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DEMANDS OF DIELECTRIC TESTING OF HVAC AND HVDC POWER CABLES WITH EXTRUDED INSULATION

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SUMMARY

Dielectric testing of extruded HVAC and HVDC cables in the factory or on-site is a challenge when it comes to longer lengths or special applications. Such verification of insulation coordination requires high voltages for quality assurance tests to represent stresses in service like wave shape, partial discharge behavior and dielectric field stress in the insulation medium. Hence, different technical solutions are available to provide the required testing voltage like AC voltage (50/60 Hz or 20...300 Hz), very low frequency voltage (0.01...0.1 Hz) or DC voltage.

Nevertheless, not each test voltage is applicable for all dielectric test requirements due to physical, technical and economical constraints. With regard to the above mentioned facts this contribution will discuss important aspects concerning economical, physical and technical challenges of dielectric testing of extruded HVAC and HVDC cables.

KEYWORDS

HVDC cables; extruded cables; test standards; dielectric testing; testing technology;

INTRODUCTION

Quality assurance in terms of dielectric testing of extruded cables is the indemnification of the full performance of the cable in the test field at manufactures site as well as after the transportation, laying and installation process like setting the joints (splices) and terminations. Said applicable tests are well defined in various IEC, IEEE standards or CIGRE recommendations and mainly consist of a withstand voltage test in combination with complementary partial discharge measurement. Special tests like impulse voltage and heating cycle tests for prequalification or type tests are also applicable. The intention is to accelerate possible failure mechanisms caused by example given voids and impurities in the insulation material respectively transport defects or assembly defects after laying procedure. Additionally, it is possible to start condition assessment of laid cables systems regarding the estimated remaining life time.
For selection of the appropriate test procedure it has to be distinguished between the testing requirements for extruded HVAC and HVDC cables and common testing requirements in general. This topic will be discussed in the following paper with focus on routine and on-site tests.

DIFFERENCES BETWEEN EXTRUDED AC AND DC CABLES

Basically the principle design of extruded AC and DC cables is similar. The conductor is covered with a semi-conductive layer followed by the polymeric insulation, a semi-conductive outer layer finishes the main insulation of the cable. However, major differences between AC and DC cables are the following:

Table 1: Major differences between extruded AC and DC cables

Headword	Extruded AC cable	Extruded DC cable
Losses	Losses in conductor, screen sheath and armor	Losses only in conductor (long lengths)
Electric field	Determined by permittivity which is linear and isotropic	Determined by conductivity which is non-linear and anisotropic; local field enhancement under transient over voltages with opposite polarity possible due to space charge built-up;
Aging	Higher grade of aging due to possible partial discharge activity / intensity	Lower grade of aging due to low partial discharge activity / intensity
Charging / Relaxation	No conduction current, only polarization of the dielectric at operating frequency	Small amount of charge carriers; space charge build-up; several hours or even weeks needed for ready-state condition;

Based on the above mentioned facts the requirements for testing are divergent for AC and DC technology because a significant influence due to different electric field distribution or charging / relaxation procedure is given. [1]

REQUIREMENTS FOR TESTING

As shown before, cables are inherently insulation systems which will be subject to failures if the insulation contains a defect or weak spot, even though most of the cable shall be still in good condition. Therefore testing at manufacturing site respectively laying site has to ensure that newly produced cables are free from weak spots in the insulation like voids, impurities or metal particles.

Weak spots resulting in failure during operation and will lead to local field enhancements which can trigger partial discharge activities and treeing processes. For newly installed cable systems assembly defects in joints (splices) and terminations during laying procedure (approx. 60% of all defects) shall be detected and avoided. [2]

With regard to diagnostic testing of service aged cables the detection of other failure mechanisms is important. Possible failures are mentioned below:

- Water trees, especially in MV XLPE cables
- Aged insulation material
- Defects caused by high temperatures of the conductor or thermal cycling or maybe current overload.
- Influence of water, chemicals, weather, etc.
- Defects caused by overvoltage resulting from lightning strikes or switching maneuvers, or mechanical damages resulting from short circuit current forces

If such tests shall be considered as usable, the test method for AC or DC has to fulfill certain requirements as follows:

Table 2: Summary of requirements for test methods based on [3]

Parameter	Quality acceptance test	Diagnostic maintenance test
Test effectiveness	Required for all types of defect	Required for types of defect searched for
Representation of stresses in service	Required by applicable standards	Desirable for comparability
Danger for healthy insulation	To be avoided	
Comparability, repeatability	Required	Necessary, but not as strict
Test procedure well-defined	Required, very exact	Necessary, but not as strict
Relevant experience	Very high requirement, standardized	Required for types of defect searched for

As per [3] the following requirements have to be considered:

Effectiveness of a test

As the withstand voltage test is a statistical process [4], there is no test procedure available detecting all dangerous defects without causing damage to parts of insulation that contain no or only minor defects. So, the probabilities for a wrong or right result of a test depend among others on the voltage wave shape, test voltage value and the duration. The given example by reducing test duration or test voltage value the probability of damage of healthy insulation is reduced at the cost of also reducing the capability of proving a defective cable to be faulty.

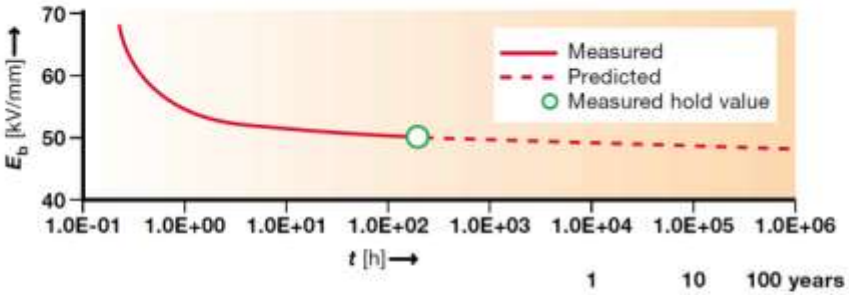
Representation of stresses in service

Test voltages shall “produce the same dielectric effect in the insulation as overvoltages in service” [5]. That means for AC cables which face mostly AC stresses in operation an AC test voltage (same order and magnitude) is suitable and vice versa a DC test voltage for DC cables. This ensures that the same stress type as the operating stress is present as well as the same electric field distribution in the insulation like in service conditions.
Different to the requirements for quality assurance tests are requirements for diagnostic maintenance tests which are more free in their choice of methods, since the outcome is not an acceptance criterion.

Test duration

As the life expectancy of XLPE, or the necessary time to fail a new cable with defects depends on the applied test voltage, a life time exponent $k \geq 9$ is given by [6], see also exemplary figure 1 [7].

Fig.1: Relative life expectancy vs. dielectric field stress



The higher the percentaged share of applied test voltage the higher the possibility that failure mechanisms are accelerated, so that defects can be found in a relatively short time. Nevertheless the increase of test voltage is limited by the requirement not to start failure mechanisms in parts of the insulation that are healthy or contain negligible defects.
Field experience in terms of detectable partial discharges and reported later service failures after on-site test for AC cables shows that up to a test voltage of 1.5 x U_0 service failures were reported and up to 30 % of detectable partial discharges were found. For test voltages up to 1.7 x U_0 or higher no service failures reports are available and up to 70 % or more detectable partial discharges were found. A more detailed evaluation as well as a tutorial is currently prepared by CIGRE working group B1.28.

Danger for healthy insulation

Tests might create the preconditions for later breakdown. Especially space charge build-up, which can occur during applied DC stress, will significantly influence the electric field distribution in a layered AC cable. When the AC cable later is operated with AC voltage, these space charges will likely still be present due to the extraordinarily low conductivity of XLPE in the region of 10^{-14} $^{S}/_{m}$ up to 10^{-16} $^{S}/_{m}$. Such space charges might lead to local field enhancement under opposite polarity reversals. [8] Therefore, a suitable test procedure prevents the formation of space charges in the cable under test.

Comparability and repeatability of tests

Due to the fact that cables are tested several times during their lifetime the test results of quality acceptance tests shall be comparable with each other. So the conditions of the test like test voltage, wave shape, test voltage and test duration must be similar.
Additionally, if a comparison of test results of different cables in terms of diagnostic testing shall be enabled, the above mentioned condition must also apply. Thus, tests should be repeatable with different test sets that use the same testing principle to ensure comparability in case the original test system should become unavailable.

Definition of test procedure

As the withstand voltage test is a statistical process [4], the chosen test procedure for detecting failures has to be well defined. Therefore, it needs to be considered which voltage amplitude, wave form and test duration is more suitable for a test on an insulation system. Furthermore, the amount of stress for the cable system depends on keeping these values in a defined range. This is especially important for quality acceptance tests, but helpful for diagnostic maintenance tests as well.

Experience

The difference between using or understanding a certain test method is becoming important. The fact is that elaborated data about effectiveness of various test techniques and published faithful analysis of failure statistics are still missing. Besides that the difference in the operating field strength of extruded cables must be considered. In a MV voltage cable the field strength is typically in the range of 3 to 5 $^{kV}/_{mm}$ and in HV / EHC cables within 13 to 20 $^{kV}/_{mm}$.
Hence, acceptance test methods shall be standardized as the result of research and evaluation.

TEST METHODS

In the following a principle overview about different dielectric test methods with focus on routine, partial discharge and on on-site installation tests will be given (see table 3 on next page). Possibilities and limits of the technologies will be discussed.
As extruded cables undergo stringent requirements for quality assurance purpose, dielectric test in terms of withstand voltage testing along with complementary partial discharge measurement apply.
Buried cables (see column A and B of table 3) which are operated with AC power frequency voltage the testing requirements are defined in various standards. [10; 11; 12]. Routine testing carried out at manufacturing site includes testing with mains frequency of comparatively short lengths along with conventional partial discharge measurement. Normally the partial discharge measurement is carried out in shielded rooms with high measuring sensitivity to test the quality of the whole cable length. At the time of installation, the separate cable elements are connected together by use of joints and terminations to reach the required system length. Before commissioning the cable system a quality check by AC voltage in combination with a partial discharge measurement test is done directly at the joints. As an alternative a VLF test may also apply, but only for medium voltage cables. In the latter test scenario it might be considered that:

- field distribution can be different from service
- lower number of polarity changes compared to mains frequency compensated by higher test voltage level (factor ~ 1.5) which enhances the field stress at the conductor significantly compared to AC
- partial discharge behavior might differ as well as signal to noise ratio

Table 3: Principle overview of cable manufacturing and testing technique for extruded MV, HV and EHV cables based on [9]

		A		B		C		D	
		MV Landcable **IEC standards e.g. 60502**		**HV / EHV AC Landcable** **IEC standards e.g. 60840, 62067**		**HV / EHV AC Seacable** **no IEC standards**		**DC Seacable** **no IEC standards but GIGRE recommendation e.g. 490**	
Manufacturer's site	**Technology**	Cable drum	Hundreds of meters to few kilometers	Cable drum	Hundreds of meters to few kilometers	Turntable, cage	Some ten kilometers	Turntable	Up to more than 100 kilometers
			Pure cable (without joints)		Pure cable (without joints)		Joints (splices) in factory		Joints (splices) in factory
	HV Testing	HV withstand test	50/60 Hz power frequency 3.5Uo for 5 min for 1 phase (60502)	HV withstand test	50/60 Hz power frequency 2.5Uo for 30 min (60840) 2.5 to 2.0 Uo for 30/60 min (62067)	HV withstand test	AC of 20 Hz to 50/60 Hz power frequency; Voltage level as A either factory or after laying	HV withstand test	HV -DC 1.85 Uo for 15 min, additional HVAC (peak=DC) is recommended (CIGRE WG 21.01 02 2003 / CIGRE recommendation no. 490)
		PD test	With AC 50/60 Hz (evaluation of delivery length)	PD test	With AC 50/60 Hz (evaluation of delivery length)	PD test	With AC of 20 Hz to 50/60 Hz (evaluation of splices)	PD test	With AC of about 20 Hz (evaluation of splices)
Shipment		Cable drums on trailer (sections of installation length)		Cable drums on trailer (sections of installation length)		Turntable on vessel (installation length)		Turntable on vessel (mostly installation length)	
Laying site	**Technology**	Laying and jointing on-site	Some kilometers	Laying and jointing on-site	Some ten kilometers	Laying only	Some ten kilometers	Laying only	Up to more than 100 kilometers
	HV Testing	HV withstand test	AC 20 to 40(300) Hz 1.73 Uo for 15 min (60502) VLF 0.1 Hz 3.5 Uo (rms value) for 15 min (60502, IEEE Std. 400.2)	HV withstand test	AC 20 to 40(300) Hz 2.0 to 1.7 Uo for 60 min (60840) 1.4 to 1.1 Uo (or 1.7) for 60 min (62067)	HV withstand test	Analogy with IEC for landcables A	HV withstand test	HV -DC 1.45 Uo for 15 min (CIGRE WG 21.01 02 2003)
		PD test	On joints for cables with (non-) conventional measurement	PD test	On joints for cables of higher ratings	PD test	n.a.	PD test	n.a.

In comparison to buried cables there exists no specific standard for submarine cables besides CIGRE recommendations and brochures. [13, 14]. Planned and conducted dielectrical tests as per table 3, column C and D may follow beside the recommended testing procedure proposed by CIGRE also manufacturer's data or requirements of the customer. Due to the long length of extruded submarine AC and DC cables of 10 km factory length to 100 km of total delivery length the requirements for testing are getting more defined by the physical testing plausibility combined with trade-offs in terms of possibilities for testing.
Nevertheless, AC-submarine cables (see column C, Table 3) are being tested by withstand voltage tests by using high AC-voltage. During this process the cables are tested on basis of on-site testing of buried cables corresponding to IEC 60060-3 [15] where a testing frequency smaller than the power-line frequency is used in order to limit the required testing current. As an analogy to the above mentioned factory length, DC-submarine cables are being logically tested using high DC-voltage (column D, Table 3).
Regarding to the partial discharge measurement applied to extruded submarine cables, it has to be mentioned that the possibilities for detection are limited. The reason is the high attenuation of the partial discharge impulses caused by wave propagation inside the cables achieving damping factors up to 100 p.u. after 10 kilometers. Nevertheless, the cables are singly tested on cable-pieces (beginning and end of cable). After connecting the factory lengths the partial discharge measurements are being taken directly at the splices. In order to gain a reliable partial discharge diagnosis the tests are done using AC-voltage, no matter if the submarine cable is intended for AC- or DC-voltage transmission. As submarine cables are difficult to access after installation, partial discharge measurements at the splices are excluded of the commissioning tests. Therefore a withstand voltage test is recommended after installation. According to the service conditions there are physically reasonable tests of the AC cables with HV AC-voltage and of the DC cables with HV DC-voltage.

TEST EQUIPMENT FOR DIELECTRIC TESTING

This chapter will discuss HV testing technology considering the state of the art technology compared with an overview of suitability for different field applications. [16; 17]

HVDC testing equipment

HVDC voltage generation circuits can be mainly distinguished between two rectifying circuits. The Greinacher circuit represents the conventional design for asymmetrical voltage duplication which allows a system design having heavy duty operation at continuous duty. Moreover, a cascading connection of single Greinacher circuits is possible but leads to big size applications. The test system can be designed for indoor as well as full outdoor application even under unfavorable condition by having one or two poles. Such systems are mainly used for factory testing of extruded DC cables.

Fig. 2: Outdoor HVDC test system type FGP 200/1200 (200 mA, 1200 kV); Manufactured by HIGHVOLT

Contrary to that the Delon circuit based on symmetrical voltage duplication has a small size and can be used for medium duty operation. It is possible to cascade single stackable modules for higher voltage applications. Furthermore, all necessary components of the test system (transformer, capacitor, and rectifier) can be built in one insulated vessel to achieve a reliable and transportable system with short mounting time. This test system meets the increasing trend for a mobile (outdoor) test system which needs less space for installation.

Fig. 3: Modular DC test system type GPM 30/800 (30 mA, 800 kV); continuous operation; Manufactured by HIGHVOLT

In addition to the different test technologies for generating high DC voltages, the build-up and stored energy W_{Cable} in the DC cable has to be considered during testing [18]. It can reach very high values up to several MJ and influences the charging / discharging time. Depending on the capacitance of the cable C_{Cable} and the test voltage U_{Test}, the stored energy can be calculated as follows:

$$W_{Cable} = \frac{C_{Cable} \cdot U_{Test}^2}{2}$$

For safety reasons and to reduce stresses on the cable a moderately discharge of the cable is necessary and can be realized within one or two hours by example given discharging resistors or water resistors. Without using such designated discharging units potential discharging times of up to 12 h or more for cables having a length of more than 100 km are possible.

HV AC testing equipment

Resonance Test System with variable Inductance (50 Hz / 60 Hz)

Resonant test systems are applied to the generation of high-voltage AC of power frequency for routine, type and development testing of (highly) capacitive test objects. There are two types: steel tank type and modular insulating case type. The test system itself consists of the exciter transformer, a reactor with variable inductance and a voltage divider / coupling capacitor. Together with the capacitive load of the test object it forms a resonant circuit.
The main advantage of the resonant test systems is the low power demand described by the quality factor q (in the range 40 to 80) as only the losses in the test circuit must be covered by the power supply. This aspect is especially a major issue for on-site testing of cables, because the feeding power S to be supplied is a criterion for the feasibility of a test. The kilometric capacitance C` is constant, so the total cable capacitance C_{cable} increases linear with length l_{cable}, the needed test power S quadratic with the applied test voltage U_{Test}. For AC test systems S can be calculated according to:

$$S = \omega \cdot C' \cdot l_{cable} \cdot U_{Test}^2 \qquad (1)$$

As discussed before an important aspect for such AC test system is the fact, that they can be designed as resonance test systems. Thus, only the active power has to be fed in the test circuit which reduces the feeding power down to 1% of the required testing power or even less. The required feeding power P can be calculated by implementing the quality factor q (ratio between test power and feeding power) as well as the efficiency of the power supply feeding of the test system $0.9 \leq \eta_{feeding} \leq 1$ in the calculation above:

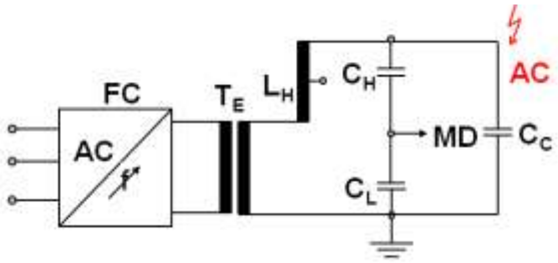
$$P = \frac{\omega \cdot C' \cdot l_{cable} \cdot U_{Test}^2}{q \cdot \eta_{feeding}} \qquad (2)$$

This type of test system is mostly suitable for indoor operation. In order to test very high capacitive loads several reactors of such a system can be connected together via a virtual electric shaft to extend the capacitive load range for testing. [9] This shaft guarantees the synchronous operation of the mechanically divided motor drives and therefore core positions (= variation of inductance). However, due to maneuverable parts, frequent transportation can lead to mechanical damages and the weight to power ratio of 3 ... 10 $^{kg}/_{kVA}$ is moderate. Therefore, an on-site application of this technology is not used for field cable testing.

AC Test System with variable frequency

Due to the need for even more compact (weight to power ratio of 2 ... 4 $^{kg}/_{kVA}$) and robust test systems with higher quality factors (q >> 100), which are especially used on-site, resonant test systems with variable frequency were engineered and represent the state of the art solution for this purpose as well as on-site testing of long AC and DC cables. The difference of the AC test system with variable frequency compared to the system with variable inductance is the static frequency converter and control system located in front of the exciter transformer and the fixed inductance L_H, s. figure 4.

Fig. 4: Circuit diagram of an AC resonant test system with variable frequency



The great benefit of this test system is the possibility to provide very high test power for on-site testing of very long cables by using a test frequency as low as 10...20 Hz or by parallel connection of several systems. Hence, with this proven technology and test system a wider range of capacitive loads can be tested compared to resonance test systems with variable inductance. With regard to equation (2) assuming that the same test parameters but differing in test frequency of f_{test} = 20 Hz and a quality factor q = 160 it is possible to test a (extruded) AC cable ten times longer with the same feeding power by the use of a test system based on variable frequency.

An additional example given in [19] demonstrates the use of this technology as test on cables with l_{cable} = 52 km in total. Moreover, with this AC resonant test system routine tests of extruded DC cables were also successfully performed [19]. Furthermore, during testing of such very long HVDC cables the test systems were connected at both ends of the cable in order to minimize the screen losses up to 25 per cent compared to single end feeding to avoid overheating of the screen [20]

CONCLUSION AND SUMMARY

Different types of test methods and their requirements were presented and discussed. Focused was their suitability to perform factory as well as after installation tests on extruded DC and AC cables. It was mentioned, that depending on the design of the extruded cable different dielectric tests may apply due to different physical and electrical behavior. Moreover, information was provided that partial discharge measurement depends on several factors like length of the cable, test frequency and test amplitude. Also different testing technologies were presented with regard to their suitability for factory and on-site testing. The following points can be concluded:

There is no universal test method available which can perform all test and diagnostic tasks. Suitable test technology and testing procedure for AC and DC cables depends strongly on material, cable design and applied test voltage to detect possible defects
Resonant test systems with variable frequency are the most efficient and most powerful test systems for on-site testing of AC cables and DC cables shall be tested with DC on-site.

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