

On-site Testing and Diagnosis of Distribution and Transmission Power Cables Using Damped AC Voltages

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Abstract: On-site testing and diagnosis of distribution and transmission power cables is one of the issues of asset management within power utilities. Due to the importance of power cables in the transmission network, it is of importance to test the initial condition during after-laying, to test the actual condition of HV power cables during operation and to test the repair work after a failure.

I. INTRODUCTION

In addition to on-site voltage testing of cable systems also non-destructive measuring techniques as e.g. partial discharges or dissipation factor measurements are becoming important instruments of asset management.

Based on the international experience as collected in the last 8 years at different power grids, cable manufacturers and normalization work of international bodies, this contribution focuses on several fundamental and applied aspects of on-site testing and diagnosis of new and service aged distribution and transmission HV power cables. Based on the above consideration and evaluation, and supported by systematic field experiences as obtained using damped AC (DAC) voltage testing, a recommendation and procedure for testing and diagnostics will be discussed in this contribution. In particular, supported by practical examples, different important aspects of testing new connections as well as condition assessment of service aged power cables up to 230kV is discussed.

The sinusoidal damped AC voltages have been proposed 20 years ago as a complementary and/or alternative method to sinusoidal continuous AC voltages [1-4]. The DAC method has become accepted in the last years for on-site testing and standardized PD measurements of all types and length of power cables [5-7]. Moreover as compared to conventional continuous AC testing, DAC systems fulfill the characteristics of modern on-site testing methods:

- Lightweight and high level of mobility of the test system \Rightarrow lower transportation, maintenance and logistic cost
- Test system compactness versus output voltage, \Rightarrow accessibility to a large type of sub-stations
- Easy system assembling and low erecting effort \Rightarrow lower costs of test executions
- Low necessary power demand for testing long cable lengths applicability for all types of cable circuits

- Possibility of sensitive standardized PD detection and dissipation factor measurement \Rightarrow comparison to factory testing experiences

It is known that a DAC system requires much less power to energize large capacitive loads and has the advantage of reduced volume and weight, as compared to conventional AC resonant systems. This is possible due to the fact that the DAC method uses a constant energizing current to energize the cable capacitance. Furthermore the capacitive test component resonates with an air core inductor without reactive power compensation.

In general, for on-site acceptance test for newly installed or repaired circuits one of the two following approaches is typically followed:

1. Potentially destructive withstand tests by over-voltage stresses applied to the test object, e.g. for 1 hour, or
2. Alternatively a voltage test of $1xU_0$ (nominal voltage) as applied for 24 hrs.

The first approach is based on the assumption that defect-free and/or non-aged insulation can withstand higher levels of voltage stress above the nominal stress and that in case of present insulation defects or ageing defects should have a lower level of withstand voltage which should produce a breakdown under over voltage during the designated test time. The outcome of the test is a simple pass or fail.

It is known that the application of the overvoltage withstand test without monitoring of other parameters such as partial discharges, is not always sufficient to identify all manufacturing and installation problems. Moreover it has to be considered that:

1. Due to the applied test voltage stresses which are higher than the operational stresses, the test may be destructive even if no failure occurs
2. Although the duration of the over-voltage test is developed from test experiences (e.g. 1 hour), it cannot be excluded that after this time a failure will occur

It has been observed that after the cable successfully passed the over voltage withstand tests, failures have occurred during the initial operation (up to several months), [5]. It has been found that defects in the cable insulation and cable accessories are responsible for these failures. Therefore to detect the weak spots in the cable insulation and cable accessories following

the installation or repair of the cables, the insulation condition assessment during on-site testing (so-called monitored testing) is becoming nowadays more and more common practice. It is known that monitored testing consists of a voltage withstand test combined with a diagnostic test, e.g. partial discharge measurement.



Figure 1. On-site application of a damped AC test system (DAC HV Technology) for a monitored after-laying test with on a 4.5 km long 110 kV power cable

II. ON-SITE ENERGIZING METHOD AT DAMPED AC VOLTAGES

DAC testing can be used as a simple withstand test or in combination with partial discharges (PD) and dissipation factor (DF) measurements. As a result the use of damped AC voltages for testing power cables is in compliance with the following international standards:

- IEC 60060-3: High Voltage test techniques – Part 3: Definitions and requirements for on-site testing
- IEEE 400: Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems
- IEC 60840: Power cables with extruded insulation and the accessories for rated voltages above 30 kV up to 150 kV Test methods and requirements
- HD 632 S2 (CENELEC): Power cables with extruded insulation and their accessories for rated voltages above 36kV ($U_m=42kV$) up to 150kV ($U_m= 170kV$)
- IEC 62067: Power cables with extruded insulation and the accessories for rated voltages above 150 kV up to 500 kV, Test methods and requirements
- IEEE 400.3: Guide for PD Testing of Shielded Power Cable Systems in a Field Environment
- IEEE 400.4 Guide for Field-Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current Voltage (DAC) (draft under preparation)
- IEC 60270: Partial discharges measurements;
- IEC 60885-3: Test methods for partial discharges measurements on lengths of extruded power cable

- IEC 60141: Tests on oil-filled and gas-pressure cables and their accessories
- IEC 60502: Power cables with extruded insulation and their accessories for rated voltages from 1 kV ($U_m = 1.2$ kV) up to 30 kV ($U_m = 36$ kV)

An international survey showed that in the majority of the cases where DAC has been applied so far, voltage withstand tests have been combined with advanced diagnostic measurements (e.g. partial discharges and dielectric losses). For a voltage withstand test, a predetermined number of DAC excitations is applied, see figure 2. Due to the shorter duration of the excitation and decaying characteristics of the voltage, DAC test results can be different from those obtained by continuous AC withstand voltage testing. Testing with DAC voltage means application of damped AC excitations to a capacitive test object e.g. power cable. The basic parameters of DAC testing are:

1. Maximum test voltage level V_T [kVpeak]
2. Test voltage steps ΔV [kVpeak]
3. Number of excitations per step N_{DAC}
4. Voltage withstand test application and duration at the maximum test voltage

During on-site testing the cable can be stressed by a series of DAC excitations, where the maximum value of the applied voltage (1st peak) represents the maximum test voltage in kVpeak. Executing a voltage withstand test at a selected voltage level, the duration may consist of a number of DAC excitations e.g. 50 or a pre-selected time period e.g. 1 hour, see figure 2.

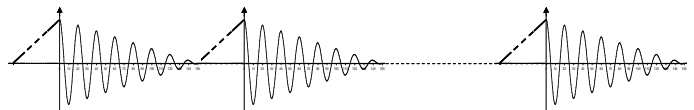


Figure 2. Overview of withstand test by damped sinusoidal AC voltage excitations. The duration of the test is determined by the number of DAC excitations which are applied to the power cable at a selected DAC test voltage

III. PARTIAL DISCHARGE DETECTION

With the application of damped AC voltages, PD measurements can be performed in two ways:

1. According to IEC 60270 recommendations with the bandwidth in the range of 100 kHz - 500 kHz
2. In RF (radio frequency) range up to 30 MHz with 100 MHz sampling rate. In this second approach, noise interference is reduced by PD detection in higher frequency range. Using the RF method the PD pulses are evaluated in the time domain and by means of time domain reflectometry (TDR) the PD origin in the cable section can be estimated.

Besides the low power demand with DAC testing, these systems take benefit of the advantages of a power supply with very low interference, formed by the test object itself and the external inductance that is part of the system. The whole

system and its system components need to be PD free, like the systems inductance. This guarantees an onsite test system with very low interference that enables a very sensitive PD measurement during voltage application.

The compact construction makes it possible to obtain enough clearing distance from other grounded and live parts in a high voltage substation, while keeping the high voltage and ground connections between the DAC system and the test object to a minimum. This delivers the most optimal signal to noise ratio possible for on-site testing.

IV. DAMPED AC VOLTAGE WITHSTAND TESTING

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

1. Non-monitored DAC hold test – a number of DAC excitations is applied and the ability to hold the maximum DAC voltage (i.e. no breakdown occurs) is recorded. The intent of a simple DAC 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, 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.
2. Monitored DAC hold 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. These additional attributes are advanced diagnostic properties, such as partial discharge detection. The development in time of the measured property can also be used to monitor the effect of the test on the cable system during voltage application.

Due to additional information, as provided by PD detection, the monitoring insulation properties during a DAC withstand test and the effect of the test voltage during its application can improve the evaluation of the insulation condition.

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 quality and reliability, two aspects are important for field tests and results evaluation:

1. The DAC test parameters, like the maximum test voltage levels, see Table 1, as well as the duration of an over-voltage application shall be chosen in such a way as to prevent or minimize the shortening of service lifetime due to the field test. In the case of withstand tests the impact on a defective insulation needs to be high enough to cause a breakdown or to exceed a critical level of a monitored property.
2. The voltage level and number of DAC excitations (which has an impact on the test duration) are important and

inseparable elements of the test and after-test performance of the cable circuit. The recommended test voltages and durations for tests are based on literature [8], international recommendations as mentioned above, and several years of field-experiences as obtained by different users of the DAC technology. Arbitrarily increasing the voltage or extending the test duration from the recommended values can potentially increase the probability of an early failure in service.

TABLE I

DAC test voltages levels (20 Hz...500 Hz) as used for DAC testing (50 DAC excitations) of new installed power cables [IEC 60502, IEC 60840, IEC 62067]

Power cable rated voltage [kV] Phase-to-phase	U_0 [kV]	DAC test voltage level VT [kVpeak]
3	3	6
6	4	12
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
275-287	159	296

V. EXAMPLES OF TEST RESULTS

A. Maintenance test HV cable

Maintenance testing was performed on a service-aged 35-year old 2.2 km long 66 kV XLPE insulated underground circuit, see figures 3 and 4 (DAC frequency 62 Hz). Starting from $1.1 U_0$, PD activity up to 1000 pC has been registered in one of the joints. Increasing the DAC test voltage up to $1.5 U_0$ has resulted in concentrated PD activity in three joints. Based on this test it has been concluded, that this cable section can be energized for network operation with a possible risk of a failure during operation. Due to the fact that PDIV was very close to U_0 and increased network stresses may result in an inception and increase of PD activity, the risk of a failure depends on the over-voltage stresses during operation. Replacement of the joint was recommended. However, if this wasn't done, it was recommended to perform the next maintenance tests within approximately 6 months in order to evaluate the progress of degradation at the above mentioned locations by comparing the change of PD activity over time.

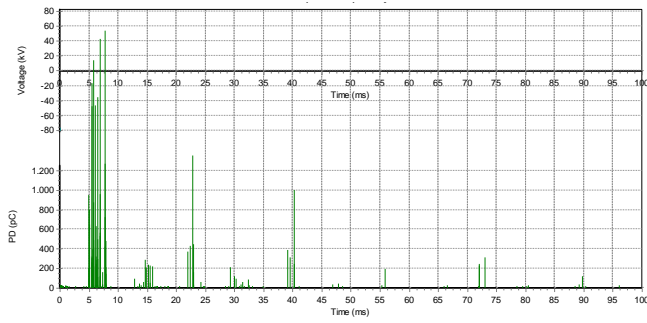


Figure 3. PD pattern as observed at $1.5 U_0$ during maintenance testing of a 30-year old 66 kV XLPE insulated 2.2 km long underground circuit.

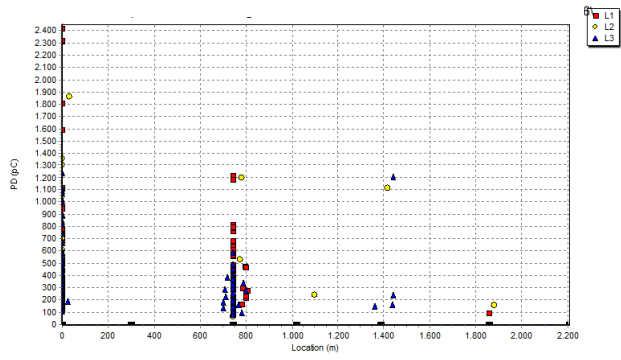


Figure 4. PD mapping as made up to $1.5 U_0$ during maintenance testing of a 30-year old 66 kV XLPE insulated 2.2 km long underground circuit.

B. After-laying testing MV cable

A newly installed 2.2 km km long, 10 kV XLPE insulated underground cable circuit has been tested in accordance to the IEC 60502 recommendation, which recommends voltage withstand testing using sinusoidal AC voltage up to $2 U_0$. It has been decided to perform monitored withstand testing, by using DAC resonant circuit with damped sinusoidal AC voltages at 224 Hz for 50 DAC excitation at $2.0 U_0$. During the whole time of withstand test, standardized PD detection has been applied. As a result of DAC over-voltage, no breakdown has been observed. Internal PD activity has been registered in all terminations at 0 m. The terminations have been investigated and the PD sources (wrong selection of the termination type, dry spots at the field grading) have been identified, see figure 5. After the repair the complete cable system was re-tested and found to be PD free. The cable has past the test successfully and was taken into operation.

CONCLUSIONS

1. Voltage withstand testing including standardized PD detection and estimation of dissipation factor (monitored testing) can be used for non-destructive on-site testing of new and service aged HV power cables.

2. The complete system solution for on-site testing and diagnosis complies with international standards and recommendations.
3. The application of the presented measurement solution makes this method a very attractive option for on-site tests and diagnosis of new and service aged power cables for transmission and service companies as well as cable manufacturers, taken into account:
 - AC sinusoidal and non-destructive stresses
 - The available testing power cables with capacitive load up to 13 uF and voltages up to 350 kV
 - Efficiency in transportation (770 kg...1400 kg), system erection and on-site test execution
 - Diagnostic information as generated for MV and HV power cables: PD detection and localization and dielectric loss estimation



Figure 5. Investigation of the terminations at 0 m location having PD up to 3500 pC at $2 U_0$.

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