in the case of no breakdown occurrence, or “Fail,” in the case of a breakdown.

C.4.2 PDIV in peak kilovolts

The PDIV in peak kilovolts is the test voltage level V_T at which the repetitive PDs have been observed.

C.4.3 PDEV in peak kilovolts

The PDEV in peak kilovolts is the test voltage level V_T at which the repetitive PDs have been extinguished.

C.4.4 PD level in picocoulombs

The PD level in picocoulombs is the PD level as observed after a voltage application. It represents the most repeatedly occurring PD magnitude.

C.4.5 PD site location mapping

PD site location mapping is the graphical and/or numerical representation of PD pulse (intensity) concentration in function of the cable length. If applicable, the location of the cables accessories (joints,

terminations) can be indicated. The PD site location mapping can also be evaluated for different test voltage levels V_T .

C.4.6 Change of PD level in function of the voltage

Applying a number of DAC excitations at the same or different voltage levels may provide information about the PD behavior in the function of these parameters. Evaluation of this behavior may be valuable for the defect(s) type evaluation.

C.4.7 PD phase-resolved patter

Applying one or more DAC excitations produces a graphic display showing the PD pulse amplitudes and intensity in function of the test voltage cycle. Evaluation of this behavior may be valuable for the defect(s) type evaluation.

C.4.8 DF parameter percentage

The DF parameter percentage is the dielectric loss parameter as observed at a specific excitation voltage level. It represents the power losses in the test object at a designated test voltage.

C.4.9 Change of dielectric loss parameter in fuction of time/voltage level

Applying a number of DAC excitations at the same or different voltage levels may provide information about the dielectric loss behavior in function of these parameters. Evaluation of this behavior may be valuable for the evaluation of oil-impregnated insulation degradation.

C.4.10 PD sensitivity

PD sensitivity is the lowest calibration signal that can be detected and the lowest calibration signal that can be localized.

Annex D

(informative)

Example PD evaluation for after-laying and -maintenance testing

When establishing the required sensitivity and maximal acceptable background noise level for the onsite PD measurement, the following aspects should be taken into account. More details can be found in IEEE Std 400.3.

- a) *The type of cable system (i.e., the type of cable and the type of accessories):* Polymeric cable systems are generally quite sensitive to PDs, whereas fluid-filled or mass-impregnated systems are usually less sensitive to PD. Regarding accessories, fluid-filled accessories can usually withstand higher PD activity than fluid-free accessories and for a longer time before failure occurs.
- b) *The operational electric stress level of the cable systems:* In solid dielectrics, the severity of PD activity increases quickly with increasing operational stress. As a consequence, HV, and especially EHV, cable systems, which are designed for operating at relatively high electric fields, are, as a rule, much more sensitive to PD's than MV systems, which operate at lower electric stress.
- c) *Test voltage level reached during the tests:* When testing cable systems at voltages higher than the nominal voltage, the actual electric stress in the system is higher than the nominal stress. Consequently, the severity of the PDs that are possibly detected, increases with the test voltage.
- d) *PD activity or disturbances:* PD activity or disturbances that may originate outside the test object also increase with the test (over)voltage; for instance, corona discharges originating at the HV connection between the voltage source and the test object.

As an example, severe defects in oil filled MV cables (PILC) or defects in accessories of MV XLPE cables may induce PDs in the range of hundreds of picocoulombs without leading to an immediate failure. Therefore, for those situations, a background noise level in the order of 100 pC can be accepted for the PD test on site. On the other hand, for (E)HV polymeric extruded cables system PDs of a few tens of picocoulombs may already lead to failure within a relatively short time. Consequently, for this case it is important to maintain onsite background noise level as low as possible.

These two examples also show the complexity of establishing general threshold values for PD levels during onsite measurements on cable systems. The threshold values used today are based on experience, long term observation of measured cable systems, and following laboratory investigations of examined parts of the cable system, e.g., joints.

In addition to the apparent charge, the evaluation of the phase-resolved PD patterns as well as the shape of the individual PD pulses can be very helpful for an assessment of the PD severity. In particular, it is important to be able to discriminate between internal PD activity (i.e., PDs originated inside the test object) and external PD activity or disturbances (i.e., PDs originated outside the test object).

To estimate the criticality of PD, fault-type identification has to be complemented by PD site localization [B24], [B57]. In expanded geometries, such as long cables, the PD identification without localization would be useless. The most commonly used method to calculate the location of a PD site is based on time-domain-reflectometry (TDR). The arrival time of original and reflected PD signals are measured with one or more sensors to calculate the origin based on the difference of the time-of-arrival of electric signals.

Another technique, signal reduction analysis, is based on the fact that PD pulses propagate through the power cable in different modes [B57]. Depending on the frequency of the propagating signal, the amplitude

will be more or less attenuated. For frequencies up to several megahertz, the PD signals are only slightly attenuated, whereas, for higher frequencies, the attenuation is higher. This effect can be used to roughly estimate the origin of the PD signals.

For the determination of the insulation condition, several PD parameters are found of importance and can be used to evaluate a PD measurement. For field application of the PD diagnostics, the PD properties as shown below turned out to be of relevance from practical experience. The properties are measured directly by the detection equipment for the cable system or derived after analyzing the measurement data for individual cable components from the PD mapping. In Figure D.1 through Figure D.3, decision flowcharts for after-laying testing of newly installed XLPE cable sections are shown. The final result of PD measurement should be provided in the form of PD measurement report. Based on this report, the condition assessment of the cable system can be determined. The PD measurement report should be able to describe the actual condition of the cable system so that the owner can use this report as data input for maintenance decisions.

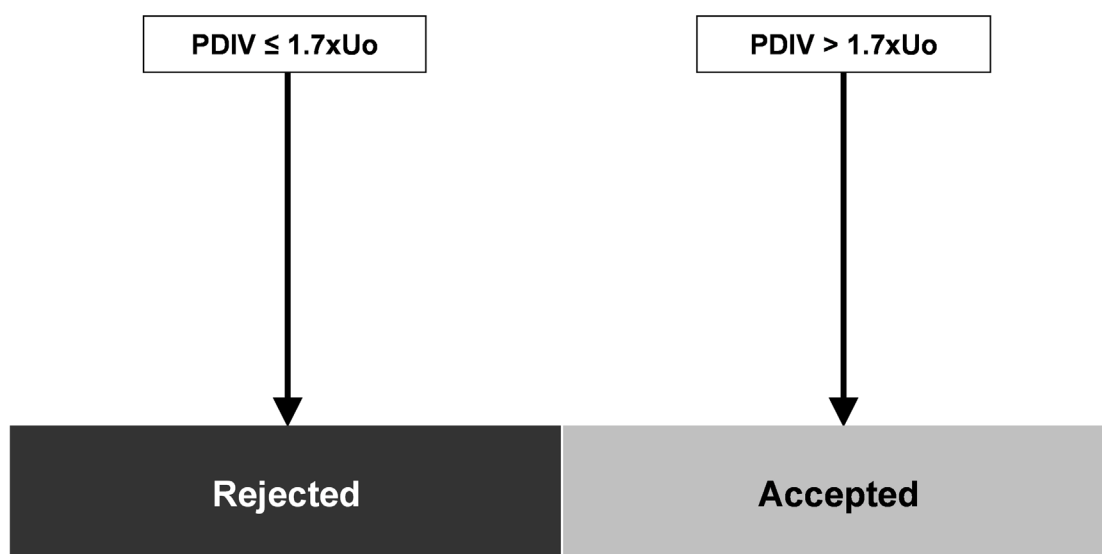


Figure D.1—Example decision flowchart for PD detection on damped DAC voltage testing after-laying cable installation (XLPE)

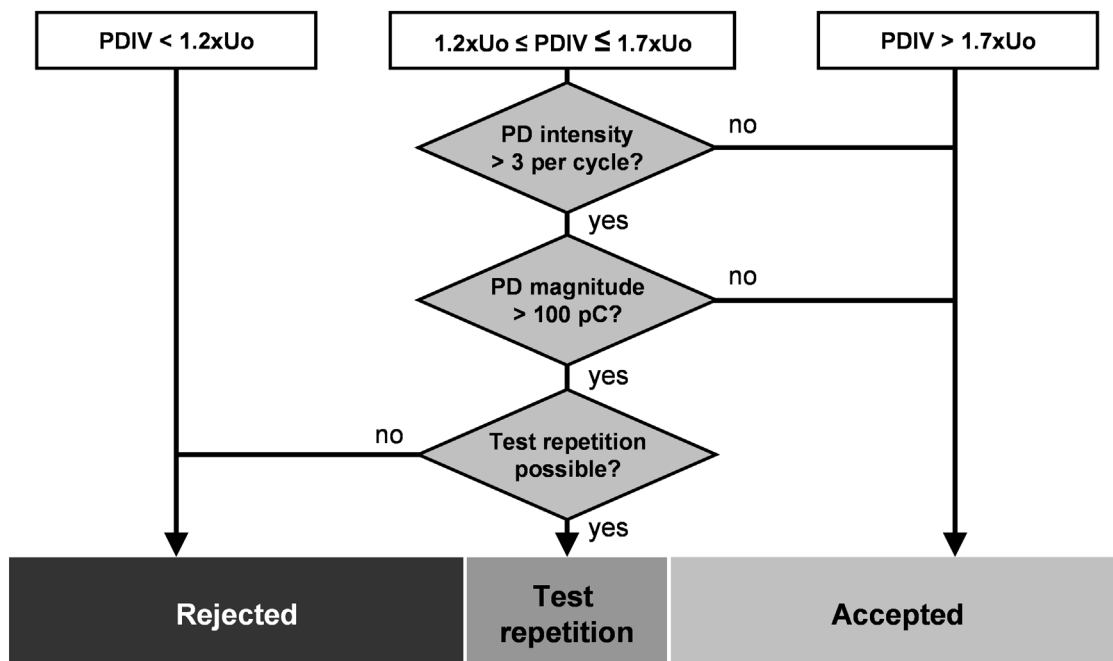


Figure D.2—Example decision flowchart for PD detection on damped DAC voltage testing after-laying cable joint.

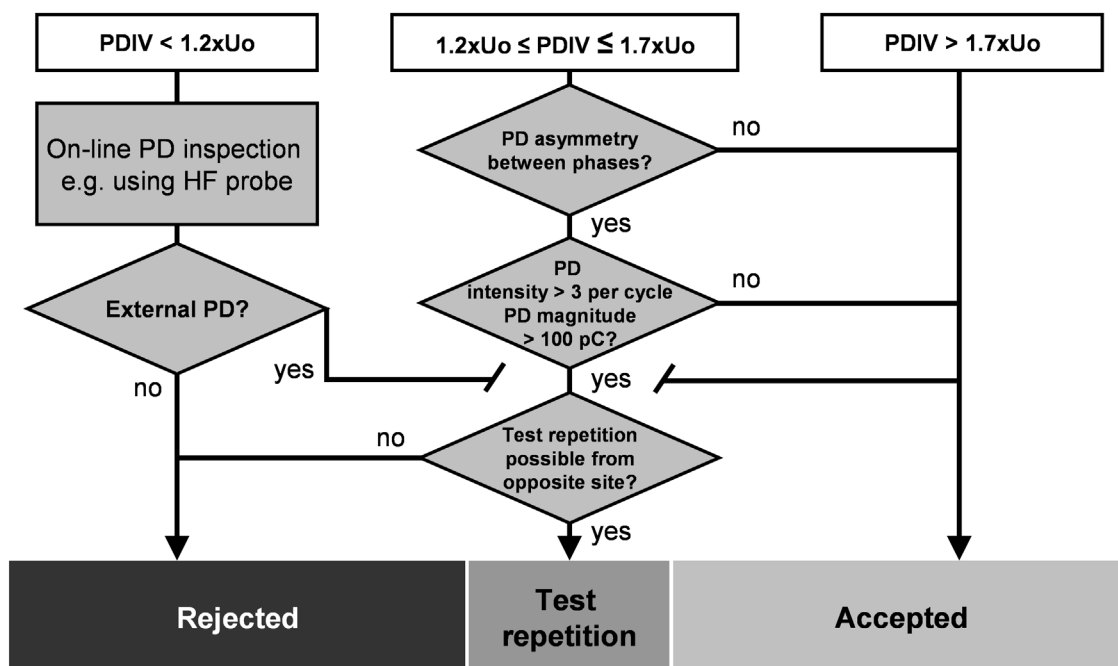
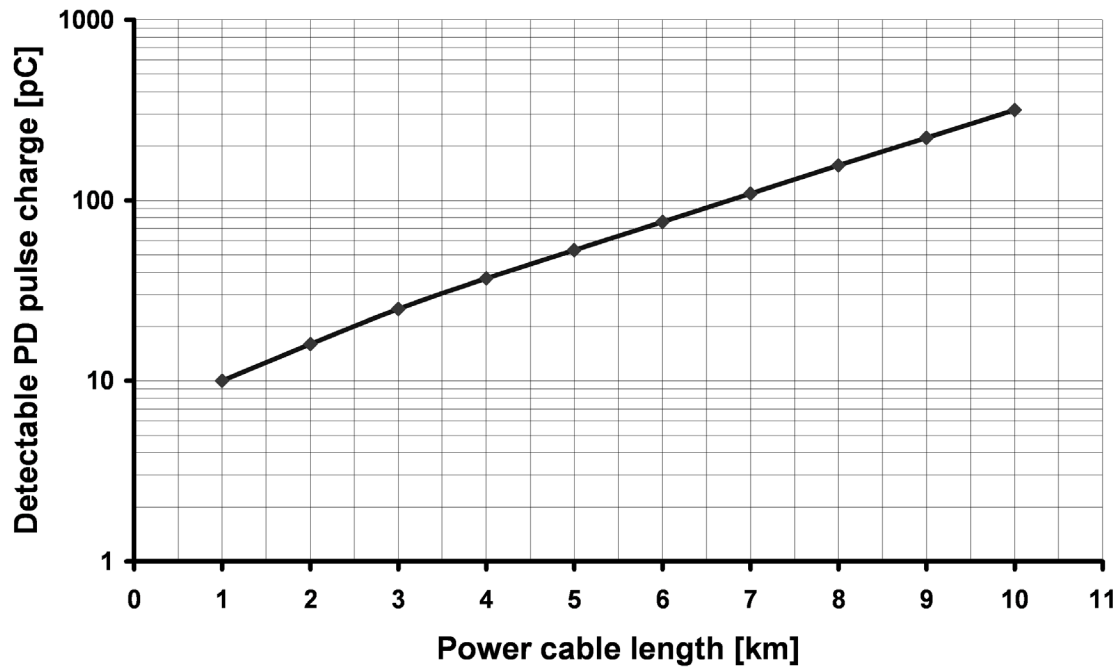


Figure D.3—Example decision flowchart for PD detection on damped AC voltage testing after-laying cable termination.

Sensitive PD measurements according to IEC 60270 and IEC 60885-3 can only be applied for a cable length up to several kilometers. For longer cable lengths, e.g., 10 km and longer, the PD threshold level is increased substantially due to attenuation and dispersion of propagating PD pulses (see Figure D.4).



From Technical Brochure 297 “Practical aspects of the detection of partial discharges in power cables,”
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Figure D.4—PD detection sensitivity versus the cable length calculated on the basis of a reference value of 10 pC achievable for a power cable of 1-km length [B57]

Annex E

(informative)

Results of the International Survey of the Use of Damped AC Voltages for Testing MV and (E)HV Power Cables

DAC testing uses damped alternating voltage at frequencies between 20 Hz and 500 Hz [B29], [B51], [B69], [B72]. In DAC systems, the actual frequency of the voltage depends on the cable capacitance and the inductor used. For cable lengths that will lead to oscillating frequencies above 500 Hz, an additional load capacitor can be used. The DAC test equipment generates damped sinusoidal voltage of quite low damping. To evaluate the use and the experiences of DAC technology for testing and diagnosis of power-cable circuits, an international survey was conducted in the Fall 2012. Since 1999, to test MV voltage cable networks (6 kV to 35 kV) and (E)HV cable networks (36 kV to 230 kV), a total of five international suppliers have provided the DAC technology to about 300 users. This study is a result of a user survey performed by the members (manufacturers, service providers, utilities) of the working group, does not provide any systematic evidence, and should be considered as state of the art. About 38% (HV users 69.2% and MV users 34%) of 120 users contacted have responded to the survey (see Table E.1). All users have been divided into three categories (see Table E.2).

Table E.1—The geographic distribution of survey responses.

Europe	72%
Asia	21%
Africa	5%
Americas	2%

Table E.2—The period of testing experiences with DAC.

More than 5 years	35%
Between 1 and 5 years	53%
Below 1 year	12%

According to the majority of users, DAC voltages are being used for after laying, after repair, and condition assessment (see Table E.3). In general, about 90% of survey responders testing E(HV) cables are using DAC for condition assessment purposes, and about 67% of those users are testing with DAC for after-laying and/or after repair purposes.

Table E.3—Purpose of testing with DAC.

After-laying testing	MV 58.8%
	(E) HV 66.7%
After repair testing	MV 82.53%
	(E) HV 66.7%
Condition assessment testing	MV 76.5%
	E (HV) 88.9%

Regarding the cable insulation type, every survey responder is testing XLPE cables with DAC. The majority of responders are also testing OF cables with DAC (see Figure E.1).

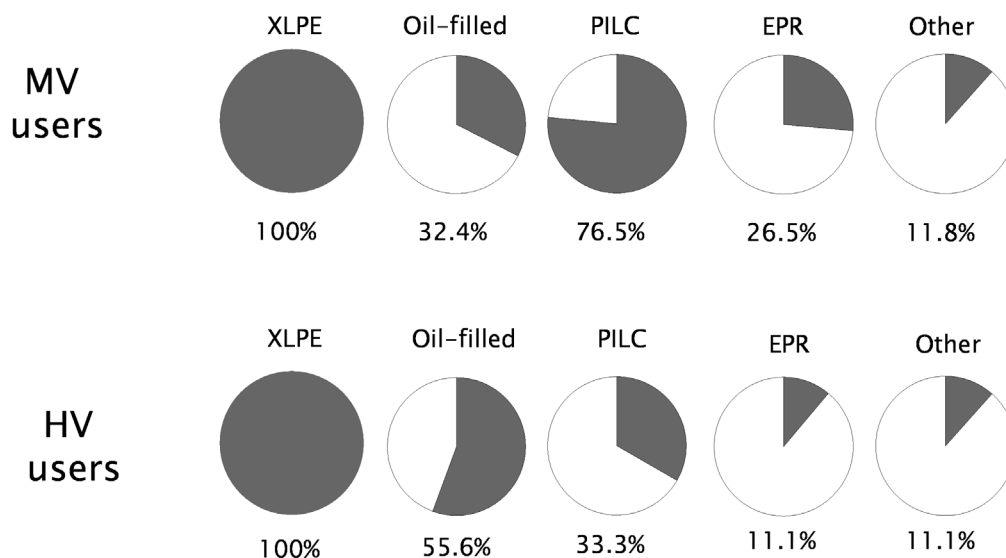


Figure E.1—Cable insulation types being tested per survey responder.

The test procedure as applied by the majority of responders is monitored voltage testing, which means a combination of DAC voltage tests with PD measurement (see Table E.4). The majority of survey responders that apply DAC voltage for (E)HV uses DAC voltage for withstand testing (see Table E.5). The maximum test voltage levels as well as the number of DAC excitations for MV and (E)HV cables as applied for different types of tests are in accordance with Table A.1 and Table A.2 from Annex A (see Table E.6).

Table E.4—Testing methods

	MV	(E)HV
DAC voltage test without PD measurement	28%	22%
DAC voltage test with PD measurement	72%	78%

Table E.5—Application of the DAC voltage withstand test

	Yes	No
MV cables (6-35kV)	38%	62%
(E) HV cables (36-230kV)	89%	11%

Table E.6—DAC testing procedures

Parameter		After-laying testing	After repair testing	Condition assessment testing
Maximum test voltage	MV (6 kV – 35kV)	$1.7 U_0 - 2.0 U_0$	$1.7 U_0 - 2.0 U_0$	$1.7 U_0$
	(E)HV (36 kV – 230 kV)	$1.4 U_0 - 1.7 U_0$	$1.4 U_0 - 1.7 U_0$	$1.4 U_0$
Number of DAC voltage excitations/voltage level		1 – 10 excitations		
Number of DAC voltage excitations for withstand test at maximum test voltage		50 excitations or 1 h	50 excitations or 1 h, or in agreement	In agreement

Regarding the experiences during testing, 40% of survey responders have observed during test an insulation breakdown, and in more than 70% of these breakdown cases PD has been detected before breakdown (see Figure E.2).

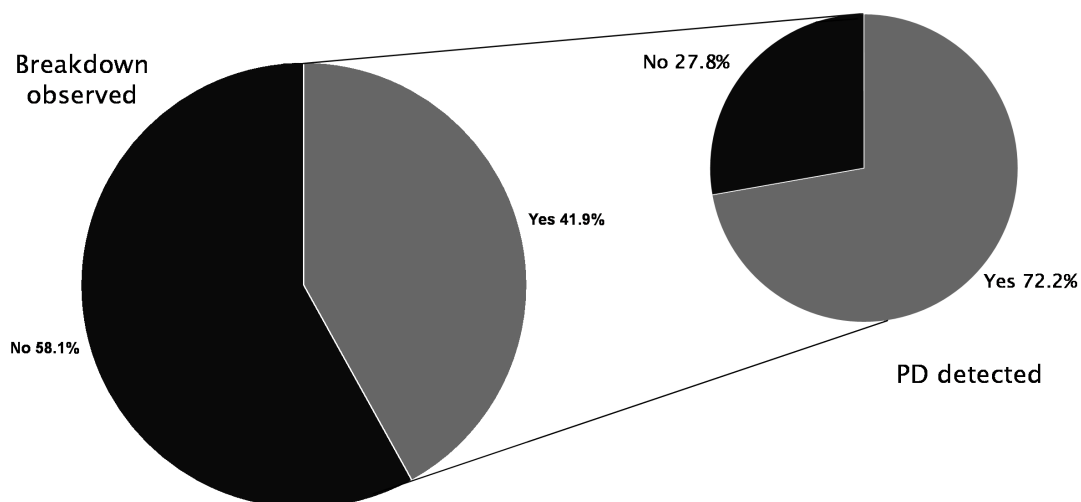


Figure E.2—Experience of responding users (38% of surveyed) with respect to whether a breakdown has ever been experienced in a DAC test and whether PD was detected.

Annex F

(informative)

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