

INTERNATIONAL STANDARD



**Superconducting ac power cables and their accessories for rated voltages
from 6 kV to 500 kV – Test methods and requirements**

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INTERNATIONAL
ELECTROTECHNICAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**SUPERCONDUCTING AC POWER CABLES AND THEIR ACCESSORIES
FOR RATED VOLTAGES FROM 6 KV TO 500 KV –
TEST METHODS AND REQUIREMENTS**

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FDIS	Report on voting
20/1858/FDIS	20/1865/RVD

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This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

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INTRODUCTION

As a result of major developments in superconducting cable systems with cold dielectric for medium- and high-voltage AC applications, CIGRE study committee B1 set up working group (WG) B1.31 in 2009 with the aim to prepare recommendations for testing superconducting AC cable systems for power transmission at a rated voltage of up to 150 kV.

The recommendations of CIGRE WG B1.31 were published in TB 538 in June 2013 [1]¹. At the time of preparation of the CIGRE recommendation, laboratory experience at voltages up to and including 275 kV was available, but operating experience was limited to 154 kV. At the time of preparation of this document, several projects up to 220 kV are in progress, and many others are planned for the near future. As the insulation system of high-temperature superconducting (HTS) cable systems considered in this document is comparable to oil-filled cable systems, it was agreed to extend the voltage range to 500 kV in order to be compatible with IEC 60141-1 [2].

In 2014, TC 20 decided to start the standardization work on testing of HTS AC cables based on the published CIGRE TB 538. Manufacturers of HTS cable systems, utilities as the main users, and independent test laboratories will benefit from this document.

A list of relevant references is given in the Bibliography (see [3], [4], [5], [6]).

¹ Numbers in square brackets refer to the Bibliography.

SUPERCONDUCTING AC POWER CABLES AND THEIR ACCESSORIES FOR RATED VOLTAGES FROM 6 kV TO 500 kV – TEST METHODS AND REQUIREMENTS

1 Scope

This document specifies test methods and requirements for high-temperature superconducting (HTS) AC power cable systems, cables and their accessories, for fixed installations, for rated voltages from 6 kV ($U_m = 7,2$ kV) up to and including 500 kV ($U_m = 550$ kV).

The requirements apply to single-core, three-core and three-phase concentric cables with cold dielectric and their accessories that are not intended for fault current limitation purposes.

This document does not cover special cables and their accessories, such as fault current limiting cables or submarine cables, for which modifications to the standard tests may be necessary or special test conditions may need to be devised.

This document does not cover test methods and requirements for the cooling system.

NOTE For considerations regarding cooling systems, refer to Annex A.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60229:2007, *Electric cables – Tests on extruded oversheaths with a special protective function*

IEC 60230, *Impulse tests on cables and their accessories*

IEC 60332-1-2, *Tests on electric and optical fibre cables under fire conditions – Part 1-2: Test for vertical flame propagation for a single insulated wire or cable – Procedure for 1 kW pre-mixed flame*

IEC 60811-202, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 202: General tests – Measurement of thickness of non-metallic sheath*

IEC 60811-203, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 203: General tests – Measurement of overall dimensions*

IEC 60811-401, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 401: Miscellaneous tests – Thermal ageing methods. Ageing in an air oven*

IEC 60811-409, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 409: Miscellaneous tests – Loss of mass test for thermoplastic insulations and sheaths*

IEC 60811-501, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 501: Mechanical tests – Tests for determining the mechanical properties of insulation and sheathing compounds*

IEC 60811-505, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 505: Mechanical tests – Elongation at low temperature for insulations and sheaths*

IEC 60811-506, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 506: Mechanical tests – Impact test at low temperature for PVC insulations and sheaths*

IEC 60811-508, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 508: Mechanical tests – Pressure test at high temperature for insulations and sheaths*

IEC 60811-509, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 509: Mechanical tests – Tests for resistance of insulations and sheaths to cracking (heat shock test)*

IEC 60811-605, *Electric and optical fibre cables – Test methods for non-metallic materials – Part 605: Physical tests – Measurement of carbon black and/or mineral filler in polyethylene compounds*

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

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1 Definitions of dimensional values (thicknesses, cross-sections, etc.)

3.1.1

nominal value

value by which a quantity is designated and which is often used in tables

Note 1 to entry: In this document, nominal values usually give rise to values to be checked by measurements, taking into account specified tolerances.

3.1.2

median value

middle value if the number of available values is odd, and mean of the two middle values if the number is even, when several test results have been obtained and ordered in an increasing (or decreasing) succession

3.2 Definitions concerning tests

3.2.1

routine test

test made by the manufacturer on each manufactured cable system component to check that the component meets the specified requirements

3.2.2

sample test

test made by the manufacturer on samples of complete cable, or components taken from a complete cable or accessory, at a specified frequency, so as to verify that the finished product meets the specified requirements

3.2.3

type test

test made before supplying, on a general commercial basis, a type of cable system covered by IEC 63075, in order to demonstrate satisfactory performance characteristics to meet the intended application

Note 1 to entry: Once successfully completed, these tests need not be repeated, unless changes are made in the cable or accessory with respect to materials, manufacturing process, design or design electrical stress levels, which might adversely change the performance characteristics.

3.2.4

prequalification test

test made before supplying, on a general commercial basis, a type of cable system covered by IEC 63075, in order to demonstrate satisfactory long-term performance of the complete cable system

3.2.4

extension of prequalification test

test made before supplying, on a general commercial basis, a type of cable system covered by IEC 63075, in order to demonstrate satisfactory long-term performance of the complete cable system, taking into account an already prequalified cable system

3.2.5

test after installation

test made to demonstrate the integrity of the cable system as installed

3.3 Other definitions (general design and cryogenic system)

3.3.1

cable system

cable with installed terminations and/or joints

3.3.2

nominal electrical stress

electrical stress calculated at U_0 using nominal dimensions

3.3.3

high-temperature superconductor

HTS

class of superconductors with a critical temperature generally higher than about 25 K

[SOURCE: IEC 60050-815:2015, 815-11-11] [7]

3.3.4

HTS cable

cable comprising one or more phase conductors consisting of HTS material and a cryostat

Note 1 to entry: An HTS cable can be a single-core, a three-core and a three-phase concentric cable, all within a common cryostat.

3.3.5

cold dielectric

dielectric material which operates within a cryogenic environment

3.3.6**HTS cable core**

either one or three concentrically arranged phase conductors consisting of HTS material with cold dielectric insulation and a screen

Note 1 to entry: A screen consists of metal or HTS material, or both.

3.3.7**single-core HTS cable**

cable with HTS cable core comprising one phase conductor placed in a cryostat

3.3.8**three-core HTS cable**

cable with three HTS cable cores, each comprising one phase conductor placed in a common cryostat

3.3.9**three-phase concentric HTS cable**

cable with an HTS cable core comprising three concentric phase conductors placed in a cryostat

3.3.10**cryostat**

container that provides the cryogenic environmental conditions to operate a superconducting device

[SOURCE: IEC 60050-815:2015, 815-15-51]

3.3.11**termination**

device fitted to the end of a cable to ensure electrical connection with other parts of the system and to maintain the insulation up to the point of connection

Note 1 to entry: The termination is also an interface between cryogenic temperature and ambient temperature.

Note 2 to entry: The termination could also comprise an interface to the cooling system.

[SOURCE: IEC 60050-461:2008, 461-10-01, modified – The notes to entry have been added.]

3.3.12**joint**

accessory making a connection between two HTS cables to form a continuous electrical circuit and a continuous thermal insulation

Note 1 to entry: The joint could also comprise an interface to the cooling system.

3.3.13**critical current** I_c

maximum direct current that can be regarded as flowing without resistance practically

Note 1 to entry: I_c is a function of magnetic field strength and temperature.

[SOURCE: IEC 60050-815:2015, 815-12-01, modified – "and strain" has been deleted from Note 1 to entry.]

3.3.14**fault current limiting cable**

HTS cable that limits fault currents to acceptable values

3.3.15**AC loss**

power dissipated in an HTS cable core owing to application of a time-varying magnetic field, electric current or voltage

Note 1 to entry: AC loss includes time average hysteresis loss of the HTS material, a coupling current loss and an eddy current loss of the conductor, an eddy current loss of the structural material, and a dielectric loss of the electric insulation.

Note 2 to entry: AC loss customarily also includes the power dissipated in the HTS material owing to application of transient changes in magnetic field or current.

3.3.16**cryogenics**

study of the production and behaviour of materials at temperatures below 120 K

3.3.17**cryogen**

liquid that boils at cryogenic temperatures below 120 K and is used to obtain very low temperatures

Note 1 to entry: The most common cryogen for HTS cables is liquid nitrogen due to its availability, cost and dielectric properties.

3.3.18**cryogenic refrigeration system****cryogenic cooling system**

system that is capable of cooling cryogen at cryogenic temperatures

3.3.19**maximum allowable working pressure**

maximum pressure (gauge) across the entire operating and testing temperature range to which the superconducting cable system may be exposed and operated

Note 1 to entry: The maximum allowable working pressure is referred to for pressure testing.

Note 2 to entry: The maximum allowable working pressure includes pressure variations within the normal operation.

Note 3 to entry: The maximum operating pressure shall be less or equal to the maximum allowable working pressure.

4 Voltage and current designations**4.1 Rated voltages**

In this document, the symbols U_0 , U and U_m are used to designate the rated voltages of cables and accessories, where these symbols have the meanings given in IEC 60183 [9].

4.2 Rated operating current

In this document, the symbol I_r is used to designate the rated operating current of the cable and accessories. The rated operating current is the RMS value of the current that the system shall be able to carry continuously under specified conditions of the cryogen. Preferably, current ratings in accordance with IEC 60059 [10] should be applied.

5 Cable materials

5.1 Cable conductor materials

This document is applicable to cables having a conductor consisting of HTS material. In addition, the cable conductor may comprise metal.

NOTE Commonly used HTS materials for the cable conductor are copper-oxide superconductors (see IEC 60050-815:2015, 815-11-08) in the form of tapes.

5.2 Cable insulating materials (dielectric insulation)

This document is applicable to cables having a cold dielectric consisting of lapped insulating tapes impregnated with the cryogen.

NOTE 1 Commonly used insulating tapes are kraft paper, polypropylene laminated paper, etc.

NOTE 2 Commonly used cryogen is liquid nitrogen.

5.3 Cable screen materials

This document is applicable to cables having a screen consisting of either HTS material or metal or a combination of both.

NOTE Commonly used HTS materials for the cable screen are copper-oxide superconductors (see IEC 60050-815:2015, 815-11-08) in the form of tapes.

5.4 Cable cryostat materials (thermal insulation)

This document is applicable to cables having a cryostat consisting of an inner envelope at cryogenic temperature and an outer envelope at ambient temperature with a thermal insulation in between.

NOTE The cable cryostat generally consists of an inner and outer tube made of stainless steel or aluminium alloys with a vacuum insulation in between.

5.5 Cable oversheathing materials (outside cryostat)

The oversheath is optional.

If an oversheath is required (e.g. using the cryostat as metal screen), it shall be tested.

Tests are specified for the following types of oversheath:

- ST₁ and ST₂ based on polyvinyl chloride (PVC);
- ST₃ and ST₇ based on polyethylene (PE).

The choice of the type of oversheath will depend on the design of the cable and on the mechanical, thermal and fire constraints during installation and operation.

6 Cable characteristics

For the purposes of carrying out the cable system tests described in this document and recording the results, the cable shall be identified. The following characteristics shall be known or declared:

- a) name of manufacturer, type, designation and manufacturing date or date code;
- b) rated voltage: values shall be given for U_0 , U , U_m (see 4.1 and 8.4);
- c) rated operating current: value shall be given for I_r ;
- d) maximum and minimum operating temperature of cryogen shall be given;

- e) maximum and minimum operating pressure of cryogen shall be given;
- f) maximum allowable working pressure of the system shall be given;
- g) type of HTS material, number of HTS tapes in each phase conductor, if applicable nominal cross-section and type of metal conductor in each phase conductor, design critical current of each phase conductor at 77,3 K and function of its temperature dependency;
- h) material and minimum thickness of insulation (t_{\min}) (see 5.2);
- i) type of cryogen;
- j) if applicable, type of HTS material, number of HTS tapes in cable screen and/or nominal cross-section and type of metal conductor in cable screen, design critical current of screen conductor at 77,3 K and function of its temperature dependency;
- k) nominal diameter of the cable core (d);
- l) nominal inner diameter of the cable cryostat (D_i);
- m) material and type of cryostat and type of thermal insulation;
- n) if applicable, material and nominal thickness of oversheath;
- o) nominal overall diameter of the cable (D) (outside the cryostat or oversheath);
- p) nominal inner diameter (d_{ii}) and calculated minimum outer diameter (D_{io}) of the insulation;
- q) minimum bend diameter;
- r) nominal capacitance, corrected to 1 km length, and loss angle ($\tan \delta$) between conductor screen and insulation screen for each dielectric in the cable core;
- s) calculated maximum electrical stress at conductor screen (E_i) and at insulation screen (E_o):

$$E_i = \frac{2U_t}{d_{ii} \times \ln(D_{io} / d_{ii})} \quad (1)$$

$$E_o = \frac{2U_t}{D_{io} \times \ln(D_{io} / d_{ii})} \quad (2)$$

where

$U_t = U_0$ for single core, three core and the outer phase of three phase concentric cables;

$U_t = U$ for the inner and middle phase of three phase concentric cables;

$D_{io} = d_{ii} + 2t_{\min}$;

d_{ii} is the declared nominal inner diameter of the insulation;

D_{io} is the calculated minimum outer diameter of the insulation;

t_{\min} is the declared minimum insulation thickness.

The values of U_0 and of U are given in Table 1.

7 Accessory characteristics

For the purposes of carrying out the cable system or accessory tests described in this document and recording the results, the accessory shall be identified.

The following characteristics shall be known or declared:

- a) cables used for testing accessories shall be correctly identified, as in Clause 6;
- b) accessories to be tested shall be correctly identified with respect to
 - name of manufacturer,

- type, designation and manufacturing date or date code,
- rated voltage values U_0 , U , U_m (see 4.1 and 8.4),
- rated operating current I_r ,
- maximum and minimum operating temperature for cryogen,
- maximum and minimum operating pressure for cryogen,
- overview drawing with overall dimensions and weight,
- installation instructions (reference and date),
- detailed drawings (reference and date).

8 Test conditions

8.1 Ambient temperature

Unless otherwise specified in the details for the particular test, tests shall be carried out at an ambient temperature of $(20 \pm 15) ^\circ\text{C}$.

8.2 Frequency and waveform of power frequency test voltages

Unless otherwise indicated in this document, the frequency of the alternating test voltages shall be in the range 49 Hz to 61 Hz. The waveform shall be substantially sinusoidal. The values quoted are RMS values.

8.3 Wave form of impulse test voltages

8.3.1 Lightning impulse voltage

In accordance with IEC 60230, the front time of the standard lightning impulse voltage shall be between $1 \mu\text{s}$ and $5 \mu\text{s}$. The time to half value shall be $50 \mu\text{s} \pm 10 \mu\text{s}$ as specified in IEC 60060-1.

8.3.2 Switching impulse voltage

In accordance with IEC 60060-1, the standard switching impulse voltage shall have a time to peak of $250 \mu\text{s} \pm 50 \mu\text{s}$ and a time to half value of $2\,500 \mu\text{s} \pm 1\,500 \mu\text{s}$.

8.4 Relationship of test voltages to rated voltages

Where test voltages are specified in this document as multiples of the rated voltage U_0 , the value of U_0 for the determination of the test voltages shall be as specified in Table 1.

For cables and accessories of rated voltage not shown in the table, the value of U_0 for the determination of test voltages may be the same as for the nearest rated voltage which is given, provided that the value of U_m for the cable and accessory is not higher than the corresponding value in the table. Otherwise, and particularly if the rated voltage is not close to one of the values in the table, the value of U_0 on which the test voltages are based shall be the rated value, i.e. U divided by $\sqrt{3}$.

The test voltages in this document are based on the assumption that the cables and accessories are used on systems of category A or B, as defined in IEC 60183 [9].

For rated voltages up to $U = 30 \text{ kV}$ under category B, a longer period, not exceeding 8 h on any occasion, can be tolerated. The total duration of earth faults in any year should not exceed 125 h.

8.5 Cryogen temperature and pressure

Unless otherwise specified in the details for the particular test, tests shall be carried out at the specified minimum pressure and maximum temperature in accordance with Clause 6.

9 Routine tests on cables and on prefabricated accessories

9.1 General

9.1.1 Tests on cable core samples

The tests specified in 9.2 to 9.3 shall be carried out on cable samples cut from the finished cable core lengths at the factory. For each test, a separate sample might be used.

- a) AC voltage test for cable followed by partial discharge test (see 9.2);
- b) critical current measurement (see 9.3).

The order in which these tests are carried out is at the discretion of the manufacturer.

NOTE At the current time, there is no accepted methodology to allow factory testing of full cable lengths after manufacturing. Sample testing is performed at various stages during the manufacturing processes and after completion. However, it is impractical to perform AC voltage tests and critical current measurements on full cable lengths. The need to cool the cable to cryogenic temperature and impregnate the dielectric tapes with cryogen makes tests on full reels of finished cable impractical. Further, in some cases, the cable reel at the factory does not include the cryostat. In all cases, the thermal contraction of the cable while on the reel would present extreme difficulties. Practical methodologies to enable factory testing of full cable lengths, similar to conventional cables, are likely to be developed in the future.

For quality control purposes, it is recommended to implement continuous thickness monitoring, or at least periodical thickness measurements, during manufacturing of full cable lengths. This monitoring should ensure that the declared minimum insulation thickness is achieved along the complete cable lengths.

9.1.2 Tests on cable cryostat

The tests specified in 9.4 to 9.5 shall be carried out on all finished cable cryostat lengths at the factory.

- a) pressure test (see 9.4);
- b) vacuum leak test (see 9.5);
- c) electrical test on oversheath of the cable, if required (see 9.6).

The pressure test shall be performed before the vacuum leak test. Alternatively, the vacuum leak test can be performed at the same time as the pressure test. The electrical test on the oversheath can be carried out before or after the pressure test.

9.1.3 Tests on prefabricated accessories

The tests specified in 9.4 to 9.5 shall be carried out on all prefabricated accessories at the factory.

- a) AC voltage test for accessory followed by partial discharge test (see 9.7.1);
- b) pressure test (see 9.7.2);
- c) vacuum leak test (see 9.7.2).

The pressure test shall be performed before the vacuum leak test. Alternatively, the vacuum leak test can be performed at the same time as the pressure test. The AC voltage test can be carried out before or after the pressure test.

9.2 AC voltage test for cable followed by partial discharge test

9.2.1 General

The test shall be performed on cable core samples with a minimum active length of 1 m using alternating voltage at power frequency. The test cable core shall be immersed in the cryogen in accordance with Clause 6. The maximum temperature of the cryogen shall be greater than or equal to the maximum operating temperature and its minimum pressure shall be less than or equal to the minimum operating pressure.

One sample from each shipping reel shall be taken and subjected to the voltage test. If the length of the cable core on the shipping reels exceeds 1 000 m, one sample from each end of the reel shall be tested. Each dielectric in the cable shall be subjected to the electric tests.

9.2.2 Procedure

The test voltage shall be raised gradually to the specified value, which shall then be held for 30 min between the conductors adjacent to the dielectric in accordance with Table 1.

The voltage shall be gradually increased for the voltage test and then decreased after completion of the voltage test to the partial discharge measurement voltage in accordance with Table 1.

The partial discharge test shall be carried out in accordance with IEC 60885-3 for cables with a sensitivity of 5 pC or better.

9.2.3 Requirement

No breakdown of the insulation at test voltage shall occur and no detectable partial discharge shall occur.

If the sample from any length selected for the tests fails, an investigation of the cause for failure shall be undertaken. If agreed between the customer and manufacturer to proceed with routine testing, two further samples shall be taken from either side of the same reel and the test shall be repeated. If both additional samples pass the tests, the reel from which they were taken shall be regarded as having complied with the requirements of this document. If either fails, this reel shall be regarded as having failed to comply.

9.3 Critical current measurement

9.3.1 General

The critical current of each cable conductor containing HTS material shall be measured and recorded. The critical current measurement shall be performed on a cable core sample with a minimum length of 1 m between the voltage taps excluding the contacts. The test cable core shall be immersed in the cryogen in accordance with Clause 6.

One sample from each shipping reel shall be taken and subjected to the test. If the length of the cable core on the shipping reels exceeds 1 000 m, one sample from each end of the reel shall be tested.

The cryogen temperature (T_m) shall be recorded. In the case of cryogen circulation, the temperature (T_m) at the measurement is defined as the average between the inlet and outlet temperatures.

9.3.2 Procedure

The critical current shall be measured by the procedure in accordance with Annex B.

9.3.3 Requirement

The measured critical current shall be equal or higher than the design critical current given in Clause 6 determined at temperature T_m .

9.4 Pressure test

9.4.1 General

A pressure test shall be performed as a routine factory test on each cable cryostat length.

9.4.2 Procedure

The test shall be carried out with a pneumatic pressure equal to 1,1 times the maximum allowable working pressure as given in Clause 6 at room temperature. The pressure shall be gradually increased in steps until the test pressure is reached, holding the pressure at each step long enough to equalize piping strain. When the test pressure is reached, the pressure source shall be disconnected from the test object.

NOTE Local regulations might require the pressure test to be performed with a higher pressure.

9.4.3 Requirement

After 10 min, the pressure in the test object shall not be less than the test pressure.

9.5 Vacuum leak test

9.5.1 General

The vacuum leak test of the vacuum insulation space at ambient temperature shall be carried out for all finished cable cryostat lengths where the vacuum seal is made at the factory.

9.5.2 Procedure

The test object shall be evacuated by a vacuum pump system. The leak rate of tracer gas to the vacuum area through the outer and inner wall shall be detected by a helium leak detector (mass spectrometer). In case more than one leak detector is connected to the same vacuum space, the leak rate is the sum of all individual leaks measured.

9.5.3 Requirement

The determined leak rate shall not be higher than 5×10^{-9} Pa m³/s (5×10^{-8} mbar·l/s).

9.6 Electrical test on oversheath of the cable

When the test is required by the particular contract, the cable oversheath shall be subjected to the electrical test specified in IEC 60229:2007, Clause 3.

9.7 Tests on prefabricated accessories

9.7.1 Voltage test followed by partial discharge test

The main insulation of prefabricated accessories shall undergo the voltage routine test followed by the partial discharge test and in accordance with 1), 2) or 3) below:

- 1) on the main insulation of prefabricated accessories installed on the cable;
- 2) by using a host accessory into which a component of an accessory is substituted for the test;
- 3) by using a simulated accessory rig in which the electrical stress environment of a main insulation component is reproduced.

In cases 2) and 3), the test voltage shall be selected so as to obtain stresses at least the same as those on the component in a complete accessory when subjected to the test voltages specified in 9.2.

The procedure and requirements of 9.2.2 and 9.2.3 apply.

NOTE The main insulation of prefabricated accessories consists of the components that come in direct contact with the cable insulation and which are necessary to control the electrical field distribution in the accessory. Examples are premoulded or precast elastomer or filled epoxy resin insulating components that can be used singly or jointly to provide the necessary insulation or screening of accessories.

9.7.2 Pressure test and vacuum leak test

The tests specified in 9.4 and 9.5 shall be carried out on all finished vacuum insulated components or pressure containment components of the prefabricated accessories finished at the factory. If safety valves or burst discs with an opening pressure at room temperature less than the test pressure are foreseen, the devices may be replaced by a blind flange.

Those sections which will be assembled on site and pumped for vacuum on site shall not be subjected to the routine test.

10 Sample tests on cables

10.1 General

The following tests shall be carried out on samples taken to represent batches:

- a) conductor examination (see 10.4);
- b) measurement of thickness of insulation (see 10.5)
- c) measurement of thickness of oversheath, if required (see 10.6);
- d) measurement of diameters, if required (see 10.7);
- e) measurement of capacitance (see 10.8);
- f) lightning impulse voltage test (see 10.9).

10.2 Frequency of tests

The sample tests in items a) to e) of 10.1 shall be carried out on one length from each batch (manufacturing series) of the same type and cross-section of cable, but shall be limited to not more than 10 % of the number of lengths in any contract, rounded to the nearest whole number.

The frequency of the test in item f) of 10.1 shall be in accordance with agreed quality control procedures. In the absence of such an agreement, one test shall be made for contracts with a cable length between 4 km and 20 km and two tests for contracts with longer cable lengths.

10.3 Repetition of tests

If the sample from any length selected for the tests fails in any of the tests in Clause 10, further samples shall be taken from two further lengths of the same batch and subjected to the same tests as those in which the original sample failed. If both additional samples pass the tests, the other cables in the batch from which they were taken shall be regarded as having complied with the requirements of this document. If either fails, this batch of cables shall be regarded as having failed to comply.

10.4 Conductor examination

Compliance with the declared construction given in Clause 6 shall be checked by inspection and measurement when practicable.

10.5 Measurement of thickness of cable insulation

10.5.1 General

Each cable length selected for the test shall be represented by a piece taken from one end after having discarded, if necessary, any portion that may have suffered damage.

10.5.2 Procedure

The thickness of the insulation shall be determined on a sample according to the diameter tape method in dry conditions. The sample shall be dismantled until the dielectric is available with dielectric screening tapes removed. The diameters in this state shall be measured by means of a diameter measuring tape at 50 mm and 100 mm from the end of the piece of core. The diameter shall be measured with an accuracy of $\pm 0,1$ mm. The insulation shall then be removed to reveal the conductor screen and the diameters over the conductor screen are then measured with the diameter measuring tape. The insulation thickness at each point of measurement shall be calculated by halving the difference of the two diameters measured at that position.

10.5.3 Requirement

The calculated insulation thickness at each point of measurement shall not fall below the specified minimum insulation thickness.

10.6 Measurement of thickness of oversheath

10.6.1 General

The oversheath is optional and shall only be tested if it is required.

The test method for determining the thickness of the oversheath shall be in accordance with IEC 60811-202.

Each cable length selected for the test shall be represented by a piece taken from one end after having discarded, if necessary, any portion that may have suffered damage.

10.6.2 Requirement

The minimum measured thickness shall not fall below 85 % of the nominal thickness by more than 0,1 mm:

$$t_{\min} \geq 0,85 t_n - 0,1$$

where

t_{\min} is the minimum measured thickness, in millimetres;

t_n is the nominal thickness, in millimetres.

10.7 Measurement of diameters

If the purchaser requires that the diameter of the cable core and/or the overall diameter of the cable shall be measured, the measurements shall be carried out in accordance with IEC 60811-203.

10.8 Measurement of capacitance

The capacitance shall be measured between the conductor screen and the insulation screen for all dielectrics in the cable core. The test cable core shall be immersed in the cryogen in accordance with Clause 6 and the cryogen temperature shall be recorded with the test data.

The measured value of the capacitance shall be corrected to a 1 km length and shall not exceed the declared nominal value by more than 8 %.

10.9 Lightning impulse voltage test

The test shall be performed on a cable core sample with a minimum active length of 5 m. The test cable core shall be immersed in the cryogen in accordance with Clause 6. The maximum temperature of the cryogen shall be greater than or equal to the maximum operating temperature and its minimum pressure shall be less than or equal to the minimum operating pressure.

The impulse voltage shall be applied in accordance with the procedure given in IEC 60230.

The cable shall withstand without failure 10 positive and 10 negative voltage impulses of the appropriate value given in Table 1, column 8.

No breakdown of the insulation shall occur.

11 Sample tests on accessories

11.1 Tests on components

The characteristics of each component shall be verified in accordance with the specifications of the accessories manufacturer, either through test reports from the supplier of a given component or through internal tests.

The manufacturer of a given accessory shall provide a list of the tests to be performed on each component, indicating the frequency of each test.

The components shall be inspected against their drawings. There shall be no deviation outside the declared tolerances.

NOTE As components differ from one supplier to another, it is not possible to define common sample tests on components in this document.

11.2 Tests on complete accessory

For accessories where the main insulation cannot be routine tested (see 9.1), the following electrical tests shall be carried out by the manufacturer on a fully assembled accessory:

- a) AC voltage test followed by partial discharge test (see 9.7.1);
- b) vacuum leak test (see 9.7.2);
- c) pressure test (see 9.7.2).

The pressure test shall be performed before the vacuum leak test. Alternatively, the vacuum leak test can be performed at the same time as the pressure test. The AC voltage test can be carried out before or after the pressure test.

These tests shall be performed on one accessory of each type per contract if the number of that type in the contract is above 50.

If the sample fails any of the above tests, two further samples of the same accessory type from the contract shall be taken and subjected to the same tests. If both additional samples pass the tests, the other accessories of the same type from the contract shall be regarded as having complied with the requirements of this document. If either fails, this type of accessory of the contract shall be regarded as having failed to comply.

12 Type tests on cable systems

12.1 General

The tests specified in Clause 12 are intended to demonstrate the satisfactory performance of cable systems.

A table of the subclause references to be considered during a type test on a cable system is given in Annex D.

NOTE 1 Tests on terminations referring to environmental conditions are not specified in this document.

NOTE 2 Tests on cooling systems are not considered in this document.

12.2 Range of type approval

When type tests have been successfully performed on one or more cable system(s) of specific rated current, and of the same rated voltage and construction, the type approval shall be considered as valid for cable systems within the scope of this document with other rated currents, rated voltages and constructions provided that all the conditions of a) to f) are met:

- a) the voltage group is not higher than that of the tested cable system(s);

NOTE In this context, cable systems of the same rated voltage group are those of rated voltages having a common value of U_m , the highest voltage for equipment, and the same test voltage levels (see Table 1, columns 1 and 2).

- b) the rated current is not larger than that of the tested cable;
c) the cable and the accessories have the same or a similar construction as that of the tested cable system(s);

Cables and accessories of similar construction are those of the same type and manufacturing process of insulation and semi-conducting screens. Repetition of the electrical type tests is not necessary on account of the differences in the conductor or connector type or material or of the protective layers applied over the screened cores or over the main insulation part of the accessory, unless these are likely to have a significant effect on the results of the test. In some instances, it may be appropriate to repeat one or more of the type tests (e.g. bending test, load cycle voltage test and/or compatibility test).

- d) the calculated nominal electrical stress and the impulse voltage stress calculated using nominal dimensions at the cable conductor screen, for all dielectrics in the cable core, do not exceed the respective calculated stresses of the tested cable system(s) by more than 10 %;
e) the calculated nominal electrical stress at the cable insulation screen, for all dielectrics in the cable core, and the impulse voltage stress calculated using nominal dimensions do not exceed the respective calculated stresses of the tested cable system(s);
f) the calculated nominal electrical stresses and the impulse voltage stresses calculated using nominal dimensions within the main insulation parts of the accessory and at the cable and accessory interfaces do not exceed the respective calculated stresses of the tested cable system(s).

The type tests on cable components (see 12.5) do not need to be carried out on samples from cables of different voltage ratings and/or current ratings unless different materials and/or different manufacturing processes are used to produce them.

A type test certificate signed by the representative of a competent witnessing body, or a report by the manufacturer giving the test results and signed by the appropriate qualified officer, or a type test certificate issued by an independent test laboratory shall be acceptable as evidence of type testing.

12.3 Summary of type tests

The type tests shall comprise the electrical tests on the complete cable system as specified in 12.4 and the appropriate non-electrical tests on cable components and complete cable as specified in 12.5.

NOTE For further tests only for engineering purposes, including short circuit considerations, refer to Annex C.

The non-electrical tests on cable components and complete cable are listed in Table 2, indicating which tests are applicable to each oversheath material. The test under fire conditions is only required if the manufacturer wishes to claim compliance with this test as a special feature of the design of the cable.

The tests listed in 12.4.2 shall be performed on one or more samples of complete cable, depending on the number of accessories involved, at least 10 m in length excluding the accessories.

The minimum length of free cable core between accessories shall be 5 m.

The accessories shall be installed after the bending test on the cable. One sample of each accessory type shall be tested.

Cable and accessories shall be assembled in the manner specified by the manufacturer's instructions, with the grade and quantity of materials supplied, including lubricants, if any.

The external surface of accessories shall be dry and clean, but neither the cables nor the accessories shall be subjected to any form of conditioning not specified in the manufacturer's instructions that might modify the electrical, thermal or mechanical performance.

During tests c) to j) of 12.4.2, it is necessary to test joints with their outer protection fitted. If it can be shown that the outer protection does not influence the performance of the joint insulation, for example there are no thermo-mechanical or compatibility effects, the protection need not be fitted.

12.4 Electrical type tests on complete cable systems

12.4.1 Test voltage values

Prior to the electrical type tests, the insulation thickness shall be determined on a sample cut from the cable core by the method specified in 10.5.2. The larger of the two determined values shall be considered

If the thickness of the insulation does not exceed the minimum value by more than 5 %, the test voltages shall be the values specified in Table 1 for the rated voltage of the cable.

If the thickness of the insulation exceeds the minimum value by more than 5 % but by not more than 15 %, the test voltage shall be adjusted to give an electrical stress at the conductor screen equal to that applying when the thickness of the insulation is equal to the minimum value, and the test voltages are the normal values specified for the rated voltage of the cable.

The cable length used for the electrical type tests shall not have an insulation thickness exceeding the minimum value by more than 15 %.

12.4.2 Tests and sequence of tests

The tests in items a) to j) shall be carried out in the following sequence:

- a) bending test on the cable core (see 12.4.3) followed by installation of accessories;
- b) critical current measurement test on cable sample (see 12.4.4);

This test may alternatively be carried out on the complete assembly at any step of the sequence.

- c) pressure test (see 12.4.5);

This test may be carried out during the installation of the accessories.

- d) thermal cycle test (see 12.4.6);
e) partial discharge test (see 12.4.7);
f) $\tan \delta$ measurement (see 12.4.8);
g) load cycle voltage test (see 12.4.9);
h) switching impulse voltage test (required for $U_m \geq 300$ kV, see 12.4.10.1);
i) lightning impulse voltage test followed by a power frequency voltage test (see 12.4.10.2);
j) partial discharge test (see 12.4.7);
k) tests of outer protection for joints, if required (see Annex E);

These tests may be applied to a joint that has passed the previous tests or to a separate joint which has not been part of the assembly.

- l) examination of the cable system with cable and accessories on completion of the above tests (see 12.4.11).

Test voltages shall be in accordance with the values given in the appropriate column of Table 1.

For the tests e) to j) the assembly shall be filled with the cryogen in accordance with Clause 6. The maximum temperature of the cryogen shall be greater than or equal to the maximum operating temperature and its minimum pressure shall be less than or equal to the minimum operating pressure.

12.4.3 Bending test

The cable core shall be bent around a test cylinder (for example, the hub of a drum) at ambient temperature for at least one complete turn and unwound, without axial rotation. The sample shall then be rotated through 180° and the process repeated.

This cycle of operations shall be carried out three times in total.

The diameter of the test cylinder shall not be greater than the minimum bend diameter specified in Clause 6.

The cable core shall be bent inside a cryostat or corrugated tube of approximate dimensions as the cable cryostat to impose the surface features of the cryostat upon the subject cable under test, as would be the case during installation.

After the bending test, the cable core is cut into sections that are connected to the accessories.

12.4.4 Critical current measurement

The critical current measurement shall be performed as described in 9.3 on a cable core sample cut from the test cable core after the bending test.

12.4.5 Pressure test

The pressure test of the assembly shall be performed as described in 9.4. If safety valves or burst discs with an opening pressure at room temperature less than test pressure are foreseen, the devices may be replaced by blind flanges.

12.4.6 Thermal cycle test

The assembly shall be subjected to a thermal cycle test consisting of five cycles.

Each thermal cycle shall consist of cooling down the assembly from ambient temperature to operating temperature with stable operating conditions of the cryogen in accordance with the parameters specified in Clause 6, followed by warming up the assembly to ambient temperature.

After the thermal cycle test, the assembly shall be cooled down from ambient temperature to operating temperature with stable operating conditions of the cryogen in accordance with the parameters specified in Clause 6.

12.4.7 Partial discharge test

The test shall be performed in accordance with IEC 60885-3, the sensitivity being 5 pC or better.

For cable systems with $U_0 \leq 18$ kV, the test voltage shall be raised gradually to and held at $2 U_0$ for 10 s and then slowly reduced to $1,73 U_0$ (see Table 1, column 5).

For cable systems with $U_0 > 18$ kV, the test voltage shall be raised gradually to and held at $1,75 U_0$ for 10 s and then slowly reduced to $1,5 U_0$ (see Table 1, column 5).

There shall be no detectable discharge exceeding the declared sensitivity from the test object at $1,73 U_0$ for cable systems with $U_0 \leq 18$ kV and at $1,5 U_0$ for cable systems with $U_0 > 18$ kV.

12.4.8 Tan δ measurement

The tan δ shall be measured at a power frequency voltage of U_0 (see Table 1, column 6).

The measured value shall not exceed the declared value given in Clause 6.

12.4.9 Load cycle voltage test

The assembly shall be subjected to a load cycle voltage test consisting of 20 cycles.

Each load cycle shall consist of at least 8 h with rated operating current as specified in Clause 6 followed by at least 16 h without current in the phase conductor. For single-core and three-core cable systems, the current in the screen conductor shall exhibit a phase difference of about 180° with respect to the phase conductor current. The absolute value of the screen conductor current shall be equal to the absolute value of the phase conductor current ± 10 %. For three-phase concentric cable systems, the phase conductor currents shall exhibit a phase difference of about 120° .

During the whole of the test period, a voltage of $2 U_0$ shall be applied to the assembly (see Table 1, column 7).

Interruption of the test is allowed, provided 20 complete load cycles in total under voltage are completed.

12.4.10 Impulse voltage tests

12.4.10.1 Switching impulse voltage test

A switching impulse voltage test shall be carried out on the assembly for systems, cables and accessories of voltage $U_m \geq 300$ kV.

The impulse voltage shall be applied in accordance with the procedure given in IEC 60230 with document switching impulse withstand voltage levels in accordance with Table 1, column 10.

The assembly shall withstand without failure or flashover 10 positive and 10 negative voltage impulses.

12.4.10.2 Lightning impulse voltage test followed by a power frequency voltage test

The lightning impulse voltage shall be applied in accordance with the procedure given in IEC 60230.

The assembly shall withstand without failure or flashover 10 positive and 10 negative voltage impulses of the appropriate value given in Table 1, column 8.

After the lightning impulse voltage test, the assembly shall be subjected to a power frequency voltage test for 30 min at $2,5 U_0$ for cable systems with $U_0 \leq 18$ kV and at $2 U_0$ for cable systems with $U_0 > 18$ kV (see Table 1, column 9).

No breakdown of the insulation or flashover shall occur.

12.4.11 Examination of cable and accessories

12.4.11.1 General

Examination of the cable by dissection of a sample and, whenever possible, of the accessories by dismantling, with normal or corrected vision without magnification, shall reveal no signs of deterioration (e.g. electrical degradation, leakage, corrosion or harmful shrinkage) which could affect the system in service operation.

12.4.11.2 Examination of cable insulation

A 300 mm long sample shall be cut from the central part of the cable. Each insulation and semiconducting screen shall be dissected. In the case of single core or three-phase concentric cable, one test piece will be obtained, or three test pieces in the case of a three-core cable.

The insulation, including semiconducting screens, shall be removed by taking off a small number of tapes at a time, and the tapes examined for tears and gaps. The following requirements shall be met:

- a) the number of tapes which, in the 300 mm length, contain longitudinal or edge tears exceeding 40 % of the respective tape width shall not be more than two per core, and
- b) at no point throughout the insulation and semiconducting screens shall there be more than either:
 - 1) two coincidental tears of any length in adjacent tapes, or
 - 2) two coincidental gaps of any length in adjacent tapes, except that the maximum permissible number of said gaps is three, if these coincide with the reversal of the direction of the lay.

12.5 Non-electrical type tests on cable components and on complete cable

12.5.1 Overview on non-electrical type tests

The tests are as follows:

- a) check of cable construction (see 12.5.2);
- b) tests for determining the mechanical properties of oversheaths before and after ageing (see 12.5.3);

- c) loss of mass test on PVC oversheaths of type ST₂ (see 12.5.4);
- d) tests on PVC oversheaths (ST₁ and ST₂) at low temperature (see 12.5.5);
- e) heat shock test for PVC oversheaths (ST₁ and ST₂) (see 12.5.6);
- f) measurement of carbon black content of black PE oversheaths (ST₃ and ST₇, see 12.5.7);
- g) test under fire conditions (see 12.5.8);
- h) pressure test of cable cryostat (see 12.5.9);
- i) pressure test of components of accessories (see 12.5.10).

12.5.2 Check of cable construction

The examination of the conductor and measurements of insulation and oversheath thicknesses shall be carried out in accordance with and shall comply with the requirements given in 10.4, 10.5 and 10.6.

12.5.3 Tests for determining the mechanical properties of oversheaths before and after ageing

12.5.3.1 Sampling

Sampling and preparation of test pieces shall be carried out as described in IEC 60811-501.

12.5.3.2 Ageing treatment

The ageing treatment shall be carried out as described in IEC 60811-401, under the conditions given in Table 3.

12.5.3.3 Conditioning and mechanical tests

Conditioning and the measurement of mechanical properties shall be carried out as described in IEC 60811-501.

12.5.3.4 Requirements

The test results for unaged and aged test pieces shall comply with the requirements given in Table 3.

12.5.4 Loss of mass test on PVC oversheaths of type ST₂

12.5.4.1 Procedure

The loss of mass test for ST₂ oversheaths shall be carried out as described in IEC 60811-409 under the conditions given in Table 4.

12.5.4.2 Requirements

The results shall comply with the requirements given in Table 4.

12.5.5 Test on PVC oversheaths (ST₁ and ST₂) at low temperature

12.5.5.1 Procedure

The test at low temperature for ST₁ and ST₂ oversheaths shall be carried out as described in IEC 60811-505 and IEC 60811-506, employing the test temperature specified in Table 4.

12.5.5.2 Requirements

The results of the test shall comply with the requirements given in IEC 60811-505 and IEC 60811-506.

12.5.6 Heat shock test for PVC oversheaths (ST₁ and ST₂)

12.5.6.1 Procedure

The heat shock test on ST₁ and ST₂ oversheaths shall be carried out as described in IEC 60811-509, the test temperature and duration being in accordance with Table 4.

12.5.6.2 Requirements

The results of the test shall comply with the requirements given in IEC 60811-509.

12.5.7 Measurement of carbon black content of black PE oversheaths (ST₃ and ST₇)

12.5.7.1 Procedure

The carbon black content of ST₃ and ST₇ oversheaths shall be measured using the sampling and test procedure described in IEC 60811-605.

12.5.7.2 Requirements

The nominal value of the carbon black content shall be $(2,5 \pm 0,5) \%$.

Lower values are allowed for special applications not exposed to UV.

12.5.8 Test under fire conditions

12.5.8.1 Procedure

The test under fire conditions in accordance with IEC 60332-1-2 shall be carried out on a sample of the cable cryostat outer tube with the oversheath, if the manufacturer wishes to claim that the particular design of cable complies with the requirements.

12.5.8.2 Requirements

The results shall comply with the requirements given in IEC 60332-1-2.

12.5.9 Pressure test of cable cryostat

12.5.9.1 Procedure

A sample of the inner tube of the cable cryostat, which is in direct contact with the cryogen, assembled with at least one cryostat tube end fitting shall be subjected to a pressure test. If different types of inner tubes are foreseen for a contract, one sample of each type shall be subjected to the pressure test. The sample shall have a length of 1 m or 10 times the nominal diameter, whichever is greater. It shall be closed by appropriate fittings and fixed at one end.

For inner tubes of cable cryostats including end fittings, for which the mechanical strength can be calculated with analytical or numerical tools, the pressure test may be substituted by such calculation. In that case, suitable standards for pressure vessels and pressure piping shall be applied.

The assembly shall be hydraulically pressurized to 1,5 times the maximum allowable working pressure (see Clause 6) and the pressure shall be held for 1 min. The pressure shall then be increased gradually with a minimum of 10 increments to four times the maximum allowable working pressure (see Clause 6) and the pressure shall be held at this level for 1 min.

12.5.9.2 Requirements

At the pressure level of four times the maximum allowable working pressure (see Clause 6), the assembly shall not fail by visible leakage or rupture of any of the components. A deformation of metal components shall not be regarded as a failure of the test.

12.5.10 Pressure test of components of accessories

12.5.10.1 Procedure

One type of each prefabricated component of the accessories that is in direct contact with the cryogen and that poses a danger for the environment in the case of a failure shall be subjected to a pressure test. The component shall be closed by appropriate fittings and fixed at one end. Burst discs and safety valves that are included in the accessories are exempt from the pressure test. For the test, different types of individual components may be assembled and tested together.

For accessory components, for which the mechanical strength can be calculated with analytical or numerical tools, the pressure test may be substituted by such calculation. In that case, suitable standards for pressure vessels and pressure piping shall be applied.

The assembly shall be hydraulically pressurized to 1,5 times the maximum allowable working pressure (see Clause 6) and the pressure shall be held for 1 min. The pressure shall then be increased gradually with a minimum of 10 increments to four times the maximum allowable working pressure (see Clause 6) and the pressure shall be held at this level for 1 min.

12.5.10.2 Requirements

At the pressure level of four times the maximum allowable working pressure (see Clause 6), the assembly shall not fail by visible leakage or rupture of any of the components.

13 Prequalification test of the cable system

In the frame of this document, a prequalification test of the cable system shall not be required.

See Annex F.

14 Type test on cables

Cables will be type tested as part of a cable system.

15 Type test on accessories

Accessories will be type tested as part of a cable system.

16 Tests after installation

16.1 General

Tests on new installations shall be carried out when the installation of the cable system has been completed. Such tests are performed in order to verify the cable system integrity after the installation.

Two groups of tests are foreseen, tests of the system at ambient temperature and tests at operating temperature.

16.2 Tests at ambient temperature

16.2.1 Vacuum test

16.2.1.1 Tests on vacuum areas sealed at the factory

The vacuum pressure of areas sealed prior to shipment in the factory shall be measured. The measured value shall be compared to the last value obtained in the factory taking into account temperature effects and usual vacuum level decay effects in warm conditions. The measured value shall be such that the vacuum integrity can be judged as undamaged.

16.2.1.2 Tests on vacuum areas sealed during installation

Vacuum areas sealed during the installation process shall be subjected to a vacuum leak test in accordance with 9.5.

In cases where such a test is not possible on all components owing to the design of the overall system, the vacuum leak tests shall be done on those accessible parts only.

16.2.2 Pressure test

16.2.2.1 Procedure

A pneumatic pressure test shall be performed on the cable system prior to cool down. Any pressure relief devices that obtain their designed properties in cold conditions only shall be removed from the system and the connection area sealed with certified flanges withstanding the test pressure. All such flanges shall be identified in the test protocol.

The system shall be connected to the gas pressure source and all necessary safety measures shall be taken. A pressure gauge shall be connected to the system where it is in safe and readily visible location to the operator.

The cable system and the test medium shall have approximately the same temperature.

The final test pressure shall be 1,1 times the maximum allowable working pressure of the cable system. The system shall be pressurized in steps of approximately 10 % of the test pressure until the final test pressure has been reached. After the second step (at about 20 % of the maximum allowable working pressure) the entire system should be checked using a soap bubble solution as a safety check for leakage. The test pressure shall be held for approximately 2 min after each step. When the maximum test pressure is reached, the pressure should be held for 10 s and then reduced to the maximum allowable working pressure and held for 10 min.

All joints shall be examined for leaks with a soap bubble solution.

The pressure shall be gradually reduced to zero.

16.2.2.2 Requirement

No component of the system shall break or fail during the pressure test. No leaking shall occur on the system components. Leakage of temporary gaskets and seals installed for the purpose of the test may be permitted if the leakage does not exceed the capacity to maintain the system test pressure for the required time.

16.3 Tests at operating temperature

16.3.1 General

For the tests at operating temperature, the cryogen shall have stabilized in the cable system for a sufficient period of time.

16.3.2 DC current test

16.3.2.1 Procedure

A DC current test shall be performed when the cable system is cooled down and the cryogen is within its designed operating conditions regarding temperature and pressure in order to check the integrity of HTS tapes in the cable core. The test shall be performed on all phase conductors and superconducting screen conductors of the cable system. If the superconducting screen conductors of the system are not accessible in the installed system, the manufacturer shall propose suitable test methods in order to ensure the integrity of the superconducting material in the screens.

Preferably two conductors of the cable system shall be tested together in order to provide an easy return path for the current in a long cable system. The system shall be connected to a DC current source which is able to inject a current equal to the amplitude of the rated current (see Clause 6). A DC voltage probe shall be connected at the terminals of the two conductors under test.

The DC current shall be gradually increased in steps of maximum 20 % to $1,41 I_r$. For each step, the current and the measured voltage shall be recorded. At $1,41 I_r$, the current shall be held for 15 min, after which the current shall then be decreased to I_r . At the level of I_r , the current shall be held until the temperatures in the cryogen are stable for at least 1 h.

16.3.2.2 Requirement

The recorded voltage-current dependency up to $1,41 I_r$ shall be substantially linear. During the 1 h stable period at I_r , the variation of the recorded outlet temperature shall be within the same tolerance as the variation of the recorded inlet temperature in the cable system.

16.3.3 AC voltage test of the insulation

16.3.3.1 Procedure

The complete cable system shall be subjected to an AC voltage test. The waveform shall be substantially sinusoidal and the frequency shall be between 20 Hz and 300 Hz. A test voltage in accordance with Table 1, column 11 shall be applied for 1 h.

NOTE 1 As the individual cable lengths are not tested in the factory, special importance is put on the execution of the AC voltage test of the insulation after installation.

For installations which have been in use, lower voltages and/or shorter durations may be used. Values should be negotiated, taking into account the age, environment, history of breakdowns, and the purpose of carrying out the test.

A partial discharge measurement and tan delta measurement can be done for information purposes only.

NOTE 2 For guidance on field considerations in partial discharge measurement methods, refer to IEC TS 62478 [10].

16.3.3.2 Requirement

No breakdown of the insulation or flashover shall occur during the test.

16.3.4 DC voltage test of the overshath**16.3.4.1 General**

The overshath is optional and only shall be tested, if it is required.

16.3.4.2 Procedure

The voltage level and duration specified in IEC 60229:2007, Clause 5 shall be applied between each metal sheath or metal screen and the ground.

For the test to be effective, it is necessary that the ground makes good contact with all of the outer surface of the overshath. A conductive layer on the overshath can assist in this respect.

16.3.4.3 Requirement

No breakdown of the overshath shall occur during the test.

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Table 1 – Test voltages

1	2	3	4 ^{a,b}	5 ^{a,b}	6 ^{a,b}	7 ^{a,b}	8 ^a	9 ^{a,b}	10 ^a	11 ^b
Rated voltage	Highest voltage for equipment	Value of U_0 for determination of test voltages	Voltage test of 9.2	Partial discharge test of 9.2 and 12.4.7	Tan δ measurement of 12.4.8	Load cycle voltage test of 12.4.9	Lightning impulse voltage test of 10.9 and 12.4.10.2	Voltage test after impulse voltage test of 12.4.10.2	Switching impulse voltage test of 12.4.10.1	Voltage test after installation of 16.3.3
U	U_m	U_0	$U_0 \leq 87$ kV: $2,5 U_0$ $U_0 > 87$ kV: $2 U_0$	$U_0 \leq 18$ kV: $1,73 U_0$ $U_0 > 18$ kV: $1,5 U_0$	U_0	$2 U_0$		$U_0 \leq 87$ kV: $2,5 U_0$ $U_0 > 87$ kV: $2 U_0$		$U_0 \leq 87$ kV: $2 U_0$ $U_0 > 87$ kV: $1,7 U_0$
kV	kV	kV	kV	kV	kV	kV	kV	kV	kV	kV
6	7,2	3,6	9	6	3,6	8	60	9	–	8
10	12	6	15	10	6	12	75	15	–	12
15	17,5	8,7	22	15	8,7	18	95	22	–	18
20	24	12	30	21	12	24	125	30	–	24
30	36	18	45	31	18	36	170	45	–	36
45 to 47	52	26	65	39	26	52	250	65	–	52
60 to 69	72,5	36	90	54	36	72	325	90	–	72
110 to 115	123	64	160	96	64	128	550	160	–	128
132 to 138	145	76	190	114	76	152	650	190	–	132
150 to 161	170	87	218	131	87	174	750	218	–	150
220 to 230	245	127	254	190	127	254	1 050	254	–	216
275 to 287	300	160	320	240	160	320	1 050	320	850	272
330 to 345	362	190	380	285	190	380	1 175	380	950	323
380 to 400	420	220	440	330	220	440	1 425	440	1 050	374
500	550	290	580	435	290	580	1 550	580	1 175	493

^a If necessary, these test voltages shall be adjusted as stated in 12.4.1.

^b For the inner and middle dielectric of three-phase concentric HTS cables, these test voltages shall be multiplied by $\sqrt{3}$.

Table 2 – Non-electrical type tests for oversheathing compounds for cables

Designation of compound (see 5.5)	ST ₁	ST ₂	ST ₃	ST ₇
Checks on construction	Applicable irrespective of insulation and oversheathing materials			
Water penetration test ^a				
Mechanical properties (Tensile strength and elongation at break)				
a) without ageing	x	x	x	x
b) after ageing in air oven	x	x	x	x
c) after ageing in air bomb	–	–	–	–
d) after ageing of the complete cable (compatibility test)	x	x	x	x
Pressure test at high temperature	x	x	–	x
Behaviour at low temperature				
a) cold elongation test	x	x	–	–
b) cold impact test	x	x	–	–
Loss of mass in air oven	–	x	–	–
Heat shock test	x	x	–	–
Ozone resistance test	–	–	–	–
Hot set test	–	–	–	–
Measurement of density	–	–	–	–
Carbon black content ^b	–	–	x	x
Key				
x indicates that the type test is to be applied.				
^a To be applied to those designs of cable where the manufacturer claims that barriers to longitudinal water penetration have been included.				
^b For black oversheaths only.				

**Table 3 – Test requirements for mechanical characteristics of
oversheathing compounds for cables
(before and after ageing)**

Designation of compound (see 5.5)	Unit	ST ₁	ST ₂	ST ₃	ST ₇
Without ageing (IEC 60811-501)					
Minimum tensile strength	N/mm ²	12,5	12,5	10,0	12,5
Minimum elongation at break	%	150	150	300	300
After ageing in air oven (IEC 60811-401)					
Treatment: temperature	°C	100	100	100	110
Tolerance	K	± 2	± 2	± 2	± 2
Duration	h	168	168	240	240
Tensile strength:					
a) minimum value after ageing	N/mm ²	12,5	12,5	–	–
b) maximum variation ^a	%	± 25	± 25	–	–
Elongation at break					
a) minimum value after ageing	%	150	150	300	300
b) maximum variation ^a	%	± 25	± 25	–	–
Pressure test at high temperature (IEC 60811-508)					
Test temperature	°C	80	90	–	110
Tolerance	K	± 2	± 2	–	± 2
^a Variation: difference between the median value obtained after ageing and the median value obtained without ageing, expressed as a percentage of the latter.					

**Table 4 – Test requirements for particular characteristics of
PVC oversheathing for cables**

Designation of compound (see 5.5)	Unit	ST ₁	ST ₂
Loss of mass in air oven (IEC 60811-409)			
Treatment: temperature	°C	–	100
tolerance	K	–	±2
duration	h	–	168
Maximum permissible loss of mass	mg/cm ²	–	1,5
Behaviour at low temperature ^a			
Tests to be carried out without previous ageing			
a) Cold elongation test on dumb-bells (IEC 60811-505)			
Test temperature	°C	–15	–15
Tolerance	K	±2	±2
b) Cold impact test (IEC 60811-506)			
Test temperature	°C	–15	–15
Tolerance	K	±2	±2
Heat shock test (IEC 60811-509)			
1) Test temperature	°C	150	150
Tolerance	K	±3	±3
2) Test duration	h	1	1
^a Owing to climatic conditions, national standards may require the use of a lower test temperature.			

Annex A (informative)

Cooling system considerations

A.1 Introductory remarks

Cryogenic refrigeration is a mandatory requirement in order to exploit the advantages of superconducting materials. Superconducting cable systems, as all other superconducting devices, require a cryogenic support system to maintain the appropriate operating conditions on a continuous basis.

Cryogenic technologies are nowadays used in many areas, spanning from R & D laboratories of fundamental physics to food industry, from steel production to oil and gas industry, but despite its wide diffusion, cryogenics is still perceived by many as an "exotic" and "far from daily life" technology.

Annex A is intended as a brief introductory overview and test recommendations for cooling systems for superconducting cable systems. Further, more detailed information can be found in [1].

A.2 Cryogenic refrigeration

A.2.1 General process

Generally speaking, a refrigerator is a machine that removes heat from a source at low temperature (refrigeration temperature), T_c , and rejects it to a source at higher temperature (ambient temperature), T_w . Inside the system, a working fluid undergoes a series of cyclic thermodynamic transformations, called reverse thermodynamic cycle. The working fluid absorbs an amount of heat Q_c at low temperatures and rejects an amount Q_w at higher temperatures.

To accomplish this task, a certain amount of work W should be put into the system, for example by means of an electric motor. Figure A.1 below presents the basic flow scheme of the general refrigerator.

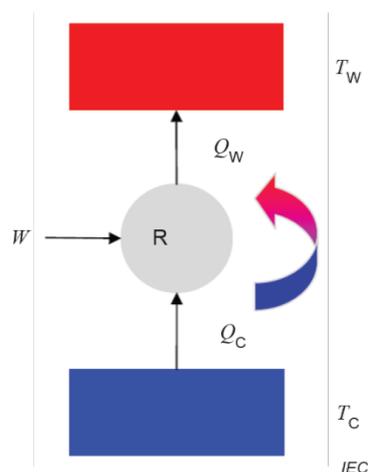


Figure A.1 – General refrigeration process with indication of temperature and energy flows

In steady-state conditions, the following balance equation holds valid:

$$Q_w = Q_c + W$$

The amount of heat removed at low temperatures, Q_c , is commonly referenced in technical literature as refrigeration capacity of the refrigerator.

The efficiency or the energy cost to keep a refrigeration process running is commonly measured with two parameters:

coefficient of performance (COP): Q_c/W
 specific energy consumption (SEC): W/Q_c (inverted COP)

which relates the number of watts required at ambient temperature to provide one watt of refrigeration at the lower operating temperature of the cycle. Both the COP and the SEC are dependent on the effective cycle followed by the fluid. The SEC is also referenced as refrigeration penalty, to better focus on the energetic effort to be spent in order to provide refrigeration at a desired low temperature.

A.2.2 General hardware components

The use of high-temperature superconducting (HTS) materials requires operation of a cable system at very low temperatures, around 77 K or below. This is accomplished by means of a cryogenic system that supplies a flow of sub-cooled liquid cryogen, for example liquid nitrogen (LN_2), through the system. While forced along the HTS system, the refrigerant absorbs the energy dissipated into the circuit and returns it to the cryogenic refrigeration unit, which removes the absorbed heat and cools the liquid to the initial temperature.

Energy loss mechanisms include heat flow from external environment through the cryostat (thermal losses), hydraulic losses of the coolant flow, internally generated heat (AC losses in the superconducting material) and joule losses at the normal conductor/HTS transition points inside terminations at the end of the cables.

Depending on cables' geometry, length, and load current, a refrigeration unit can be installed at one or more locations along the route of the system. Figure C.2 illustrates the general conceptual scheme of a cryogenic refrigeration unit suitable for HTS cable systems with indication of its main components/subsystems.

The first component is the refrigerator. It absorbs electrical power from an external source and produces cold power to remove energy losses from the liquid cryogen flowing along the cables.

The low-temperature heat exchanger is the thermal interface between the refrigerator and the cable system; here, coolant returning from the cables rejects energy losses absorbed along the route into the working fluid of the refrigerator before being fed back again.

The circulation system features one or more cryogenic pumps (redundancy) that provide the necessary pressure head to maintain liquid circulation inside the cables.

The pressure control system provides a buffer volume to limit pressure and coolant volume fluctuations within the cable cooling system during cable load transients. For example, cable short circuits dissipate large amount of energy into the system over a very short duration, creating a near instantaneous increase in temperature (and subsequently of the coolant volume as the cryogen density is temperature-dependent). The rate and magnitude of the temperature variation depends on the nature of the temperature change.

During initial cool-down of the cables, a great amount of cryogen is consumed. The storage tank is a standard commercial cryogenic tank that provides the necessary inventory of cryogen to sustain the process and fill the system.

Another fundamental component, not shown in Figure A.2, is the monitoring and control system. The control system is the "neural system" of the cryogenic unit and is critical for its reliable operation; it comprises sensors and transducers installed at many points of the cryogenic unit to monitor relevant process parameters (temperatures, pressures, flow rates, etc). The information acquired from the field consists in processes by electronic equipment to generate status synoptic for the operators. In addition, the advent of increasingly powerful, integrated and economic programmable electronic controllers allows for a high level of plant automation.

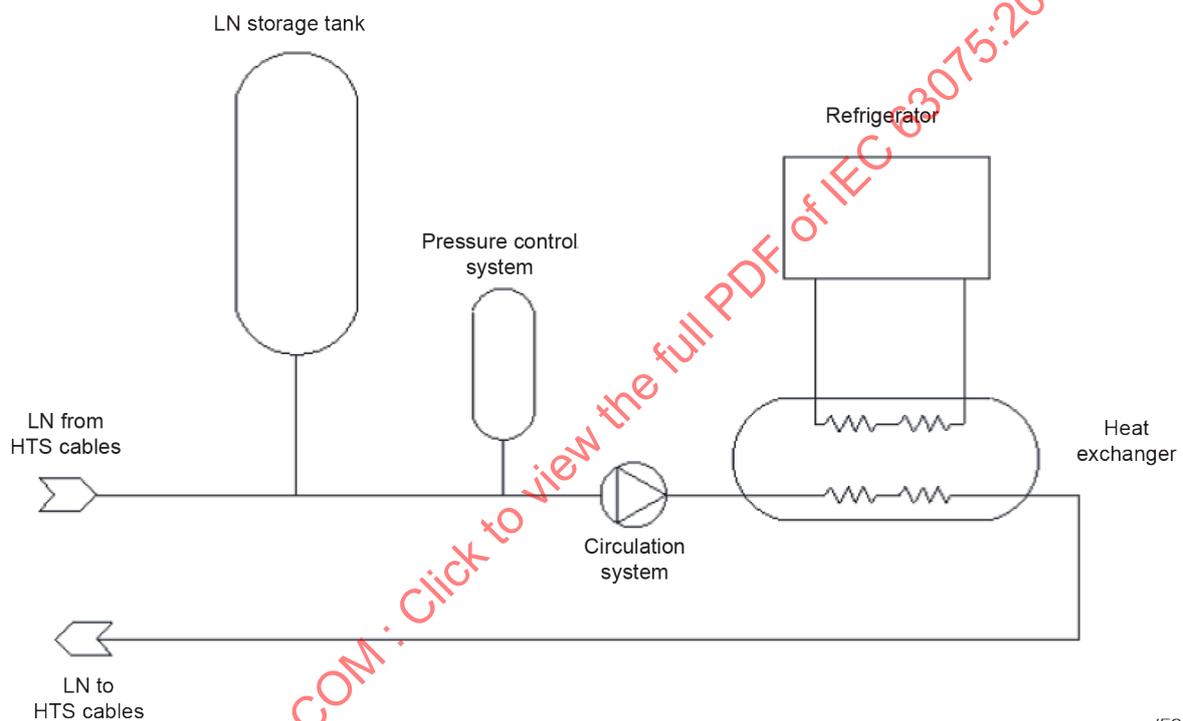


Figure A.2 – General system components and process flow

A.3 Recommendations for tests after installation

A.3.1 General

Besides the internal quality assurance tests performed at the manufacturer of the cooling system, the following tests of the cooling system are recommended after the installation.

A.3.2 Pressure test followed by vacuum leak test

A pneumatic pressure test of the piping in contact with the cryogen shall be performed. After the pressure test, the integrity of the vacuum spaces shall be checked with a helium leak test. Alternatively, the vacuum leak test can be performed during the pressure test.

A.3.3 Cooling capacity test and efficiency measurement

The cooling capacity of the system shall be demonstrated when the system is connected to a load simulating the cable behaviour. Alternatively, the cooling capacity can be demonstrated when the system is connected to the cable system with the addition of an adjustable load to reach the design capacity of the system. Based on the measurements obtained during the test, the efficiency of the system can be determined.

A.3.4 Circulation pump mass flow and pressure test

The circulation pump capability with respect to mass flow and pressure shall be demonstrated by introducing a hydraulic short circuit that includes a valve. For different pressures, the mass flow shall be recorded and compared with the design values. Alternatively, circulation pump capability with respect to mass flow and pressure can be demonstrated when the system is connected to the cable system.

A.3.5 Temperature and pressure control test

The cooling system shall demonstrate the capability of controlling the inlet temperature to the cable system and the outlet pressure of the cable system. This test can be performed together with the cooling capacity test and the circulation pump test.

A.3.6 Noise measurements

In case there are specific local regulations regarding noise level, the noise level of the cooling system shall be determined in accordance with these regulations.

A.3.7 Other measurements

If required, other measurements can be performed, for example the behaviour of the system during power outages and other transient situations.

Annex B (normative)

Critical current measurement

B.1 Critical current measurement test

B.1.1 General

This test shall be conducted to check the performance of the superconducting phase conductor(s) and, if applicable, the superconducting screen as required in Clause 9 and Clause 12.

B.1.2 Procedure

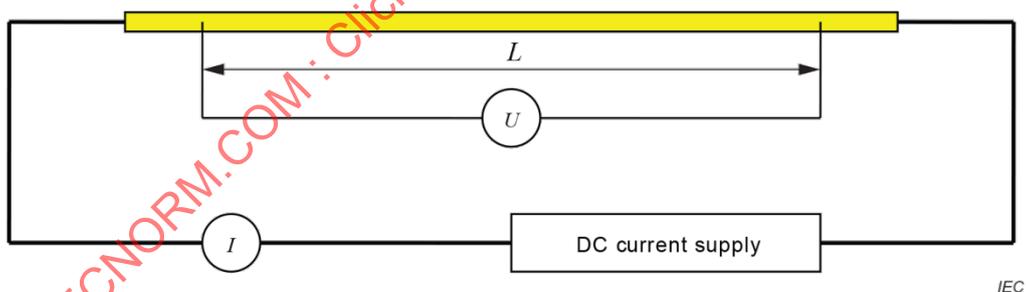
The assembly shall be cooled by the liquid cryogen and maintained at a stable temperature in the range between 64 K and 80 K. The test results shall be adjusted to a temperature of 77,3 K, corresponding to Clause 6, items g) and j).

The critical current shall be measured by the electrical four-probe method described in B.1.3.

The critical current shall be determined by using an electrical field (E_c) of 100 $\mu\text{V/m}$.

B.1.3 Test method

As shown in Figure B.1, two voltage taps shall be installed on the superconducting conductor and the distance between the voltage taps (L) shall be noted. DC current shall be injected in the conductor sample with a controllable DC current supply. The relation between measured current (I) and voltage (U) shall be recorded; an example is given in Figure B.2. The critical current (I_c) is reached when the measured voltage between the taps corresponds to $L \cdot E_c$.



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Figure B.1 – Test setup for electrical four-probe method