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Condition Assessment of HVDC Cables during their Lifecycle

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Abstract

Recent market developments towards power generation in remote renewable power plants such as concentrated solar power plants in deserts or large off-shore wind parks, raise an interest for long distance power transmission via extruded HVDC cables. HVDC cables require quality assurance during the complete product lifecycle, mainly: a) R&D activities for design verification and - validation b) routine tests in the factory for confirmation of proper manufacturing c) acceptance test after erection and commissioning to exclude defects caused during transport and installation d) ageing monitoring and quick fault detection and location detection during service life. Considering increasing voltage levels, increasing cable lengths and ground or even offshore installation, the dielectric testing of extruded HVDC cables in the factory and on site remains challenging. The long-term validation of insulation coordination requires high voltages for quality assurance tests which represent typical expectable stresses during service. Typical examples are wave shape, partial discharge behavior and dielectric field stress in the insulation medium. Hence, different technical solutions are available to generate these required high voltages for testing of HVDC cables. This paper discusses essential technical and commercial aspects of HVDC cable quality assurance and presents suitable methods for HVDC cable testing.

Keywords: Fault Location, HVDC Cable Test Standards, HVDC Cables Test Equipment, On-line Monitoring

1. Introduction

Over the past decades, various solutions have been developed to transmit electrical energy over long distances. High-voltage direct current transmission has already established itself in recent decades as an optimal method for ensuring low-loss transport even over long transmission distances. Currently, the energy transmission network is being progressively adapted to the requirements of a more decentralized energy production, which relies to a large extent on renewable energies. Since such resources are not always and everywhere available, the expansion of transmission capacities from relative remote energy parks to metropolitan areas is becoming increasingly important in order to continue providing reliable energy transmission. Up to now, many transmission lines have been implemented as overhead lines. These are relatively simple and inexpensive to build, but their large space requirement is a disadvantage. In contrast, HVDC cable connections are comparably space-saving and can be installed underground or subsea. They are operated for several decades, and this places particularly high demands on high-quality HVDC cables and especially on their insulation. The complete life cycle of an HVDC cable, consisting of development, production and operation, is therefore supported by frequent tests to assess the quality of the insulation (see Table 1). The tests identify weak points that appear as breakdowns, partial discharges, or the localization of a faulty point in the event of a breakdown. To ensure the traceability of the tests, the requirements for the test are summarized in standards, such as IEC 62895[3], which are largely based

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on the recommendations of CIGRE Technical Brochure No. 496[4]. Test requirements on HVDC cables with ratings above 500 kV are currently under development.

2. HVDC Quality Tests

2.1 Prequalification Tests

The prequalification test is a basic assessment of the long-term behavior of a newly developed HVDC cable system. The cable system to be prequalified consists of a mechanically preconditioned cable with length of ~100 m, and at least one joint / termination which shall be later used during operation. The prequalification test simulates operational stresses which represents the entire cable lifecycle in a comprehensive sequence as per Table 2. [3,4] require a test duration of at least 360 days. The individual sequences are illustrated in Figures 1-3.

There are slight differences between cables, which are fed by Line Commutated Converters (LCC) and Voltage Sourced Converters (VSC) as VSC is operated without any polarity reversals.

2.2 Type Tests

The type test provides an assessment of the cable system and production-relevant aspects, taking into account the applicable technical boundary conditions. The individual tests are similar to the prequalification tests, but the test sample is subjected to higher test voltages (see Table 1) and lower repetition rates (see Table 2). The minimum setup requirements for a type test according to[3,4] are shown in Figure 4 where all components must be mechanically pre-conditioned.

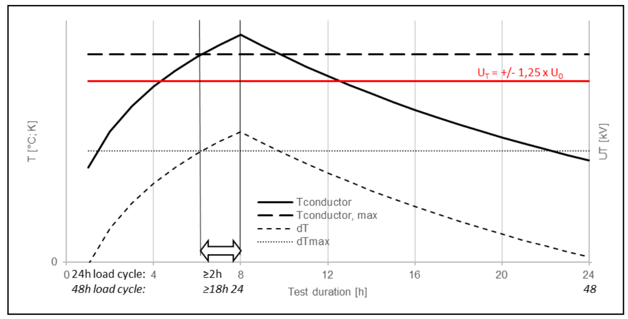

Figure 1. 24 h and 48 h load cycle test.

Table 1. Overview of electrical tests during a HVDC cable life

<table>
<tr><td rowspan="7">Quality tests</td><td rowspan="3">R&D
-usually done once at a reference/after significant modifications</td><td>Development tests (laboratory)</td><td>Basic principles, high variety of tests, not introduced in this paper</td></tr>
<tr><td>Prequalification tests (laboratory)
$U_{T, DC} = 1.45 \times U_0$
$U_{T, DC} = 1.25 \times U_0$ (polarity reversal)
$U_{T, LI/SI} = 2.15 \times U_0$</td><td>Verification of system
(long-term performance)</td></tr>
<tr><td>Type tests (factory)
$U_{T, DC} = 1.85 \times U_0$
$U_{T, DC} = 1.45 \times U_0$ (polarity reversal)</td><td>Validation of system and its production under relevant boundaries</td></tr>
<tr><td rowspan="2">Customer Order Engineering/ Manufacturing
-ongoing quality assurance and quality trend monitoring potentially with minor design or manufacturing process modification</td><td>Routine test (factory)
$U_{T, DC} = 1.85 \times U_0$</td><td>Continuous quality check of individual component</td></tr>
<tr><td>Sample tests (factory / laboratory)</td><td>Frequent quality check of assembly sections regarding a certain criteria</td></tr>
<tr><td>Erection and commissioning
-after transport and installation</td><td>Onsite test
$U_{T, DC} = 1.45 \times U_0$</td><td rowspan="3">Components assembled to complete (sub-) system under various ambient conditions</td></tr>
<tr><td>Off-line testing
-frequent service and after repair</td><td>Onsite test
Fault location detection</td></tr>
<tr><td>Diagnostic tests</td><td>Online testing
-continuous health monitoring</td><td>Trend observation
(sub-station)</td></tr>
</table>

Remark: The test voltages levels U_T are defined in [2] and apply for a design life of 40 a. Other factors for XX years of design life can be calculated by factor $K = \sqrt[10]{\frac{XX}{40}}$.

2.3 Routine Tests

The routine test is performed on each produced cable length and serves to verify the quality of the manufactured cable. Likewise, the routine test serves as a factory acceptance test prior to shipment. HVDC routine testing, sometimes also called factory acceptance test, is defined to a 1h load of

$$U_T = -1.85\ U_0 \tag{1}$$

As detection of weaknesses or even defects might be limited, additional HVAC tests are recommended. In this case the typical very long lengths of HVDC cables are challenging when it comes to suitable test equipment. With recent developments of HIGHVOLT

Prüftechnik Dresden GmbH, a new range of testable lengths has been opened which will be introduced in chapter 3.

2.4 HVDC Commissioning Tests

HVDC withstand testing after installation shall detect any failures on the insulation that might have occurred

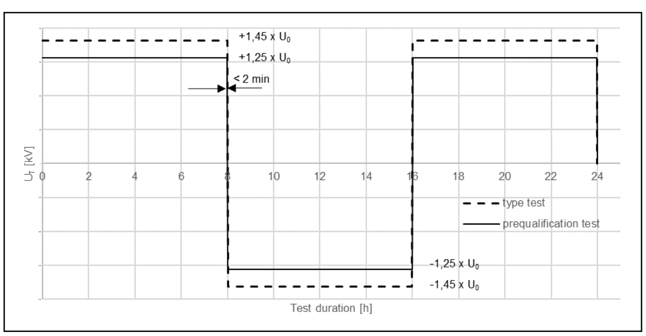

Figure 2. Polarity reversal test.

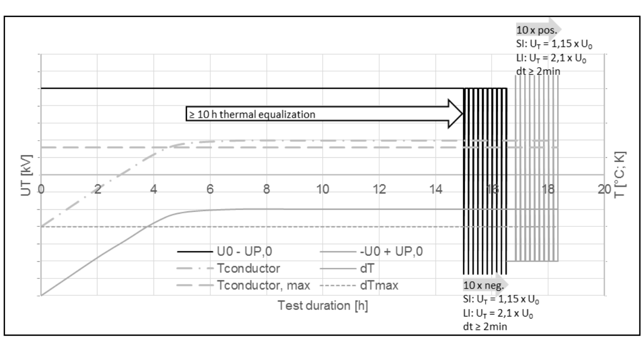

Figure 3. Test procedure for example of 500 kV HVDC cable superimposed SI/LI test.

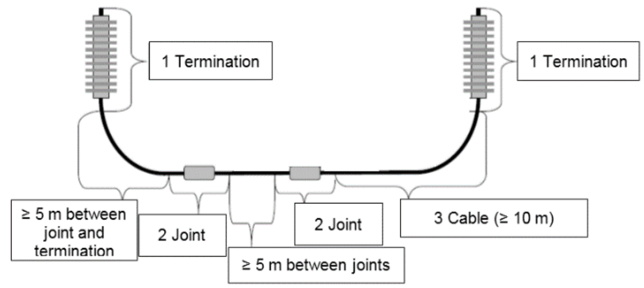

Figure 4. Minimum setup requirements according [3] for testing components (1: termination, 2: joints, 3 cable under test).

during transport and installation of the cable system. It consists of a 1 h test at the voltage level as per Table 1.

As a defect based on ageing or any or any other external impact could potentially occur anytime during a cable life, it is strongly recommended to take a reference value of the propagation speed in the insulation by Time Domain Reflectrometry (TDR) to save this "as built characteristics" for later use if needed. In addition, to increase accuracy, it is recommended to apply experiences of decades from

HVAC testing, for checking the joint quality by PD measurement in HVDC cable sections suitable up to 80 … 100 km with state-of-the art resonant test systems at

$$U_T = 1.1 \ldots 1.7\ U_0\ [7] \tag{2}$$

The insulation of an exemplary HVDC cable could have the following characteristics:

- Capacitance C' e.g. 0.22 µF/km
- Conductor resistance R' e.g. 0.009 Ω/km
- Screen resistance R_{Sc}' e.g. 0.23 Ω/km
- Loss factor tan δ e.g. 0.0003

Obviously, the currently increasing cable lengths for routine tests and especially for the tests after installation lead to an increasing overall capacity, which can easily sum up to several µF. During a dielectric test, the HVDC cables under test are not only exposed to the test voltage for 1 h. During charging and discharging of the cable, voltages higher than the rated value occur for several hours. To limit these additional stresses to a minimum, it is recommended to add special discharge devices to the test system.

Table 2. Prequalification test for LCC-fed cables (grey) and VSC-fed cables (white) valid up to 320 kV [2]

Tests	**24h Load Cycle**		**Load Cycle and Polarity reversal**	**High Load**		**Zero Load**	**24 h Load Cycle**		**Load Cycle and Polarity reversal**	**Superimposed Impulse**
Cycles	30	30	20	40	40	120	30	30	20	1
U_T	$+ 1.45\ U_0$	$-1.45\ U_0$	$+/-1.25\ U_0$	$+1.45\ U_0$	$-1.45\ U_0$	$-1.45\ U_0$	$+1.45\ U_0$	$-1.45\ U_0$	$+/-1.25\ U_0$	$1.2\ U_0$
Cycles	40	40	-	40	40	120	40	40	-	1
U_T	$+ 1.45\ U_0$	$-1.45\ U_0$	-	$+1.45\ U_0$	$-1.45\ U_0$	$-1.45\ U_0$	$+1.45\ U_0$	$-1.45\ U_0$	-	$1.2\ U_0$

Table 3. Type test for LCC-fed (grey) and VSC-fed cables (white) valid up to 320 kV [2] and 500 kV [3]

Tests	**24 h Load Cycle**		**Load Cycle and Polarity reversal**	**48 h Load Cycle**
Cycles	8	8	8	3
U_T	$-1.45\ U_0$	$+1.45\ U_0$	$+/-1.25\ U_0$	$+1.45\ U_0$
Cycles	12	12	-	3
U_T	$- 1.45\ U_0$	$+1.45\ U_0$	-	$+1.45\ U_0$

Tests	**Superimposed SI**				**Superimposed LI** (optionally)		**2 h DC test**
Cycles	1	1	-	-	1	1	1
U_T	$+U_0 \rightarrow -1.15\ U_0$	$-U_0 \rightarrow +1.15\ U_0$	-	-	$-U_0 \rightarrow +2.1\ U_0$	$+U_0 \rightarrow -2.1\ U_0$	$-1.45\ U_0$
Cycles	1	1	1	1	1	1	1
U_T	$+U_0 \rightarrow +2.15\ U_0$	$+U_0 \rightarrow -1.15\ U_0$	$-U_0 \rightarrow -2.15\ U_0$	$-U_0 \rightarrow +1.15\ U_0$	$-U_0 \rightarrow +2.1\ U_0$	$+U_0 \rightarrow -2.1\ U_0$	$-1.45\ U_0$

2.5 PD Measurement

The PD test circuits for HVDC tests are identical to HVAC measurement (see IEC 60270 Figure 1 a to d [5]). An amendment to IEC 60270 was published in 2015, recommending the evaluation for statistical and comparable purposes as per annex H[6]:

- Number of apparent charges q_i during a measuring time T ≥ 30 min with evaluation of charges exciting a relevant threshold $q_{i,\ threshold}$ only (Figure 5)
- Accumulated apparent charges:

$$q_a = \int_0^T q_i dt \ with\ q_i \geq q_{i,threshold} \tag{3}$$

These readings can be used for statistical process control comparing several manufacturing lengths with each other or trends in ageing might be evaluated based on the slope of accumulated apparent charges over time but also the quantity of the apparent charges with a clustering according to Figure 6 might be helpful[7].

Up to now, no standardized test method for DC cables exists, but as transient effects are applying, the value of HVDC test voltage is significant, a measuring duration T ≥ 30 min is recommended with a minimum time resolution of 2 ms for an appropriate differentiation of partial discharges and their recharging[5,7]. A suitable threshold level could be set using the doubled background noise level measured prior to the PD test.

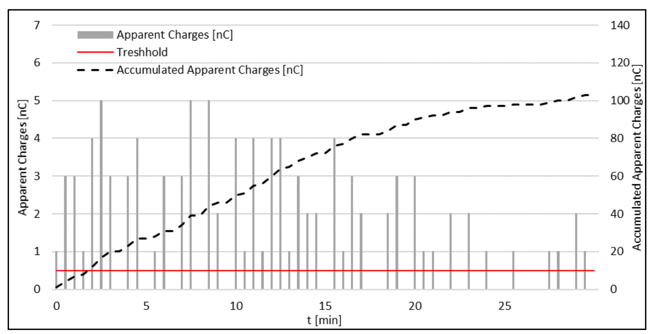

Figure 5. Example of measured charges at HVDC source according[6].

Decades of experiences in PD testing of HVAC cables can be used for an additional evaluation of PD characteristics by phase angle and polarity where the discharges occur. Established procedures and proven equipment are available, based on resonant circuits with

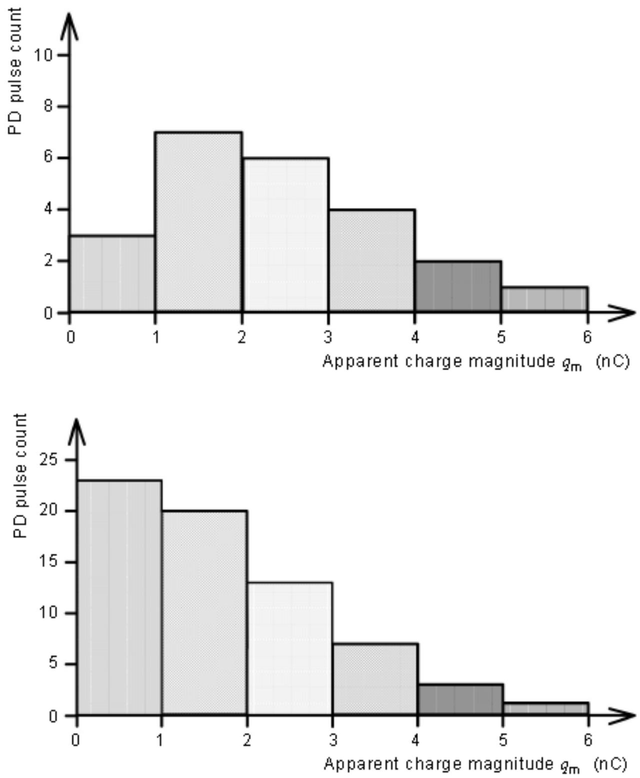

Figure 6. Exemplary pulse statistics acc. to[6]:
-top: clustered charges
-bottom: charges exceeding certain limits.

variable inductances or -frequencies. The resonance of the test circuit is set according to the Thomson equation:

$$f = \frac{1}{2\pi\sqrt{LC}} \rightarrow C = \frac{1}{4 * \pi^2 * f^2 * L} \tag{4}$$

Test systems, using variable frequencies between 10 … 300 Hz (according to IEC 60060-3) allow larger capacity ranges (corresponding to cable lengths) to be tested with:

$$C_{\downarrow} \min / C_{\downarrow} \max = (f_{\downarrow} \max^{\uparrow} 2) / (f_{\downarrow} \min^{\uparrow} 2) = [\![10]\!]^{\uparrow} 2 / [\![300]\!]^{\uparrow} 2 = 1/900 \tag{5}$$

compared to the range of resonance circuits with variable inductance:

$$\frac{C\min}{C\max} = \frac{L\max}{L\min} = \frac{1}{20} \tag{6}$$

Modular systems allow further range extensions by parallel operation of reactors (see Figure 10).

3. HVDC Diagnostic Tests

Diagnostic tests are an essential part of a maintenance program for the HVDC cable in operation. Besides PD measurements, which can provide conclusions about the condition of the insulation, fault location allows a quick detection of the faulty spot after a breakdown. For fault location detection and online monitoring it is very useful to have the Time Domain Reflectrometry (TDR) reference velocities of the cable insulation available from commissioning tests as already described in chapter 2.4.

3.1 Fault Location Detection

Fault location detection can be done by measuring the travelling waves, which are caused by a breakdown. A large number of test systems have been available during the last decades, which use the well established TDR. Instead of further exposing the cable with multiple impulses from external sources, state-of-the-art developments allow combining the immediate detection of a fault with the ability of a direct analysis of the transient impulse, which is caused by the breakdown. The additional measurement can be performed with a transient recorder anytime during factory acceptance tests, during commissioning or service and even during operation.

3.2 Online Monitoring

As mentioned in chapter 2, the power transmission capacity is continuously increasing. Consequently, any potential failure due to ageing or external impacts on the HVDC cable has a significant impact on the remaining transmission grid, as the energy demand must be compensated. Hence, a fast failure detection is essential to minimize the downtime costs after a breakdown and to ensure the availability of the electrical grid. For such system-relevant cables (DC but also AC), an appropriate transient recorder, installed at critical points (e.g. substations or converter stations) can be used as online monitoring system. These recorders are coupled to the grid by voltage dividers which must comply to the requirements of the grid.

In case of a breakdown, the failure is immediately recorded and can be allocated to the affected cable link. Repair activities can be initialized at the same time without repetition of tests. The fact that a single breakdown is usually sufficient for localization allows a limited influence on the defect for a precise root cause analysis.

This technology can be used for cable distances of more than 200 km. First measurements at a length of 131 km confirmed an accuracy of < 1 % of the cable length. Even in case of retrofit installations to an existing cable, where the reference TDR measurement is usually not available, the fault location detection can still be performed. Installing detection systems at both ends of the cable and comparing the reflection time ratio from both ends to the defect still allows an extremely accurate location of the fault.

4. Test Equipment

Increasing voltage levels for prequalification and type tests are a major challenge for test equipment. In addition, test systems must provide sufficient energy to charge and discharge the cable within a reasonable time limit.

4.1 HVDC Generators

The Greinacher-Cascade is the classical option to generate high DC voltages. Systems like the GP, made by HIGHVOLT Prüftechnik Dresden GmbH, are available with up to four stages and able to generate up to 2000 kV, which is sufficient for the mandatory tests described in 2.1 and 2.3 and also complying with the ripple limits as per IEC 60060-1. In case of LCC technology, the polarity can be changed manually or automatically.

Another technical principle is the Delon-Cascade, which is used e.g. for HIGHVOLT's modular GPM system. The 400 kV modules can be easily cascaded in series or parallel. This design allowed realized test voltages of up to 2200 kV (see Figure 7).

Its modular design even allows mobile test systems which easily can be transported and -assembled for on-site tests after installation (see Figure 8, Figure 9)

Figure 7. GPM 10/2200: 10 mA rated current and 2200 kV output voltage.

4.2 Fast Discharge Devices

In standards, suitable test procedures for a sufficiently reliable defect detection are defined by voltage level and test duration. Especially with increasing voltage levels and cable lengths for HVDC cables, the stored energy

$$E = \frac{1}{2} C \llbracket l U^{2} \tag{7}$$

results in remarkable longer discharge durations and longer times, where the voltage remains above its rated value U_0. To limit these additional stresses on a cable, fast discharge devices such as ERE by HIGHVOLT should be part of HVDC test systems, used for routine and onsite tests of long cables. Depending on the design, length and voltage level of the individual cable, discharge devices reduce the discharge times from several hours to some minutes.

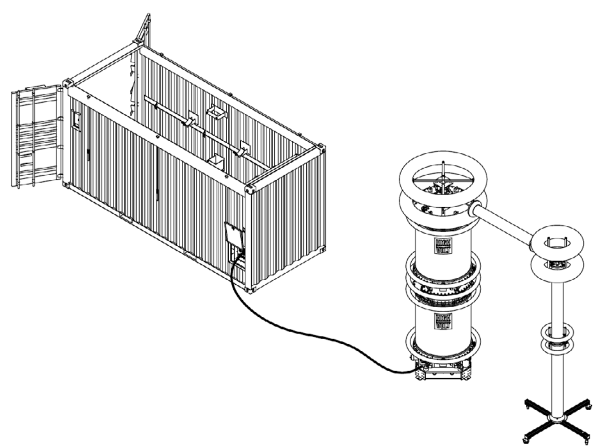

Figure 8. GPM 30/800, consisting of two modules 40 mA, 400 kV; assembled for on-site test.

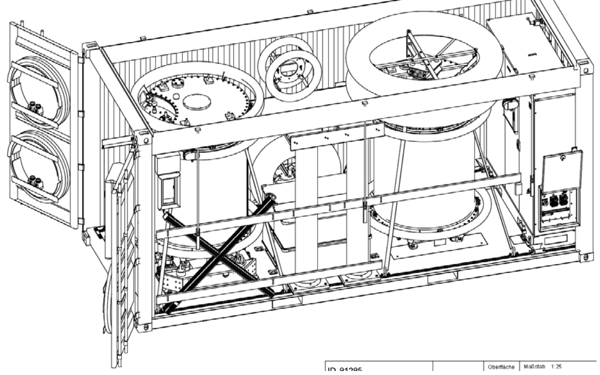

Figure 9. GPM 30/800 stored in a 20’ transport container.

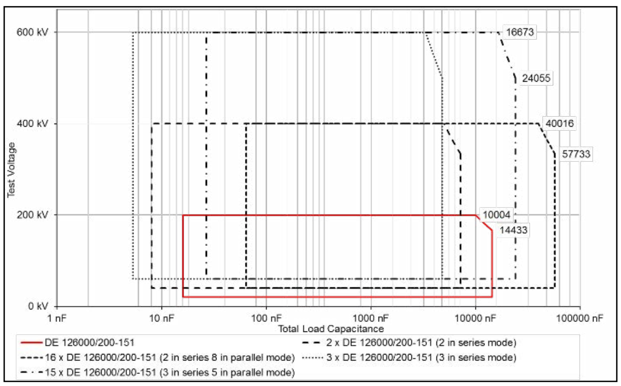

Figure 10. Load diagram of modular resonance test system type WRV with recently developed reactor type DE 126000/200-151.

4.3 HVAC Generators

With the latest development of a modular series resonant test of fixed inductance reactors an increase to new ranges of total cable length which can be tested as realized. The testable capacities/lengths and voltage levels are shown in Figure 10 (consider $U_{test,\ AC} = \sqrt{2} \cdot U_{test,\ DC}$), with typical test voltage levels $U_{test,\ AC} = 1.1 \ldots 1.7\ U_0$, according to IEC 60480 and IEC 62067. Thanks to its modular design it can be used for factory and on-site tests with different combinations for individual cable lengths and voltage levels.

The required test system power respectively the maximum testable cable length can be estimated by:

$$S = 2\pi f C' l U_T^2 \tag{8}$$

Figure 11. Reactor type DE 120000/225-122 for PD testing circuits.

4.4 Fault Location Systems

The fault location equipment consists of a high-resolution transient recorder to record, evaluate and export the measured data. The recorder is connected to the measuring circuit via a suitable wide-band measuring divider. Further coil-based sensors are under development.

5. Conclusion

Recently Developed test equipment meets the technical and economic market requirements in electrical testing of HVDC cables complying with IEC 62895 [3] and CIGRE 496[4], combined with the ability of on-line cable monitoring and immediate fault location in the case of a breakdown. Specially designed discharging devices limit the stresses on the DC cable before and after the test sequence. PD measurement experiences with HVDC needs to be gathered in addition to the widely available experiences on PD measurement with HVAC.

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