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RECOMMENDATIONS FOR TESTING DC EXTRUDED CABLE SYSTEMS FOR POWER TRANSMISSION AT A RATED VOLTAGE UP TO 250 kV

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Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV

Prepared by Cigré WG 21-01

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1 INTRODUCTION

1.1 Background

The potential of polyethylene-insulated cables for DC submarine high voltage applications was recognised and studied in the 1950s following the successful implementation of thousands of kilometres of polyethylene submarine communication cables. Experimental polyethylene DC cables were produced in the 1960s for operation at 200 kV to ground.

The commercial application of extruded DC cables was hampered by a tendency for the cables to fail during polarity reversal tests. This was generally attributed to the presence of space charges trapped within the cable insulation.

In the 1990s, the development of new insulating materials and novel converter stations resulted in renewed commercial interest in extruded DC cable for both submarine and land applications. As increasing use of this emerging technology is foreseen, there is need for a common approach to cable qualification and routine testing.

At the time of preparing this document there is laboratory experience at voltages up to and including 500 kV, but operating experience is still limited to a few projects at 80 kV and recently two commissioned systems at 150 kV. However, it is the opinion of WG 21-01 that within a few years HVDC extruded cable systems will be in operation at voltages up to and including 250 kV. The present document has, therefore, been developed for DC power transmission cable systems up to 250 kV. The possibility of extending this range to higher voltage levels should be examined when sufficient service and testing experience at the lower voltage levels has been accumulated.

There are established CIGRÉ recommendations for paper lapped HVDC cables and long extruded AC cables. There are IEC and other standards for extruded AC cables for land use. A number of specific features prevents them from being applied to extruded DC cable systems and hence, in 1999, CIGRÉ Study Committee 21 established a Working Group to develop test recommendations for testing extruded DC cable systems.

The philosophy adopted has been that the tests recommended should apply to the complete HVDC cable system as installed and as intended to function. Wherever possible, the tests have been based on existing recommendations, standards and practices. New tests have, however, been introduced where required by considerations specific to the new technology. It has also been recognised that the new technology may involve the use of many different materials such as thermoplastic or cross-linked polymers (either filled or unfilled) and differing manufacturing processes. In consequence, the tests recommended are largely functional and not specific to one material or manufacturing process.

1.2 Scope

This document recommends a series of tests on extruded cables for DC power transmission systems (land or submarine cables and their accessories in fixed installations) up to and including 250 kV. Within the scope of these recommendations “extruded” shall mean either filled (e.g. with mineral or carbon) or unfilled and either thermoplastic (e.g. Polyethylene [PE], etc) or thermoset (e.g. crosslinked polyethylene [XLPE], Ethylene Propylene Rubber [EPR], etc) insulations.

1.3 Summary of Tests

Development Tests	Tests made during the development of the cable system
Prequalification Test	Test made before supplying on a general commercial basis a type of cable system covered by this recommendation in order to demonstrate satisfactory long-term performance of the complete cable system.
Type Tests	Tests made on cables and accessories before supplying on a general commercial basis a type of cable system covered by this recommendation to verify the properties of a cable system prior to supplying that particular system.
Routine Tests	Tests made by the manufacturer on every manufactured component (length of cable or accessory) to demonstrate the integrity of the manufactured component.
Sample Tests	Tests made on samples of complete cables or components, at a specified frequency, to verify that the product meets the design and manufacturing specifications.
Tests after Installation	Tests made on the completed cable system after installation and prior to use to demonstrate system integrity.

1.4 Definitions

1.4.1 Definitions - General

- A cable system consists of cables and accessories. Cable accessories are typically joints and terminations. There may be other types of accessories associated with a cable system (e.g. measuring devices or fixtures). These need only to be incorporated in the test objects to the extent that they are deemed to have an impact on the operational characteristics of the cable system.
- A test object is a cable length or an accessory to be subjected to testing.
- A Return Cable is the low voltage DC cable used for the return current in monopolar operation of the HVDC schemes. The return cable can either be connected over the full length between the converters or only be for part of the length connecting a converter to an electrode station.
- A Transmission Cable refers to the HV cable of a monopolar (or bipolar) scheme. The term is used in this document where appropriate to distinguish from the return cable.
- A test loop is a combination of series connected test objects (Figure 1) simultaneously under test.
- A test set-up is a combination of clearly separate test loops. A number of test loops may be simultaneously under test, possibly using same test equipment.
- LCC, Line commutated converter, is (for the purpose of this document) a converter that has the feature of changing voltage polarity on the cable system by means of a control action.

- VSC, Voltage source converter is (for the purpose of this document) a converter that does not have the ability to change the voltage polarity of the cable system.

1.4.2 Definitions - Test Objects

- An extrusion length is the length of cable conductor with the insulation and semi-conductive layers as continuously extruded in the same non-interrupted extrusion operation (excluding possible scrapped sections cut off from the starting and ending sections).
- A manufacturing length is a whole extrusion length (or parts thereof if cut), where construction elements (outside the outer semi-conducting layer) have been applied.
- A delivery length is defined as the shipping length of completed cable, possibly including factory installed accessories. A delivery length may encompass one or more jointed manufacturing lengths (or parts of manufacturing lengths), as would be typical for a submarine cable. A typical delivery length for a land cable would be the completed cable length on the cable drum.
- A factory joint is a joint between extrusion lengths / manufacturing lengths manufactured under controlled factory conditions.
- A repair joint is a joint between two cables that are completed with all construction elements.
- A field joint, is a joint between two cables that are completed with all construction elements and in a state as installed in the field in the actual cable system.
- A transition joint, is a joint between two extruded cables of different designs. (A transition joint may be further classified as a factory, a repair or a field joint).

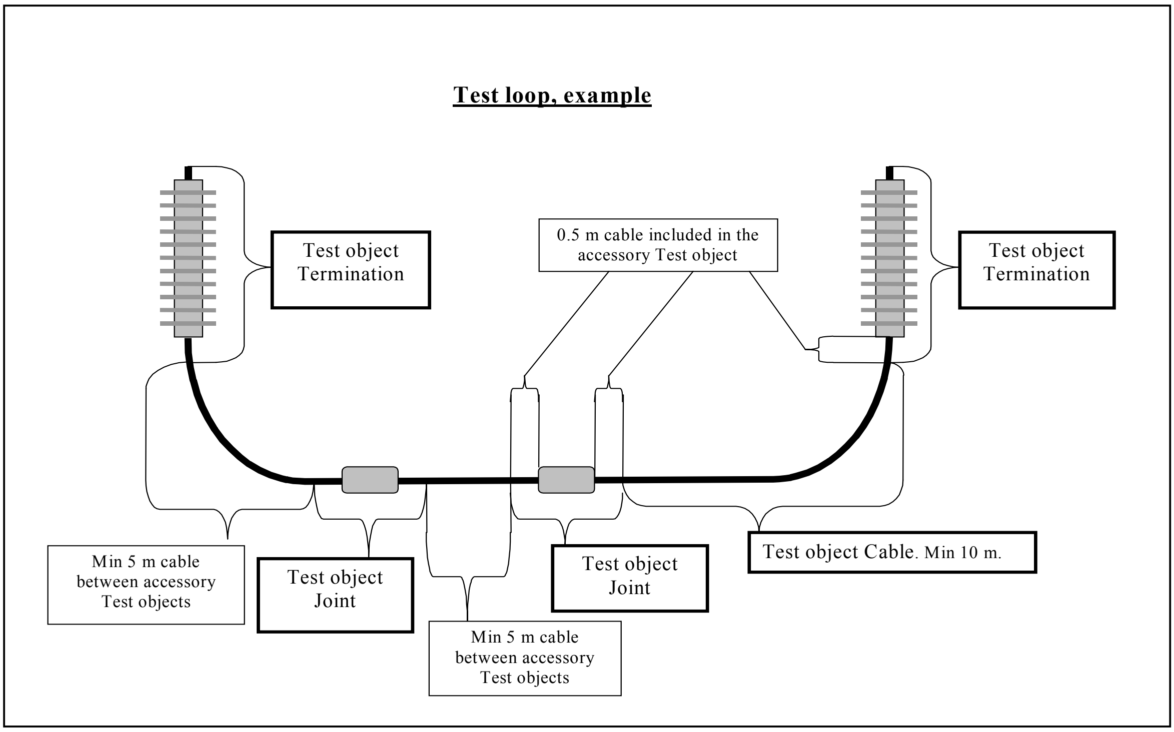

Figure 1: Possible configuration of test objects within a test loop

1.4.3 Definitions - Test Voltages

- U_0 is the rated DC voltage between conductor and core screen for which the cable system is designed.
- U_T is the voltage during the type test and routine test. For the scope of this recommendation $U_T = 1.85 \times U_0$.
- U_{TP1} is the voltage during the prequalification test (load cycle test), type test (polarity reversal test) and test after installation. For the scope of this recommendation $U_{TP1} = 1.45 \times U_0$.
- U_{TP2} is the voltage during the prequalification polarity reversal test. For the scope of this recommendation $U_{TP2} = 1.25 \times U_0$.
- U_{P1} is 1.15 × the maximum absolute peak value (Figure 2) of the lightning impulse voltage, which the cable system can experience when the impulse has the opposite polarity to the actual DC voltage.
- $U_{P2,S}$ is 1.15 × the maximum absolute peak value (Figure 2) of the switching surge voltage, which the cable system can experience when the surge has the same polarity as the actual DC voltage.
- $U_{P2,O}$ is 1.15 × the maximum absolute peak value (Figure 2) of the switching surge voltage which the cable system can experience when the surge has the opposite polarity as the actual DC voltage
- $U_{RC,AC}$ is the maximum voltage a return cable can be subjected to due to temporary damped alternating overvoltage. This voltage is typically induced by a commutation failure, and the value should be supported by the supplier's system calculations of the HVDC link. The nature of the overvoltage is depending upon the configuration of the HVDC link and needs to be calculated for each case.
- $U_{RC,DC}$ is the max DC voltage in normal operation of the return cable.

Note
All voltages shall be applied without substantial interruption.
The ripple content of the DC test voltages shall not be greater than 3 percent.
Calibration shall be according to [1]
The basis for the selection of test factors is described in Appendix A.

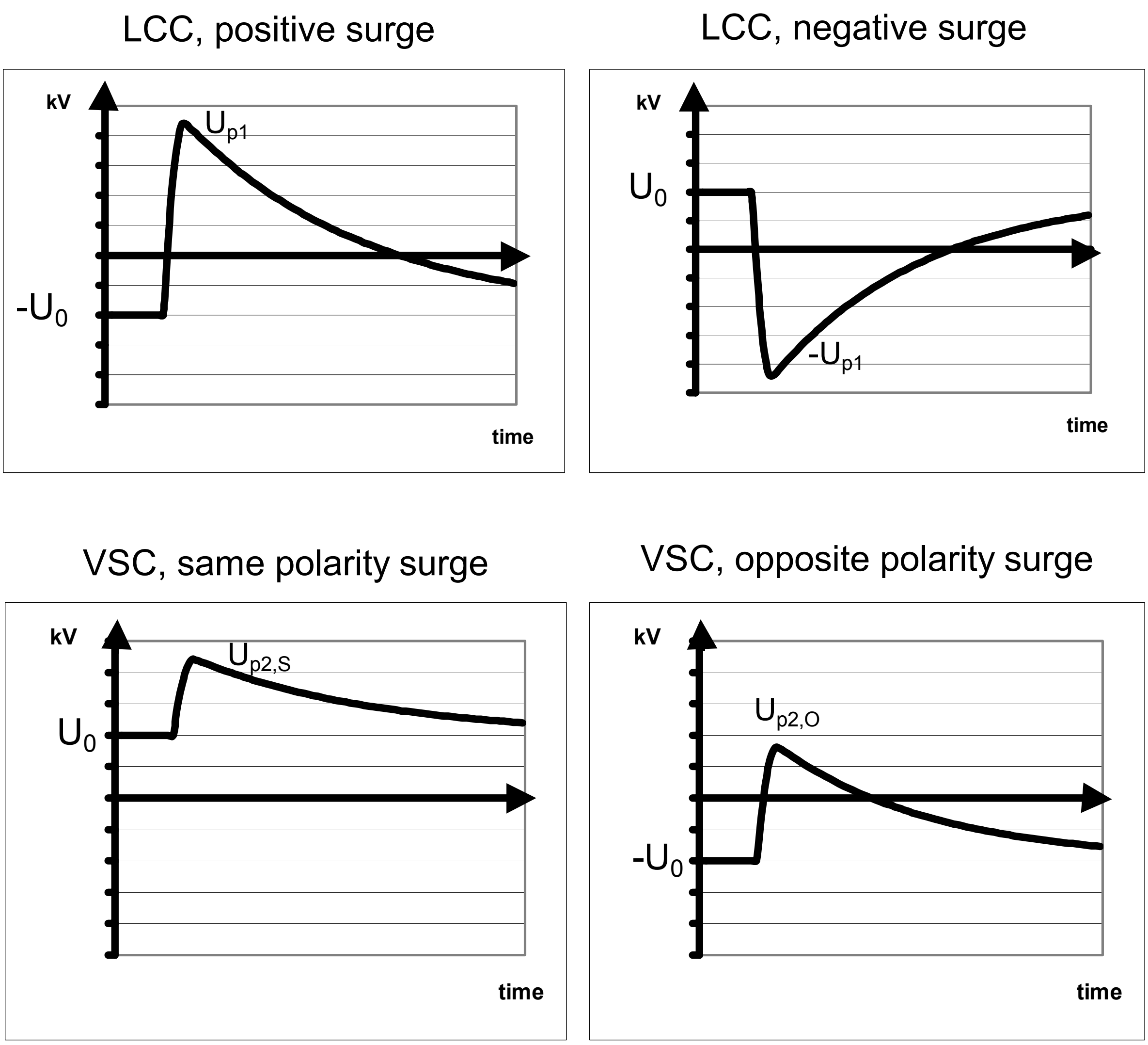

Figure 2: Schematic representations of the impulse test voltages. (Due to the constraints within the DC system design $U_{P2,S}$ does not necessarily equal $U_{P2,O}$, i.e. the same-polarity surge is limited by surge arresters, but the opposite-polarity surge may be limited by the converter.)

1.4.4 Definitions – Thermal Cable Design Parameters

- $T_{cond,max}$ is the maximum temperature at which the cable conductor is designed to operate. This value is to be stated by the supplier.
- ΔT_{max} is the maximum temperature difference over the cable insulation (not including semiconductive layers) at which the cable is designed to operate. This value is to be calculated and stated by the supplier, who shall also provide evidence of the correlation between this design value and data measured during testing.

1.4.5 Definitions – Thermal Conditions for Tests

- The heating method used shall be conductor heating. The heating may be provided by either DC or AC current, possibly in combination with external thermal insulation or cooling. The actual ΔT and T_{cond} during testing need to be demonstrated.
- Load Cycles
  Load cycles consist of both a heating period and a cooling period.

  24 hour load cycles (for prequalification and type tests) consist of an 8 hour heating period and a 16 hour cooling period. During the last 2 hours of heating, the conductor temperature shall be $\geq T_{cond,max}$ and a temperature drop across the insulation $\geq \Delta T_{max}$ shall be maintained.

  48 hour load cycles (for type test only) consist of a 24 hour heating period and a 24 hour cooling period. During the last 18 hours of heating a conductor temperature $\geq T_{cond,max}$ and a temperature drop across the insulation $\geq \Delta T_{max}$ shall be maintained. 48 hour load cycles are only required as part of the type test procedure to ensure that electrical stress inversion is well advanced within the cycle.
- High Load
  High Load consists of a continuous heating period.
  Within the first 8 hours of the heating period conductor temperature $\geq T_{cond,max}$ and temperature drop across the insulation $\geq \Delta T_{max}$ shall be achieved and maintained for the rest of the High Load test.
- Zero Load
  No heating is applied.
- Impulse Test (superimposed impulse, switching, lightning)
  Conductor temperature $\geq T_{cond,max}$ and temperature drop across the insulation $\geq \Delta T_{max}$ shall be reached for a minimum 10 hours before voltage impulses are applied and shall be maintained throughout the duration of the test .
- Unless otherwise specified in the details for the particular test, tests shall be carried out at an ambient temperature of (20 ± 15) ° C.

1.4.6 Definitions – Conditions for Tests

POLARITY REVERSAL TEST

The temperature and voltage conditions are defined in sections 1.4.5 and 1.4.3 respectively.
Starting with positive voltage, the voltage polarity shall be reversed every 8 hours and one reversal shall coincide with the cessation of loading current in every 24 hour loading cycle.
The recommended time duration for a polarity reversal is 2 minutes.

SUPERIMPOSED LIGHTNING IMPULSE VOLTAGE TEST

Prior to the first impulse of each test the test object shall be heated so that the temperature conditions as defined in section 1.4.5 are achieved for at least 10 hours and the test object shall have been subjected to U_0 (of the relevant polarity) for at least 10 hours. These conditions have been selected to reflect the electrical dynamics present within extruded insulations used for HVDC.
Superimposed lightning impulse voltage shall be applied according to the procedure given in [2].

If the impulse test is not strictly practicable due to sample length and set up limitations, it is recommended that the waveform be altered while remaining as close as possible to the standardized risetime and decay time. If modification of the waveform does not prove effective, the manufacturer may, at his discretion, shorten the installation provided that the length of cable between the ends of adjacent accessories is at least 5m.
The cable samples shall withstand without failure 10 positive and 10 negative voltage impulses at the voltage level U_{P1}.
A lightning impulse test (Appendix C) can be selected as an alternative to the superimposed lightning impulse test provided that the Bahder coefficient has been established for the actual cable under test. The impulse voltage (from Appendix C) shall be applied according to the procedure given in [3].

1.5 Range of Approval

1.5.1 Prequalification Test

The prequalification test is intended to indicate the long-term performance of the complete cable system and should normally be completed after the development tests have been carried out. The prequalification test need only be carried out once, unless there is a substantial change in the cable system with respect to materials, manufacturing processes, construction or design parameters. Substantial change is defined as that which might adversely affect the performance of the cable system. The supplier shall provide a detailed case including test evidence if modifications are introduced, which are claimed not to constitute a substantial change.

The prequalification test qualifies the manufacturer as a supplier of cable systems with the same or lower voltage rating, the same or lower maximum conductor temperature and the same or lower calculated maximum electrical stress at operating conditions. A cable system prequalified according to these recommendations for LCC is also prequalified for VSC. A cable system prequalified according to these recommendations for VSC is not also prequalified for LCC.

1.5.2 Type Test

The type approval shall be accepted as valid for cable systems within the scope of this recommendation if the following conditions are met:

1. the actual designs, manufacturing processes and service conditions for the cable system are in all essential aspects equal
2. service U_0, U_{P1}, $U_{P2,S}$ & $U_{P2,O}$ are equal or less
3. the mechanical stresses to be applied during pre-conditioning are equal or less than those of the system already tested
4. service $T_{cond,max}$ is equal or less than those tested
5. the actual conductor cross section is equal to a previous test, or within the range of previous tests of cables with different cross-sections
6. the calculated maximum electrical stresses, under all operational conditions at the conductor and the insulation screens, in the main insulation parts of the accessory and its boundaries are equal to or lower than for the tested cable and accessory
7. a cable system qualified according to this recommendation for use with LCC is also qualified for use with VSC, but not the opposite.

Irrespective of the above, the non-electrical type tests shall be judged on the basis of equal, in all essential aspects, including the materials, manufacturing processes and relevant design elements used.

2 DEVELOPMENT TESTS

The manufacturer should complete all analyses and development testing prior to commencing the prequalification test. The precise nature and extent of development work and analyses shall be left to the discretion of the manufacturer but may include the following:

- An evaluation of the materials and processes employed. Such evaluations would normally include electrical resistivity assessments, breakdown tests and space charge measurements.
- An analysis of the electric stress distribution within the cable system insulation for a range of typical installation and loading conditions.
- An assessment of the longterm stability, possibly involving factory experiments to assess the ageing effects of various parameters, e.g. electrical stress, temperature, environmental conditions etc.
- An assessment of the sensitivity of the electric stress distribution to the expected variations in cable dimensions, material composition and process conditions (extrusion, post extrusion treatments and finishing).

3 PREQUALIFICATION TESTS

3.1 Test Objects

Approximately 100m of cable including complete accessories (at least one of each type) with a dielectric design suitable for practical applications shall be tested. Where appropriate mechanical preconditioning may be considered before starting the prequalification test.

3.2 Sequence of Tests

General:

1. Minimum duration is 360 days.
2. Conductor temperature and temperature difference across the insulation shall both be controlled to the design level. Design levels in accessories and adjacent cables may differ.

Note: The main objective of the prequalification test is to satisfactorily demonstrate the insulation integrity during long times under DC, given the long dielectric time constants as compared to AC. It is however recognized that other aspects of a specific installation may be important, such as the thermo-mechanical effects due to the installation conditions. The representation of specific installation conditions in the test set-up should be considered.

The sequence of tests for LCC and VSC are shown in the tables below

Line commutated converter LCC

	LC	LC	LC+ PR	HL	HL	ZL	LC	LC	LC+ PR	S/IMP
Days	30	30	20	40	40	120	30	30	20	BIL
Voltage (U_0)	+ 1.45	- 1.45	1.25	+ 1.45	- 1.45	- 1.45	+ 1.45	- 1.45	1.25	System Design
Total days	30	60	80	120	160	280	310	340	360	

Voltage commutated converter VSC

	LC	LC	HL	HL	ZL	LC	LC	S/IMP
Days	40	40	40	40	120	40	40	BIL
Voltage (U_0)	+ 1.45	- 1.45	+ 1.45	- 1.45	- 1.45	+ 1.45	- 1.45	System Design
Total days	40	80	120	160	280	320	360	

LC = Load Cycle HL = High Load PR = Polarity Reversal ZL = Zero Load
S/IMP = Superimposed Impulse Test

Sections 1.4.5 & 1.4.6 provide guidance on test conditions.

The length and sequence of the thermal conditions were selected with regard to the particular electrical effects that can occur in extruded insulations when operated under HVDC. The technical basis for the test durations is given in Appendix A.

A minimum rest period without voltage but with heating of 24 hours is recommended between the high load tests at different polarities.

To permit previous service or test experience or the specific requirements of an application to be taken into account, the test sequences may be amended in line with the technical considerations outlined in Appendix B.

The manufacturer may, at his discretion, conduct tests and / or examinations after completion of the prequalification test for engineering information only.

3.3 Success Criteria, Re-testing and Interruptions

The criterion for a successful outcome to the prequalification test is that all tests shall have been performed without breakdown of that test object.

If there is a breakdown in a test object the complete prequalification test shall be repeated for that particular test object.

If a breakdown of a test object occurs, causing an interruption to the ongoing testing of connected test objects, the test may be resumed after the failed test object is removed. The actual load cycle, surge or impulse during which the failure occurred shall be repeated for the remaining test objects. If breakdown occurs during a constant load period the time elapsed without voltage applied shall be added to the remaining test period.

After any interruption, for example an interruption caused by external factors (loss of power, irregular external flashover of terminations etc) the test may be resumed. The actual load cycle, surge or impulse during which the interruption occurred, shall be repeated. If the interruption occurs during a constant load period the day the interruption occurred shall be repeated.

4 TYPE TESTS

4.1 Test Objects

All components of the cable system (cable and accessories) shall be subjected to type testing. It is acceptable to test different parts of a system in different test loops. However these test loops must cover all relevant cable system components.

All test objects offered for type testing, shall have successfully completed routine testing prior to being subjected to type testing.

By definition, an accessory includes 0.5 m of cable on each side (Figure 1), measured from the point on the cable where no disassembling or dismantling for the purpose of installation of accessory has taken place.

The non-interrupted cable length between accessories (Figure 1) in a test loop shall be a minimum of 5 m.

A minimum of 10 m of continuous non-interrupted cable shall be included in a test loop.

Where the actual cable insulation thickness deviates from the stated nominal thickness, the procedure specified in [4] shall apply.

Any non-continuous design feature (such as a metallic connection between metallic layers) shall be included in the cable test object.

Test objects for land or submarine application shall be subjected to the appropriate mechanical pre-conditioning.
Test objects for the electrical and non-electrical type tests must not be the same physical samples unless required by the recommendation for the non-electrical test.

4.2 Non-electrical Type Tests

The cable system shall be subjected to the applicable non-electrical type testing as specified in [4].

Cable joints intended for burial on land shall be subjected to the Outer Protection Test specified in [4].

Cable systems intended for installation on land where water blocking is included shall be subjected to a water penetration test as specified in [4].

Cable systems intended to be installed as submarine cables shall be subjected to water integrity testing as specified in [5]. This test would also qualify the cable for installation on land.

Cables with metallic earthing connections through plastic sheaths shall be subjected to the test in [2].

Cable systems employing longitudinally applied metallic foils may, where appropriate, be subjected to the tests in [6].The WG recognises that there may be certain DC designs (for example small cables, armoured cables etc) where the precise details of guidelines will not be applicable.

4.3 Electrical Type Test

The principal overview of the electrical type tests is described in Figure 3 below.

Principal Overview of Electrical Type Tests

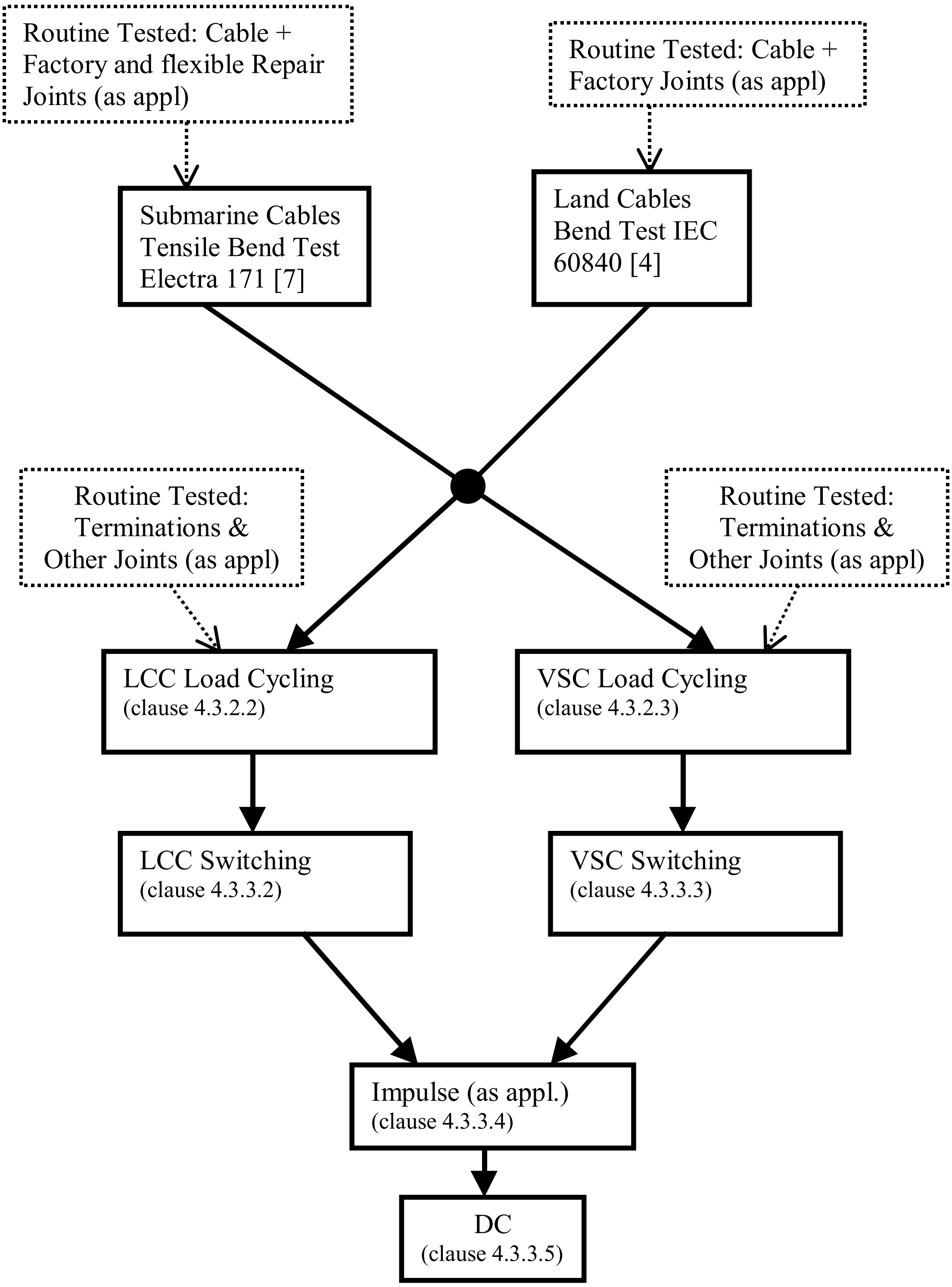

Figure 3: Schematic representation of the sequence of tests for Land and Submarine Cables

4.3.1 Mechanical Pre-conditioning before Electrical Type Test

The intent of the mechanical pre-conditioning is to subject the test objects to the maximum mechanical stress that the cable system will experience during handling, installation and recovery. Consequently the factory joints and flexible repair joints for submarine cables shall be included, but field joints for land-cables are not to be included.

Cable systems to be installed on land shall be subjected to mechanical pre-conditioning as specified in [4].

Cable systems intended to be installed as submarine cables shall be subjected to mechanical preconditioning as specified in [7].

4.3.2 Load Cycle Test

4.3.2.1 General - Load Cycle Test

The load cycle test shall be performed on test objects that have been subjected to the appropriate mechanical pre-conditioning. Accessories in the cable system that are not relevant for mechanical pre-conditioning, are to be installed as test objects together with the pre-conditioned test objects.

The temperature conditions are defined in section 1.4.5.

If the test loop consists of cables with different designs connected with a transition joint, then each cable design is qualified to the relevant thermal conditions ($T_{cond,max}$ and ΔT) and the transition joint is qualified to the higher temperature.
(Note: this means that cable on one side of the transition joint under test, may not have been qualified in this test to its maximum temperature in the scheme).

4.3.2.2 Load Cycle Test - Cable System to be qualified for LCC Operation

The test objects shall be subjected to:

- Eight 24 hour load cycles at negative polarity at U_T.
- Eight 24 hour load cycles at positive polarity at U_T.
- Eight 24 hour load cycles with polarity reversal cycles at U_{TP1}.
- Three 48 hour load cycles at positive polarity at U_T.

A rest period without voltage but with heating is permitted between test blocks. A minimum rest period of 24 hours is recommended.
Positive polarity was selected for the 48 hour load cycles as this is believed to be the most onerous condition for accessories.

4.3.2.3 Load Cycle Test - Cable System to be qualified for VSC Operation

The test objects shall be subjected to:

- Twelve 24 hour load cycles at negative polarity at U_T.
- Twelve 24 hour load cycles at positive polarity at U_T.

- Three 48 hour load cycles at positive polarity at U_T.

A rest period without voltage but with heating is permitted between test blocks. A minimum rest period of 24 hours is recommended.

Positive polarity was selected for the 48 hour load cycles as this is believed to be the most onerous condition for accessories.

4.3.3 Superimposed Impulse and Surge Voltage Test

The thermal conditions for the tests are described in Section 1.4.5.

4.3.3.1 General - Superimposed Impulse Voltage Test

The superimposed impulse voltage test is to be performed on test objects that have successfully passed the load cycle test.

Section 1.4.5 describes the test procedure.

4.3.3.2 Switching Surge Withstand Test - Cable System to be qualified for LCC Operation

- the test object at U_0, 10 consecutive impulses to $-U_{P2,O}$
- the test object at $-U_0$, 10 consecutive impulses to $U_{P2,O}$

4.3.3.3 Switching Surge Withstand Test - Cable System to be qualified for VSC Operation

- the test object at U_0, 10 consecutive impulses to $U_{P2,S}$
- the test object at U_0, 10 consecutive impulses to $-U_{P2,O}$
- the test object at $-U_0$, 10 consecutive impulses to $-U_{P2,S}$
- the test object at $-U_0$, 10 consecutive impulses to $U_{P2,O}$

4.3.3.4 Lightning Impulse Withstand Test

If the intended installation of the cable system is such that it is not exposed to lightning strikes (direct or indirect), these tests need not be done.

-the test object at U_0, 10 consecutive impulses to $-U_{P1}$
-the test object at $-U_0$, 10 consecutive impulses to U_{P1}

4.3.3.5 Subsequent DC Test

After the successful completion of the surge and impulse testing as above, the test object shall be subjected to 2 hours at a negative DC voltage of U_T, no heating.

A rest period prior to this test is acceptable.

4.3.4 Success Criteria, Re-testing and Interruptions

The criterion for a successful outcome to the type test is that that all tests have been performed without breakdown of that test object and that all other non electrical requirements have been complied with.
In case of interruptions / deviations in test parameters during load cycles / polarity reversal test or superimposed impulse voltage test, the test in question shall be repeated.

In case of a breakdown of insulation, when testing several objects simultaneously, the faulty object may be removed and the incident treated as an interruption. The faulty object is considered to have failed the test requirements. Any fault within any extension (0.5m) to a test object, for example an accessory, is considered to be associated with that test object only.

In the case of an irregular external flashover of end terminations the flashover shall be treated as an interruption. Irregular flashover is usually related to unusual dust conditions or objects close to the termination.

4.4 Return Cable - Type Test

4.4.1 General

Return Cables are grounded at one end and are subjected to a DC voltage determined by the cable resistance and the current at the other end of the link. System calculations, taking into account the different fault scenarios, should be performed by the supplier to determine the relevant temporary overvoltages in the power frequency domain for the Return Cable for the actual link. In particular, temporary overvoltages caused by commutation failure may be the criteria for dimensioning of the return cable insulation and accessories. To verify that the cable system can withstand overvoltages caused by commutation failure an AC voltage test at power frequency test shall be performed.

If different designs (different insulation thicknesses) are used along the return path, each design needs to be considered individually.

Return cables may be protected by surge arresters, in which case this feature needs to be taken into consideration in the system studies and consequently in determining $U_{RC,AC}$.

4.4.2 Mechanical Preconditioning

The Return Cable test object shall be subjected to mechanical preconditioning acc. to clause 4.3.1, as applicable.

4.4.3 Thermomechanical Preconditioning

After mechanical preconditioning, the Return Cable test object shall be subjected to thermomechanical preconditioning, consisting of 24 daily load cycles. During the execution of this preconditioning the relevant thermal properties for the return cable shall be fulfilled according to the principles stipulated in clause 4.3.2.1. No voltage needs to be applied.

4.4.4 AC Voltage Test

After the mechanical and thermomechanical preconditioning, the Return Cable test object shall be subjected to a no load AC test at a power frequency voltage of 1.15 x $U_{RC,AC}$ at ambient temperature. The voltage shall be applied for 30 minutes.

4.4.5 Lightning Impulse Withstand Test

If applicable, the Return Cable test object shall be subjected to a lightning impulse withstand test with the relevant test voltages and according to the principles given in clause 4.3.3.4.

4.4.6 Cable Design with Integrated Return Conductor

If the Transmission Cable is such that the return path is integrated, the return path function should be tested together with the Transmission Cable in an integrated test program.

5 ROUTINE TESTS

Routine tests (which include what is in some other documents referred to as the Factory Acceptance Test) are made to demonstrate the integrity of the delivery lengths.

5.1 Transmission Cables

Every delivery length of cable shall be submitted to a negative DC voltage equal to the test voltage defined for the load cycle test U_T and applied between conductor and sheath for 15 minutes.

The experience of using DC voltage for routine testing of extruded DC cables is limited. It is the opinion of the Working Group that in addition to the DC test, testing with AC voltage could be considered provided that the insulation system and the cable design allows AC testing. Long manufacturing lengths and high voltage levels may render AC testing impractical. In the event that AC testing is employed, the voltage level, frequency (power or other frequencies) and time of application shall be agreed between the manufacturer and purchaser.

If required for the particular contract or order, the oversheath may be subjected to the routine electrical test specified in [8].

5.2 Return Cables or Conductors

Every delivery length of cable shall be submitted to a voltage test applied between conductor and sheath.

AC testing is to be preferred for the testing of Return Conductors, the voltage level and time of application shall be agreed between the manufacturer and purchaser. Long manufacturing lengths and high voltage levels may however render AC testing impractical; in this case a suitable DC voltage, agreed between manufacturer and customer, shall be applied. It is recommended that the DC test voltage be no lower than the highest of either 2.5 x $U_{RC,DC,}$ or 25 kV; the voltage shall be applied between conductor and sheath for 15 minutes.

6 SAMPLE TESTS

For the tests in this section, refer to the respective IEC specification for AC extruded power cables [4].

6.1 Frequency of Tests

The frequency of tests shall be according to [4].

6.2 Conductor Examination

6.3 Measurement of Electrical Resistance of Conductor

6.4 Measurement of Thickness of Insulation and Non-Metallic Sheath

6.5 Measurement of Thickness of Metallic Sheath

6.6 Measurement of Diameters, if required

6.7 Hot Set Test for XLPE and EPR Insulation (where applicable)

6.8 Measurement of Density of HDPE Insulation (where applicable)

7 AFTER INSTALLATION TESTS

7.1 High Voltage Test

The installed HV cable system shall be submitted to a negative polarity DC voltage of U_{TP1}. The test duration shall be 15 min.

The installed return cable system shall be submitted to a negative polarity DC voltage that has been agreed between the manufacturer and the customer. The test duration shall be 15 min.

7.2 Test on Polymeric Sheaths

For underground cables electrical testing of the outer sheath subsequent to laying should be considered. If appropriate the test shall be performed according to [8].

7.3 TDR measurement

A TDR (Time Domain Reflectometry) measurement could be performed for engineering information.

8 REFERENCES

[1]	High-voltage test techniques. Part 1: General definitions and test requirements	IEC 60060-1
[2]	Recommendations for tests of power transmission DC cables for a rated voltage up to 800 kV (Electra 72, 1980 - revision)	Electra 189
[3]	Impulse tests on cables and their accessories	IEC 60230
[4]	Power cables with extruded insulation and their accessories for rated voltages above 30 kV (U_m=36 kV) up to 150 kV (U_m=170 kV) - Test methods and requirements	IEC 60840
[5]	Recommendations for testing of long AC submarine cables with extruded insulation for system voltage above 30 (36) to 150 (170) kV	Electra 189
[6]	Guidelines for tests on High Voltage cables with extruded insulation and laminated protective coverings	Electra 141
[7]	Recommendations for mechanical tests on sub-marine cables	Electra 171
[8]	Tests on cable oversheaths which have a special protective function and are applied by extrusion	IEC 60229
[9]	Recommendations for tests on D.C. cables for a rated voltage up to 550 kV	Electra 32
[10]	Recommendations for tests of power transmission DC cables for a rated voltage up to 600 kV	Electra 72
[11]	B.Aladenize, R.Coelho, F.Guillaumond & P.Mirebeau: On the intrinsic space charge in a DC power cable	Journal of electrostatics, 39, (1997) p235-251
[12]	B.Aladenize & al, Field distribution in HVDC cables: dependence on insulating materials	JICABLE 99, paper B7.8
[13]	Power cables with extruded insulation and their accessories for rated voltages above 150 kV (U_m=170 kV) up to 500 kV (U_m=550 kV) - Test methods and requirements	IEC 62067
[14]	Recommendations for electrical tests prequalification and development on extruded cables and accessories at voltages >150 (170) kV and ≤400 (420) kV	Electra 151

9. APPENDICES

APPENDIX A DERIVATION OF TEST PARAMETERS

DC VOLTAGE FACTORS

The multiplication factors for the test voltages and periods have been determined based on consideration of the available Voltage-time (V-t) characteristics. The precise nature of the V-t characteristic has not been determined for DC operation. However the Working Group was of the opinion that the Inverse Power Law model provided a conservative basis for the work. The precise details of the approach are shown below,

$$V^n \cdot t = \text{const.}$$

where

V : voltage

t : time

n : life exponent from V – t characteristic

test volatge Vdc is;

$$Vdc = V_0 \times K_1$$

where

V_0 : system voltage

K_1 : deterioration coefficient

$$K_1 = \sqrt[n]{t_0 / t_1}$$

where

t_0 : design life(40years)

t_1 : test duration

Using the approach described above it is possible to determine the test voltage factors that are equivalent to a prescribed system life when testing for a shorter time. In this work the WG has used a system life of 40 years. The approach requires knowledge of the ageing parameter “n” which is determined empirically from endurance tests on cables. The knowledge of “n” under DC was not sufficient for the WG to identify a precise value. However they were able to estimate a lower limit (n = 10) which was used to determine the test voltage factor.

	Prequalification Test	Type Test
Design Life - t_0 (years)	40	40
Test Duration – t_1 (days)	360	30
Deterioration Factor – K_1	$\sqrt[10]{40*365/360}$	$\sqrt[10]{40*365/30}$
Test Factor	1.45	1.85

On this basis the WG identified the test factor of 1.45 as equivalent to approximately 40 years operation at rated voltage when applied for 1 year and the test factor of 1.85 when applied for 30 days

IMPULSE

In the light of the good experience which has resulted from the use of the previous Electra recommendations within [9] [10] [2] it was decided that the same approach to selection of test factors would be applied.

POLARITY REVERSAL

The approach for test factors is based on the principle of applying the same additional voltage for the polarity reversal as that applied for the constant voltage test . This approach has been used in previous DC recommendations. The table sets out previous practice relating the polarity reversal tests and the used test factors.

For example: At a polarity reversal in real operation, the cable system experiences a voltage step of $2U_0$. Applying a test factor of 1.45 in a polarity reversal test gives that the cable system under test experiences a voltage step of $2 \cdot 1.45\ U_0 = 2.9U_0$, i.e. $0.9U_0$ more than in real operation.

Document	**Condition**	**Test Factor**	**Test Voltage**	**Additional Voltage in Test vs Operation**	**Comment**
Electra 32 [9] Type test	Constant voltage	2	2 U_0	U_0	
	Polarity reversal	1.5	2 ($1.5 \times U_0$)	U_0	
Electra 72 [10] Type test	Type test constant voltage	2	2 U_0	U_0	
	Polarity reversal	1.5	2 ($1.5 \times U_0$)	U_0	
Electra 189 [2] Type test	Constant voltage	1.8	1.8 U_0	0.8 U_0	Test in Cold condition
	Polarity reversal	1.4	2 ($1.4 \times U_0$)	0.8 U_0	
This recommendation: Type test	Constant voltage	1.85	1.85 U_0	0.85 U_0	Test in Hot condition
	Polarity reversal	1.45	2 ($1.45 \times U_0$)	0.9 U_0	
This recommendation: Prequalification test	Constant voltage	1.45	1.45 U_0	0.45 U_0	Test in Hot condition
	Polarity reversal	1.25	2 ($1.25 \times U_0$)	0.5 U_0	

USE OF AC VOLTAGE FOR ROUTINE TESTS

The experience with using DC voltage for routine testing of extruded DC cables is limited. However there is evidence from the use of DC voltages as an installation test for AC cables to indicate that it may not be sufficiently searching. It is the opinion of the Working Group that for routine tests, in addition to the DC test, testing with AC voltage should be recommended but not required.

When considering the potential use of AC the Working Group recognizes that there may be circumstances that render AC testing impossible or impractical, such as a cable insulation that is not suitable for AC stressing or long manufacturing lengths. This is to be agreed upon on individual basis between the supplier and the purchaser. It is also necessary to agree on the exact performance of the test (test time, test voltage, frequency).

DURATION OF TESTS – Prequalification & Type Tests

The field distribution within a DC power cable in operation differs from the Laplace field ($\propto 1/r$) due to the fact that the conductivity of the insulation depends on its temperature (which decreases from the conductor to the sheath) and the local electric field. These phenomena generate a divergence, which is in addition to that derived from the cable geometry.

The evolution of the additional divergence can be represented as a function of a dimensionless parameter t/τ where τ is the "time constant": $\tau = \rho\,\varepsilon$ where ρ is the volume resistivity and ε the permittivity.

Calculations show that a time equivalent to 10 τ has to pass to approach the steady state distribution of the divergence. The table gives the range of times to stability (10 τ) as a function of temperature for different materials that are likely to be used for DC extruded cables. Practically this means that the time to achieve a stable electrical stress distribution will depend upon temperature. Thus it is important to select test times that permit probable insulation systems to reach a stable electrical stress distribution. These considerations provide the foundations for the times of the Zero Load, High Load and 48 hour Load Cycle Tests.

Temperature (°C)	**ε (F/m)**	**ρ (Ω.m)**	**Time for stability 10 τ (hours)**
20	$2 \times 10^{-11} < \varepsilon < 3 \times 10^{-11}$	$10^{15} < \rho < 5 \times 10^{16}$	$55 < 10\,\tau < 4300$
60	$2 \times 10^{-11} < \varepsilon < 3 \times 10^{-11}$	$2 \times 10^{13} < \rho < 5 \times 10^{14}$	$1 < 10\,\tau < 43$
90	$2 \times 10^{-11} < \varepsilon < 3 \times 10^{-11}$	$10^{12} < \rho < 5 \times 10^{13}$	$0.06 < 10\,\tau < 4.3$

Injection of charges from the electrodes also operates, however the 10 τ time constant covers the time needed for these injection processes.

In addition, considering the actual usage of HVDC links, the experimentation constraints and the total time of the tests the WG adopted the following testing times. The WG judged that they would "test" the performance of the proposed HVDC insulation systems in a practical manner[11], [12]:

Condition	Temperature	Testing time (Days)	Time for stability 10 τ (Days)
Zero load (Pre qualification)	≈20°C	120 min	$2.3 < 10\,\tau < 180$
48 Hour Load Cycle: (Type Approval)	60°C to 90°C (manufacturer design)	1 heating period	$0.003 < 10\,\tau < 1.8$

APPENDIX B: TECHNICAL BASIS FOR THE DETAILED PREQUALIFICATION TEST SCHEMES

The development of the detailed technical test schemes described in Section 3.2 has been guided by the following principles

1. Minimum duration is 360 days
2. Conductor temperature and temperature difference across the insulation, for part of the test loop, shall both be controlled to the design level within the loading portions of the test
3. The tests shall commence with a minimum of 60 days of 24 hours load cycles at U_{TP1} for thermo-mechanical conditioning
4. There shall be, in total, a minimum of 120 days of load cycles; for LCC, a minimum of 80 days shall be at U_{TP1} and a minimum of 40 days of polarity reversals at U_{TP2}
5. There shall be a minimum of 30 consecutive days under constant high load (see section 1.4.5) at positive polarity U_{TP1}
6. There shall be a minimum of 30 consecutive days under constant high load (see section 1.4.5) at negative polarity U_{TP1}
7. There shall be a minimum of 120 consecutive days with zero load (see section 1.4.5) at negative polarity U_{TP1}
8. The test shall be completed with a superimposed lightning impulse test (see section 1.4.5).

APPENDIX C EQUIVALENT LIGHTNING IMPULSE TEST

Equivalent lightning impulse test may be selected as an alternative to the superimposed lightning impulse test (prequalification and type test) by allowing for the effect of any space charge accumulation in the insulation. The voltage used for the equivalent lightning impulse is higher than that used for the superimposed lightning impulse because it must allow for the space charge distortion of the electrical field which may cause a higher electrical field in the insulation. In order to estimate the distortion by space charge, Bahder's Coefficient (K) should be used. Bahder's Coefficient depends on both the insulation material of the cable system and the cable system design. Bahder's Coefficient is defined by following equation.

$$K=(V_i - V_r) / V_{dc}$$

Where,

V_i : lightning impulse breakdown voltage

V_r : superposing opposite polarity impulse breakdown voltage on the DC prestress voltage

V_{dc} : DC prestress voltage

The voltage of equivalent lightning impulse test can be calculated by using Bahder's Coefficient as follows.

$$V_{imp} = (V_p M + V_0 K)$$

Where,

V_{imp} : equivalent lightning impulse voltage

V_p : arrester protection level

V_0 : system voltage

M : safety margin for impulse level

This value (M) is recommended to be at least 1.15 and is proposed in [2].

The temperature conditions for the test are defined in section 1.4.5.

APPENDIX D COMPARISON WITH GUIDELINES AND RECOMMENDATIONS FOR TRANSMISSION CABLE TESTS

	Recommendations for Testing DC Extruded Cable System for Power Transmission at a rated voltage up to 250 kV	**Recommendations for Tests of Power Transmission DC Cables for A Rated Voltage up to 800kV, [2]**	**Cables with Extruded Insulation and Their Accessories for Rated Voltages above 150kV up to 500kV, [13]**	**Recommendations for Testing of Long AC Submarine Cables with Extruded Insulation for System Voltage above 30 to 150kV, [5]**	**Rec. for Electrical Tests Prequalification and Development on Extruded Cables and Accessories at Voltages >150kV and <400kV, [14]**
	WG21-01 DC Extruded Cable, up to 250kV	CIGRE Electra 189, 2000 DC800kV, Paper-insulated Cable	IEC 62067 AC500kV, Extruded Cable	CIGRE Electra 189, 2000 AC150kV, Extruded Submarine Cable	CIGRE Electra 151, 1993 AC400kV, Extruded Cable, PQ
Development Test	Tests shall be at the discretion of the manufacturer.				Evaluation of material and processes Evaluation of Weibull parameters Determination of “n”
Prequalification Test	100m including accessories 360days, $1.45U_0$ Different procedures for LCC & VSC Load Cycle Test (min 120) High Load Test Zero Load Test Superimposed LI Test		Load cycle Test : $1.7U_0$, 1year : 180 heating cycles Lightning impulse voltage test : 10positive, 10negative		Long term AC test with heat cycles Impulse test AC test
Type Test	Non-electrical Test Mechanical Pre-conditioning 30 days $1.85U_0$ Different procedures for LCC & VSC Load Cycle Test Superimposed Lightning Impulse Test Subsequent DC Test	Load cycle test : $+1.8U_0$x10,$-1.8U_0$x10 Polarity reversal test (after LC) : $1.4U_0$x60, every 4h, 10 l.c. Superimposed impulse test :$-U_0$+1.15Imp, U_0-1.15Imp	Bending test Partial discharge test Tanδ measurement Load Cycle Test Switching impulse voltage test	Water penetration test Conductor penetration Outer sheath penetration Partial discharge test Loss angle measurement Load cycle test Partial discharge test Ligthning Impulse test	
Routine Test	Delivery Length DC Test : $-1.85U_0$x15min	High-voltage test : $1.8U_0$, 15min. Conductor resistance test Capacitance test Power factor test Factory acceptance test : $1.8U_0$, 15min.	Partial discharge test Voltage test Electrical test on oversheath	On manufacturing length High voltage test Partial discharge test on factory installed joints Factory acceptance High voltage test TDR	
Sample Test	according to IEC 60840				
After Installation Test	High Voltage Test : -1.45 U_0x15min Test on Polymeric Sheaths : according to IEC 60229 TDR for information	DC voltage test : $1.4U_0$, 15min.	DC voltage test (oversheath) AC voltage test (insulation)	AC voltage test : $1.7U_0$, 90min. : $1.0U_0$, 24hours	