

**229**

**HIGH TEMPERATURE  
SUPERCONDUCTING (HTS)  
CABLE SYSTEMS**

**Working Group  
21.20**

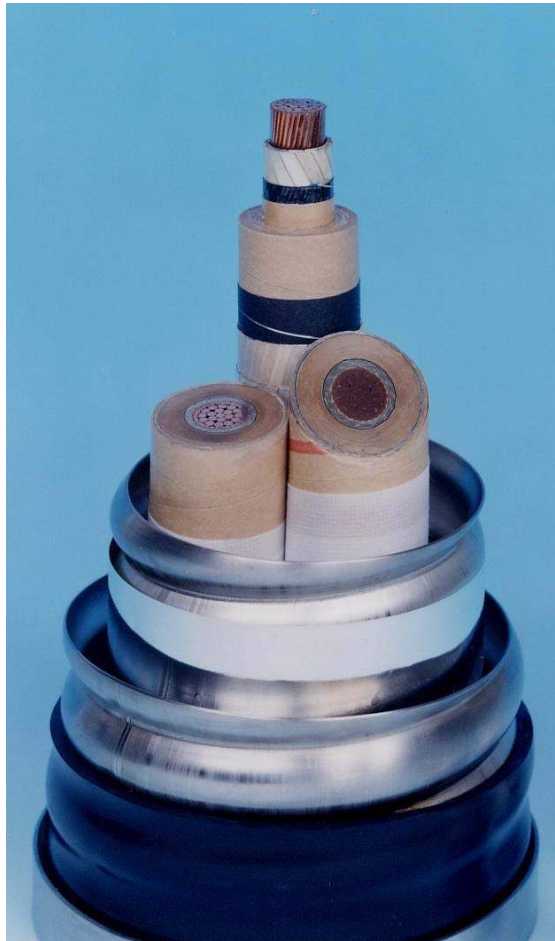
**June 2003**



**CIGRE STUDY COMMITTEE SC 21  
HV INSULATED CABLES**

**HIGH TEMPERATURE SUPERCONDUCTING (HTS)  
CABLE SYSTEMS**

**WG21-20 FINAL REPORT**



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**HTS CABLE SYSTEMS**  
**WG21-20 FINAL REPORT**

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# 1 INTRODUCTION

## 1.1 Terms of Reference

The WG 21-20 with the title “High Temperature Superconducting Cable Systems” was established by CIGRE Study Committee SC 21 during its 1999 meeting in St. Petersburg, USA. The first convenor was S. NORMAN (United Kingdom), who was replaced in August 2000 by M. NASSI (Italy).

The Terms of Reference were defined as follows:

“- To review the emerging technologies and applications of HTS cable systems in the field of energy transmission and distribution, considering its scope of studies according to the areas of technical relevance to HTS cables in manufacture and application.

- To make recommendations to facilitate the definition, manufacture, introduction and integration of HTS cable technologies as appropriate into energy transmission networks.

- The scope of the WG could be categorised into three or maybe four areas of study:

- HTS System Components

- Testing

- Applications and Systems

- Techno-economic Aspects.

- The WG will select specific study topics and decide its priorities in consultation with the SC21 Committee. In all of these areas, but especially in the area of test criteria, the new WG will be addressing previously “uncharted” fields in so far as SC 21 is concerned. The WG should therefore seek to establish a technical understanding in each area, and to become a “technical point of reference” in the field.

- Because HTS technology offers the possibility to transmit very high power levels at voltages significantly below those used with conventional HV/EHV cable systems, the lower voltage limits usually applied to the study of cable systems within CIGRE should not necessarily be applied to the activities of the new WG.

- It is anticipated that the “deliverables” of the WG will include briefing reports for SC21, Reports for Electra and / or Technical Brochures.”

## 1.2 Definition of WG Work Programme and Deliverables

The WG “brainstormed” on possible areas of application of HTS cables, advantages and challenges to the implementation of HTS cable systems, and on the possible areas in which the WG could make a specific contribution within the WG programme.

It was unanimously agreed that a “top-down” approach would be taken to initiate the WG’s work, i.e. commence at the “systems” level rather than at the “component” level. It was also felt that any work to define systems (or even components) should follow a “functional definition of requirements” approach rather than a “constructional” approach.

## 1.3 Planned deliverables:

During the first formal meetings it was envisaged to deliver four documents:

report on « HTS cable system specifications »

report on « HTS cable system test »

report on « System Aspects »

report on « Economical Aspects »

The initial timetable was as follows: 11/1999 → 10/2002.

## 1.4 Actual deliverables

During its three years activities with altogether seven meetings the WG realised, that there was World wide not sufficient experience yet with regard to HTS cable systems practical applications and respective economical aspects which would allow to draw firm conclusions as needed for the third and forth deliverables.

Therefore the WG proposed to prepare for the moment only the 1<sup>st</sup> and 2<sup>nd</sup> deliverables and to merge them in the present final report.

As far as the 3<sup>rd</sup> and 4<sup>th</sup> deliverables are concerned, the WG proposed to freeze the work carried out so far and to postpone the activities to a later stage when a clearer situation of market opportunities will allow to achieve significant results.

CIGRE SC21 Committee agreed to this proposal and disbanded the WG at its August 2002 meeting in Paris, but asked to make a WG final report with adding a general description of the state of the art on the HTS cable technology.

## 2 STATE OF THE ART OF SUPERCONDUCTING CABLES

### 2.1 Superconductivity

- One of the most spectacular physical manifestations of superconductivity is that certain materials, known as superconductors, can carry a direct current with practically zero losses as soon as their temperature falls below a temperature known as the "critical temperature". This "critical temperature" varies according to the superconducting material. However, this phenomenon is limited by two factors: at a given temperature, in self field, the maximum current density that can be carried by the material is limited to a value known as the "critical current density"; this density diminishes as a function of the temperature. Moreover, when the material is subject to a magnetic field, its critical current density diminishes. This behaviour can be schematically illustrated by the following diagram (Fig.1).

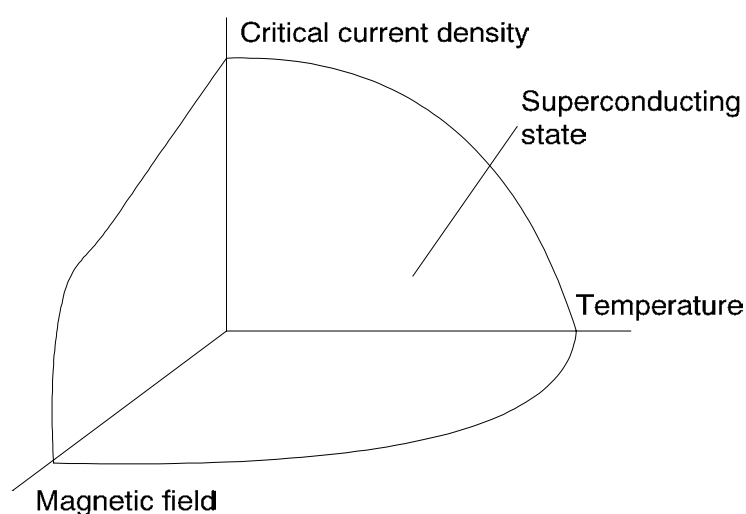


Figure 1: simplified phase diagram of a superconducting material

- The phenomenon of superconductivity was discovered in 1911 by K. Onnes on mercury operating at 4K in liquid helium. From 1911 to 1986, other superconducting materials, essentially consisting of metals (Nb) or metallic compounds (Nb<sub>3</sub>Sn) were subsequently discovered, but their "critical temperature" scarcely exceeded around twenty K, which in practice made it necessary to use liquid helium to make them work; these materials are therefore called "**low temperature superconductors**" (LTS). The applications of superconductivity began nevertheless, starting in 1960, taking into account the technological progress achieved in other fields, but did not extend to electrical engineering devices used on the power system, basically for reasons of cost associated in particular with the cost of cryogenic technology.
- In 1987, superconductivity was revealed in new materials based on oxides (BiSrCaCuO, YBaCuO, etc.), capable of retaining their superconducting characteristics up to temperatures higher than that of liquid nitrogen (77K at 1 bar). The discovery of this type of material, called "**high temperature superconductors**" (HTS), renewed interest in the applications of superconductivity to power system devices, and superconducting cables in particular.

Below a brief reminder of the techniques for manufacturing high temperature superconducting tapes is presented, followed by a description of the two main cable technologies on which research and development work has been undertaken in these last 15 years.

### 2.2 Manufacture of "high temperature superconductor" tapes

Most high temperature superconductive materials are oxide compounds and do not lend themselves well to the shaping required to produce metal tapes or wires. There are basically two processes to remedy this problem:

- "*OPIT*" technology" (*Oxide Powder In Tube*): the superconducting oxides (or precursor compounds) in powder form are inserted into a silver tube which then undergoes many drawing

operations and heat treatments. This technology has reached a pre-industrial stage, but the use of silver limits its prospects of cost reduction. The best of the tapes now offered on the market reach critical current values of 130 A (4 mm x 0.2 mm tape); at present the prices are around 200 \$/(kAm), and some manufacturers are predicting values between 50 and 70 \$/(kAm) in 2 to 3 years time[1].

- *"CC" (coated conductor) technology*: this begins with a metallic supporting tape (also called the substrate) on which layers of "buffer" materials are deposited by various means (laser, beams of ions, electrolytic, mechanical and evaporation methods, etc.), then the layer of superconducting material. These combinations of layers and methods of deposition give rise to a number of processes, each having their advantages and disadvantages in terms of performance, reproducibility, cost, speed and thickness of the deposit, etc. This technology is still only in the laboratory stage, but offers more significant prospects of cost reduction than "OPIT".

To summarise, the "high temperature" superconducting tapes used to manufacture this new type of cable offer the possibility:

- of transmitting high current densities: several tens of amperes rms per mm<sup>2</sup> of useful cross sectional area today at industrial level to a few hundred amperes per mm<sup>2</sup> in future
- and this is achieved with extremely low losses: only a few W/mcable today to a few tenths of a W/mcable in future for several thousands of amperes.

These characteristics in principle make it possible to envisage transmission links with a high power throughput whilst remaining very compact.

### 2.3 "High temperature superconducting" cable technologies

There are two main types of superconducting power transmission cables (see Fig.2):

#### 2.3.1 The "warm dielectric" (WD) type

in which only the central conductor is superconducting, encased in a flexible cryogenic jacket equipped with superinsulation with regard to heat, and cooled to the temperature of liquid nitrogen. The other components of the cable (dielectric, screen, etc.) are identical to those of the usual fluid filled cables or those with synthetic insulation (Photo 1). The WD type is also called RTD "Room Temperature Dielectric".

#### 2.3.2 The "cold dielectric" (CD) type

in which all cable components, apart from the outer protective sheath, i.e. especially the central conductor, the electrical insulation and the outer wire screen, are encased in the superinsulating cryogenic jacket and cooled to the temperature of liquid nitrogen (Photo 2). The cryogenic jacket can be of rigid or flexible design. The 3 phases can be encased together in the same cryogenic jacket or separately in 3 different jackets (particularly at EHV).

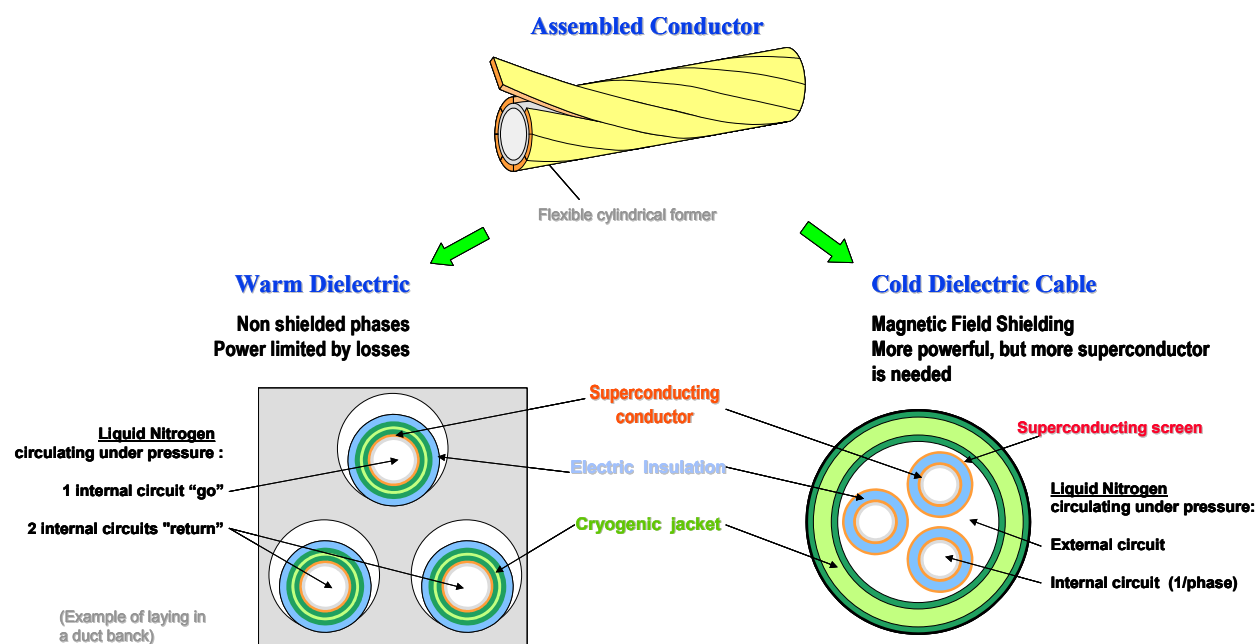
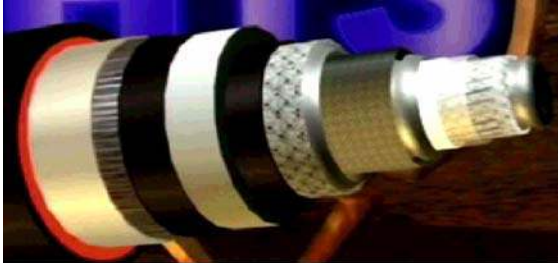


Figure 2 : simplified design of WD and CD cable



*Photo 1*  
*single phase WD cable ( complete)*



*Photo 2*  
*single phase CD cable (without cryostat)*

## **2.4 Terminations and joints**

Accessories for HTS cables are much more complicated in design and much more difficult to install than those of conventional cables. A prime challenge is the connection of the numerous superconducting tapes to each other in joints and to copper stalks, respectively, at terminations. The mechanical weakness of the HTS tapes does not allow to adopt conventional connecting methods known from copper or aluminium conductors. Instead, sensitive soldering techniques have to be applied to provide safe current transition and to avoid reduction of the critical current. This issue is even more complicated with CD HTS cables due to their coaxial configuration of inner and outer conductors.

Furthermore, the terminations have to withstand the three following stresses: thermal gradients (liquid nitrogen inside, room temperature outside), additional mechanical forces (due to pressurised liquid nitrogen) and electrical fields (as for usual cable).

The accessories design is depending upon the know-how of each manufacturer, and many prototypes have already been tested; however, a lot of principal and detailed issues need further considerations.

## **2.5 The cryogenic jacket**

This type of jacket has already been used in industry for decades for cryogenic lines carrying liquefied gas at low temperatures (nitrogen, air, oxygen, etc.) as in the chemical, iron and steel, biological or medical industries. Briefly, this type of jacket consists of a double wall in which a certain relatively high level of vacuum is obtained ( $< 10^{-7}$  bars) to attenuate losses by convection. Several reflective layers are placed between the two walls to attenuate losses by radiation between the inner and outer walls of the jacket. Losses of 1 to 2 W/m of cryogenic line are thus achieved. The use of a less expensive insulating structure, such as insulating foams, is not recommended, as the losses amount to several tens of W/m. Taking into account the efficiency of the cooling systems (see below) this would lead to losses of several hundred W/m for the operator. Furthermore, for long length links, the cryogenic jacket has to withstand high pressure(see following § 2.6).

## 2.6 The cooling systems

To operate HTS cable links, cooling systems must be incorporated to evacuate the different types of losses: i) losses by conduction of heat through the walls of the cryogenic jacket, ii) electromagnetic losses in the superconductive materials; iii) losses due to the viscosity of the circulating cooling fluid; iv) for the cold dielectric option, dielectric losses. The cooling medium is liquid nitrogen (LN). An example of a possible cooling arrangement (there are others in existence) on a link a few km length is given in Fig.3 below: the liquid nitrogen flows through unit lengths between primary joints (cooling fluid injection and extraction points) spaced a few km apart along the link. Circulation pumps are needed to keep the liquid nitrogen flowing, so to compensate for the pressure drops caused by the flow of nitrogen: pressures of 10 or even 20 bars may be required, and the cryogenic jackets must be able to withstand these pressures.

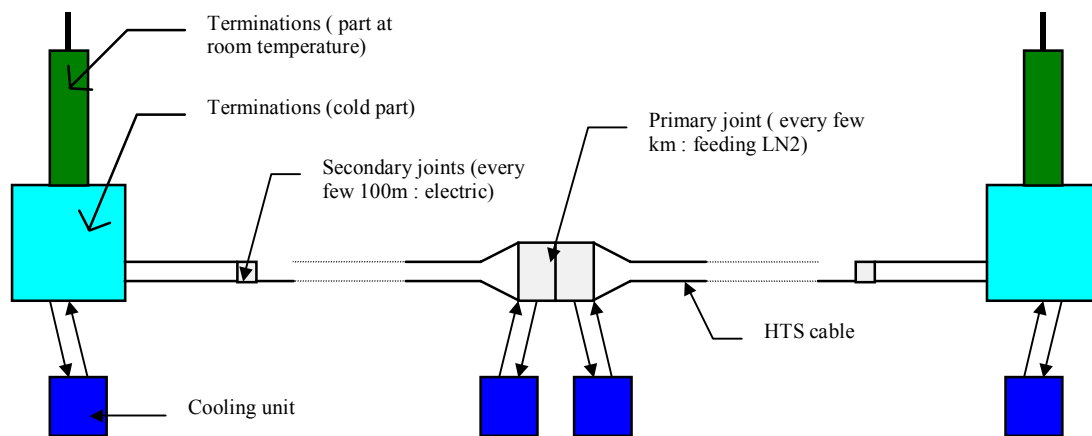


Figure 3 : global drawing of a HTS link

The cooling machines generally used or envisaged for cooling the cables are of two types: the Stirling cycle (intended more for short links where the cold power<sup>2</sup> does not exceed 5 to 10 kW) or the Braiton cycle (more for long links with higher cold power values). Taking the temperature level into account, the efficiency of these machines scarcely exceeds 6% to 7%, which means that they consume 15 Watts of electrical power to supply 1 Watt of cold. A cold exchanger between the cooling machine and the nitrogen circuit cooling the cable is used in most cases, thus bringing the overall efficiency of the cooling system to around 5%.

## 2.7 Comparisons between the "warm dielectric" and "cold dielectric" technologies

The "warm dielectric" type is in principle more easily manufactured since, apart from the conductor, its design is very close to that of the usual cables, whether they are of the oil-filled or synthetic type. The requirements of reliability, compactness and ability to withstand the forces of the cryogenic jacket are however quite difficult to fulfil.

When the 3 phases are very close together (with trefoil or cradle laying), the magnetic field induced by each phase will cause an increase in the electromagnetic losses of the superconducting tapes with which the adjacent phases are equipped. The mutual electromagnetic influence between the phases is also manifested in not insignificant electro-dynamic forces on the conductors, in particular when the fault currents reach high values. These forces are transmitted to the thermal insulating components of the cryogenic jackets and thus it is more difficult to achieve a compromise between the cost and quality of the insulation. It should also be noted that eddy current losses affect the cryogenic jackets, too, if their dimensions are not carefully studied. In addition, in the case of retrofitting oil-filled pipe-type cable plants, the throughput capacity will have a second cause of limitation on account of eddy current losses in the steel ducts.

Finally, another drawback lies in the difficulty of access to the cryogenic jackets, which prevents any periodic further pumping of the insulating vacuum. Whilst power system managers request a service life of at least 40 years for a link, it does not seem possible today to guarantee for this

<sup>2</sup> The cold power corresponds to the frigories to be supplied by the cooling unit.

period of time and for all the cryogenic lines of a link, that the vacuum will remain at the level necessary to maintain acceptable thermal insulation.

The "cold dielectric" type is less easy to manufacture than the "warm dielectric" on account of its structure of two superconductive components, i.e. the inner conductor and the outer screen, even though its electrical insulation of preferably paper-polypropylene tapes is similar to the structure of an oil-filled cable. Firstly, so far there is no feedback from full-scale experience of the operation of such insulation at LN temperatures.

Moreover, with regard to the cable terminations, the dielectric stresses (particularly at EHV), the mechanical stresses (liquid nitrogen at pressure which may reach 10 to 20 bars, see above) and the thermal/mechanical stresses (temperature difference between the surroundings and the liquid nitrogen) make the design of these terminations a difficult task and increase the risk of failure.

The presence of the superconducting screen practically doubles the cost of the superconductive material in comparison with the preceding design. However, this screen cancels out the magnetic field outside the cable, which gives the advantage of reducing the losses (thus making it possible to transmit more power) and not causing any problem in the case of retrofitting inside steel ducts.

For the configuration with a rigid cryogenic jacket, it will firstly be necessary to install and to connect cryogenic sections in lengths of around ten meters before pulling the phases through the whole lengths.

In theory, the "cold dielectric" allows access to the cryogenic jacket to carry out a repair or maintenance operation occasionally, even if in practice the power system operators wish to avoid such operations along the link, particularly in urban areas where access may be difficult.

## **2.8 Constraints associated with the use of superconducting cables**

The presence of the cryogenic jacket automatically gives rise to a certain number of specific difficulties, such as the problem of accessibility indicated above. From a more global viewpoint, principally the following main features will be mentioned:

- the general complexity of the cryogenic system, with its measuring and control devices, the independent operation of which over fairly long periods of time is not yet achieved. The need for periodic inspections of the system and maintenance work on the cooling units may constitute a serious obstacle to the widespread use of this technology insofar as these disadvantages do not affect competing conventional solutions. It seems necessary to have redundancy in part of the modules of the cooling system so that maintenance tasks or repairs can be carried out without shutting down its operation; otherwise the cooled cable would no longer be operational during these periods.
- the absence at present of an economically acceptable solution for repairing a cable or accessory damaged by an incident of the dielectric fault type, leading to the breakage of the cryogenic jacket, or by mechanical damage outside this jacket. This type of failure would in fact require reheating operations, repair (or replacement) and the connection of the damaged components (insulating and superconducting tapes, cryogenic jackets), the re-establishment of the vacuum insulating the cryogenic lines and finally the re-establishment of the cold conditions in the system. The feasibility of these operations is still uncertain, in particular for the connections between superconducting tapes and re-establishment of the correct insulating vacuum for the cryogenic lines at the site of the fault. The time taken for the repair would in any case very significantly affect the availability of the link, an interruption in service exceeding one month having to be envisaged for the faulty cable<sup>3</sup>.
- the level of investments necessary for superconducting links, which will remain higher than those for conventional links. It would seem however that there are cases in which the extra cost for superconducting cables would be economically justified, especially the increase in power by retrofitting conventional links in saturated ground, thus avoiding the construction of a very expensive tunnel in certain local configurations [2].
- the present lack of experience of major problems for the operator such as :
  - the service life of the superconducting tapes and that of the cold electrical insulation;

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<sup>3</sup> The time taken for cryogenic pumping of a line insulated by vacuum increases quadratically with its length and this should be performed simultaneously with a stoving operation. This operation takes several days for lengths in excess of 10 m. It would take several weeks to re-establish the cold conditions in sections of superconducting links a few km long.

- the questions of safety specific to the use of large volumes of cryogenic media at high pressure (10 to 20 bars): risk of burns by splashing or asphyxia through lack of oxygen in the event of major leakage.

## 2.9 Integration in electrical network

The advantages of HTS cables links have been described in [3]: high current transmission permitted by HTS cable can avoid introduction of EHV voltage levels or use of shunt reactors for compensation. The insertion of HTS cable links in networks generally involves issues similar to those encountered with conventional cables. For the same level of rated voltage, inductance and capacitance of WD cable are roughly the same as those of usual cables; for CD cables, capacitance is roughly the same as for usual cable, but inductance is much lower; hence, addition of series inductances is required for CD cable links operated in parallel with a traditional line to compensate low impedance values and balance load flows. Furthermore, a few specific problems appear however: for high load flows at the medium voltage level, current transmitted can come close to the switch thresholds of breakers currently fitted to the network, thereby requiring an upgrading unnecessary otherwise. However, superconducting technologies could represent some drawbacks for network operators (as compared to conventional extruded cables) as the new technology will, at the very least, require some maintenance of the liquid nitrogen cooling and circulation system. Furthermore, as already said, in the event of line failure, unavailability would be longer due to the time required to cool again the line to the appropriate temperature.

## 2.10 The present situation of superconducting cable developments throughout the world

The present developments are motivated by the possibility of combining significant power values, typically 100 to 300 MVA HV or EHV cable systems, occupying very little space. This means that the majority of prototypes are designed for use underground in urban areas, often by retrofitting existing links of the usual type (USA, Japan). France alone has the distinction of undertaking a project oriented towards high throughputs at EHV: 1000 MVA/ 225 kV for big city feeders, or 3000 MVA/400 kV for interconnections.

Technically speaking, Japan (essentially Sumitomo/TEPCO and Furukawa) is developing the "cold dielectric" only, as the three phases are contained in one single duct to be retrofitted, which implies the cancelling out of their mutual electromagnetic influences (cf. § 2.7). In the USA and in Europe, both technologies are being tested, as cable laying configurations may vary. It should be noted that for all the prototypes the cooling medium is liquid nitrogen, the superconducting material used is BSCCO, and they operate with alternating current.

The development and testing of high temperature superconducting cables in the laboratory started at the beginning of the 1990's. In addition, since 2001, tests have begun on industrial sites, the first cable tested on an electrical power system being that of NKT. The table below shows the main parties concerned and the projects in progress or completed recently.

Laboratory and site tests : projects in progress or recently achieved

	Main characteristics	Stage of progress
<b>EDF/Pirelli ([4])</b> (lab)	225 kV / 3000A rms / 40 m / single-phase / cold dielectric	cable part constructed, project stopped during 2002
<b>TEPCO/Sumitomo([5])</b> (lab)	66 kV / 115 MVA/ 1000A rms / 100 m / three-phase in 1 cryogenic line / cold dielectric	30-m version constructed ( 1 super/ 3), 100-m version tested in 2002
<b>Pirelli /Siemens([6])</b> (lab)	110 kV / 2 kA rms / 50 m/ single-phase / cold dielectric	test on dummy cable completed, project stopped
<b>Detroit Edison / Pirelli / /AMSC / EPRI ([7])</b> (site)	24 kV / 2400A rms / 120 m /three-phase / warm dielectric installed in a substation	Testing in progress on 1 phase (at end of 2002)
<b>NST/NKT/Copenhagen Energy/DTU([8])</b> (site)	36 kV / 1600A rms / 30 m / three-phase / warm dielectric, between busbars in a substation	started up in May 2001, I=1000A has been reached
<b>Southwire / IGC / ORNL([9])</b> (site)	12.4 kV / 1250A rms / 30 m / 3 phases in 1 cryogenic line / cold dielectric, at Southwire headquarters	started up at beginning of 2001, 3000 h operation at I <sub>mean</sub> = 900A

Other projects are under discussion: in the USA, for superconducting cables installed on the grid (some of which will be 50% financed by the DOE in the context of the SPI3 program [10]), and in Japan, for a laboratory prototype a few hundred m long, in the context of the SuperGM project.

**The synopsis of the two preceding paragraphs (constraints on the use of superconducting cables, the stage of cable development throughout the world) leads us to expect a learning period of several years before achieving industrial practice ensuring the right level of reliability and safety. Actually, it was clear all along the tasks made by the Working Group, that, despite of the significant improvement achieved during the last years on laboratories prototypes, many questions were not solved and remain still open, mainly due to the lack of feed back experiment, especially about real life in site and life cycle. Significant time and means have been already spent by workers on HTS devices, but it appears that a lot of costly works will still have to be done, before reaching reliable and commercial applications. But before launching these works, a thorough analysis of the future potential market of HTS cable is to be made.**

### 3 HTS CABLE SPECIFICATION

#### 3.1 Introduction

Preparing a HTS cable system specification means to look at the future, assuming HTS cable systems already an acquired technology and taking as a reference what happens for the conventional cable systems. This also means that customers/consultants will have the necessary knowledge of the new technology.

In this situation three basic cases will occur:

- Feasibility study
- Rough quotation
- Binding tender

➔ *For each of these three cases, we emphasize only hereunder what is specific for HTS cables; (for complete data, see Annexes 1,2 and 3 and notes in Annex 4).*

#### 3.2 Feasibility study

##### Data to be provided by the customer to the supplier:

Besides values (U, I, f) given for usual cable, some other values should be specified by the customer for HTS cable (see details in Annex 1):

- Short Circuits Characteristics (current, duration, re-closure procedure) have an influence on core design (protection of HTS tapes) and cooling unit design (avoiding LN temperature divergence). The particular electrical characteristics of HTS cables (inductance and capacitance, especially for CD cable) require a checking analysis on power flowchart and short-circuit level on the network that will include the HTS link.
- Type of cable: warm dielectric or cold dielectric ( $I_n$  limit depends on type).
- Type of cryostat (for cold dielectric): rigid or flexible and single-phase or three-phase (influence on component cost and laying).
- New installation or retrofit (retrofit is difficult with rigid cryostat).
- Route characteristics: length, profile and particular route constraints have an influence on cryostat pressure and cooling circuit pump pressures (pressure drop due to difference of route altitude and LN flow rate).
- Possible location for refrigeration units, because of the place taken by such units.

#### 3.3 Rough quotation

##### Data to be provided by the customer to the supplier

In addition to data already given for feasibility studies in § 3.2, the customer should add some precisions about installation data of HTS cable system:

- Over-current as a function of frequency and duration of over-current period. It could be specified by indicating for example:

<i>Event</i>	<i>Frequency</i>	<i>Duration</i>	<i>Overcurrent</i>
<i>1</i>	<i>1 day</i>	<i>10 s</i>	<i><math>n1 * I_n</math></i>
<i>2</i>	<i>1 month</i>	<i>10 min</i>	<i><math>n2 * I_n</math></i>
<i>3</i>	<i>1 year</i>	<i>10 days</i>	<i><math>n3 * I_n</math></i>

These values are requested to calculate the necessary margin for designing the quantity of HTS tapes and the overload of the cooling unit.

- New installation: buried, in tunnel, in duct, in pipe.
- Retrofit: in tunnel, in duct, in pipe.

The characteristics of the two latter items have influence on cryostat design.

#### 3.4 Binding tender

For the sake of completeness we are dividing the data in three categories even if all this information will be collected in a single contractual document:

- Data to be provided by the customer to the supplier
- Data to be provided by the supplier when answering the tender

- Data to be provided by the supplier after the awarding of the contract

### 3.4.1 Data to be provided by the customer to the supplier

In addition to data provided by the supplier, already given for feasibility study in § 3.2 and rough quotation of HTS cable in § 3.3 and beside data usually provided for conventional cable, the following data have to be added by the customer for a binding tender in case of a HTS cable.

#### 3.4.1.1 Cable data

- Type of material: if the customer wants a specific material for HTS tapes (OPIT, coated conductor, ...), he must precise which one, because this has influence not only on the cost of HTS material, but also on other design parameters (average temperature of LN, ...)
- Applicable standard due to the specifics of HTS cable system: to be defined under a specific task.
- Tests: type tests, factory - routine tests, sample tests . First considerations about what could be these tests are described in § 4 and § 5.

#### 3.4.1.2 Cryogenic lines data

- Applicable Standards (design, manufacturing, testing, safety).
- The customer could require some level of thermal efficiency of the cryogenic lines, in order to get low operating losses cost; so, the following data could be given by the customer:
  - Maintenance could be necessary to remake a good value of vacuum inside the cryogenic jacket:
    - Allowed time between maintenance
    - Maximum time for maintenance
  - Maximum thermal efficiency degradation permitted by the customer between maintenance intervals.

*Note : a balance should be done then between the reduction cost of losses due to a good thermal efficiency and the cost of the maintenance and cryogenic jacket design.*

#### 3.4.1.3 Accessories data

- Applicable standard due to the specifics of HTS cable system: to be defined later under a specific task.

#### 3.4.1.4 Installation data

Additional data to those already provided in feasibility study and rough quotation should be added: The contractor should generally acquire all the information related to the installation condition (pipe/duct conditions, bending radii, space availability etc... see details in Annex 3) by means of a route survey. These conditions have a significant impact on the cryogenic environment suitable for the cable, for example:

- unavailable space could increase the length between 2 cooling units and lead to increased pressure of LN ( due to flow pressure drop); this increases also the average temperature and decreases the efficiency of HTS tapes.
- Water supply for the cooling unit must be easily achieved.
- Ambient temperature must be also provided, because some freezing points could appear on upper part of terminations if the HTS link is not energised or loaded at a low level of current.

#### 3.4.1.5 System data

Cable screen connection (for warm dielectric only): single point bonding or cross bonding system seems preferable to solid bonding, taking into account the very high level of current considered for HTS cables.

#### 3.4.1.6 Refrigeration plant

- Applicable Standards (design, manufacturing, testing, safety).
- Depending on the required safety level for his link, the customer will have to provide data related to operational and maintenance limit, time allowed for link's maintenance, repair and outage, level of control, etc ... (see details in Annex 3).

*Note: a balance should be done then by the customer between the cost of an HTS link's outage and the overcost of redundancy components of the refrigeration plant, that permits to decrease the time of an HTS link outage.*

### 3.4.2 Data to be provided by the supplier when answering the tender

Besides data usually provided for conventional cable (capacitance, inductance, dimensions, pulling strength,...), some other values must be specified by the supplier for HTS cable (see details in annex 3).

#### 3.4.2.1 Cable data

- Type of cable: warm or cold dielectric, single or flexible cryostat, 1 or 3 phases in cryostat (if not stated precisely by customer when asking for tender).
- Cross-sectional drawing (main dimension, cable outer diameter with tolerances).
- Tape material (if not stated precisely by customer when asking for tender).

#### 3.4.2.2 Cryogenic lines data

- Size and weight.
- Maintenance :
  - General maintenance procedure
  - Foreseen time between maintenance
  - Foreseen time for maintenance

(Same note as for 3.4.1.2).

#### 3.4.2.3 Accessories data

- The supplier will give general data about size and weight of HTS accessories that are generally larger and heavier than conventional cable accessories (particularly for cold dielectric type) and therefore suitable space must be foreseen to contain them.
- In addition, data about thermal losses could be required by the customer.

*Note : at present only terminations for outdoor or indoor installation are under development. These components will be taken into consideration for the definition of the relevant testing procedure. At present feeding joints are not taken into consideration.*

#### 3.4.2.4 Installation data

- Main characteristics of the refrigeration units are requested by the customer to foresee suitable space near the terminations and primary joints (feeding LN).
- General procedures for installation, cooling down and warming up, repairing etc. are specific for HTS apparatus; they are requested by the customer to foresee time for first installation or link's outage in case of failure.

#### 3.4.2.5 System data

Overall cold losses (W/m), specific of a HTS link, will be asked by the customer in order to have the efficiency of the cryogenic lines and HTS cable in different operating conditions of the link (not energised and energised with different values of load.)

#### 3.4.2.6 Refrigeration plant

In order to have a first overlook for operating the refrigeration plant, the customer will ask for scheme and general technical description (electric, hydraulic, control and monitoring, ...), and general procedure for operational + maintenance limit.

### 3.4.3 Data to be provided by the supplier after the awarding of the contract

In addition to data already provided by the supplier when answering a tender in § 3.4.2 and to data usually provided for conventional cable, the following data<sup>4</sup> have to be added by the supplier after the awarding of the contract in a case of a HTS cable system (see details in Annex 3):

- Description of the cable part (see Data Sheet samples in Annex 4) and more detailed values on tapes (critical current density) and HTS conductor ( $I_c(T)$ ,  $V(I,T)$ ,  $n$  value).
- Detailed description and drawing of accessories, cryogenic lines and refrigeration plants.
- Detailed procedure for operating the refrigeration plants, running the complete system (cooling down, normal operating, warming up, emergency etc.).

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<sup>4</sup> *Apart from the overall performances for system, cable and accessories it is very difficult, at this stage, to determine which type of data can be disclosed to the customer avoiding any infringement of IPR*

## 4 TESTS AT HTS POWER CABLES WITH LAPPED COLD DIELECTRIC (CD) INSULATION

### 4.1 General

These are first considerations on electrical routine, sample, type, prequalification and after laying tests on high voltage HTS power cables, which are designed with lapped cold dielectric insulation.

In a first approach the following international test specifications were taken as a reference:

- IEC 141-2, 1963 : Tests on oil-filled and gas-pressure cables and their accessories,
  - Part 2: Internal gas-pressure cables and accessories for alternating voltages up to 275 kV
  - Part 4: oil-impregnated paper-insulated high pressure oil filled pipe-type cables and accessories for alternating voltages up to and including 400 kV
- HD 634 S1, Dec. 1997 : Tests on internal gas-pressure cables and accessories for alternating voltages up to and including 275 kV ( $U_m = 300$  kV)

By checking the individual paragraphs of these specifications with regard to their complete or partial applicability to HTS CD cables, the common and the different features of conventional and HTS cables should be identified.

It soon became clear from this analysis, that a greater number of specific aspects with testing of HTS CD cables need special and detailed investigation before an appropriate test programme including adequate test requirements can be recommended.

#### 4.1.1 Scope

The present draft proposal for a new specification shall apply to tests on radial-field tape-insulated HTS cables and their accessories in which, during normal operation, an impregnation with liquid nitrogen LN is applied internally. I.e. LN is in direct contact with the conductors and the insulation with a pressure extending typically from 2-3 bars to 10-20 bars in some cases (for long length see §2.6).

#### 4.1.2 Normative references

Though mostly unchanged compared to conventional cables, some of the normative references will have to be adapted, e.g.:

- IEC 60228 (conductor) for superconducting core and screen.
- IEC 60811-1 (common tests method for insulating and sheathing materials of electric cables) for LN temperature: mechanical properties (part 1) , thermal ageing method (part 2) and tests at low temperature (part 4).

#### 4.1.3 Definitions

As far as the cable system is concerned, definitions keep unchanged, but some addendum has to be foreseen for cryogenic part and cooling unit.

#### 4.1.4 Voltage designation

Will remain identical between conventional and HTS cables.

#### 4.1.5 Test conditions

For tests at conventional cables normally the ambient temperature is defined.

It has to be decided, whether and which of the envisaged tests at HTS CD cables might be performed at ambient and which at LN temperature.

#### 4.1.6 Characteristics

For the purpose of carrying out the tests described in the standard and recording the results, the cable and accessories shall be clearly identified. Some of the typical characteristics could be:

##### 4.1.6.1 *Electrical data*

- Rated Voltage  $U_0, U, U_m, U_p$
- Nominal Current  $I_n$  (A), Critical Current  $I_c$  (A)
- Over-current (A) as a function of duration of over-current period

- Short Circuit Characteristics: Current (kA), Duration (ms), Re-closure procedure

#### 4.1.6.2 *Design data for HTS CD cables:*

- type of conductor (“cross section”?)
- material and nominal thickness of insulation
- nominal diameters over conductor, cable core etc. (verified in sample tests)
- nominal capacitance  $C$  and  $\tan \delta$
- number of cores in the cryostat (single or three phase)
- characteristics and dimensions of cryostat
- nominal LN pressure

#### 4.1.6.3 *Design data for HTS accessories:*

- conductor connection techniques
- dimensions and materials
- installation requirements
- etc.

These data are understood as reference values, which will be referred to and verified during the tests.

## 4.2 **Test methods and requirements**

IEC Standards for power cables are specifying test methods and requirements. Typical tests are routine, sample, type and after laying tests and in some cases so-called prequalification tests. In the following it is considered how to apply these traditional procedures to HTS cable systems with cold dielectric.

### 4.2.1 **Routine test**

Routine tests are generally carried out by the manufacturer on each length of cable forming part of a contract to check that the specified requirements are met.

For the electrical tests (e.g. capacitance,  $\tan \delta$ , high voltage tests), the cables are suitably terminated and normally the tests are carried out at atmospheric pressure and at ambient temperature.

As most conventional cables with lapped insulation are fully impregnated before they are shipped from the factory, elevated test voltages are acceptable and applied in the range of twice the service voltage ( $2U_0$ ).

For not-fully impregnated cables, i.e. internal gas pressure, the test requirements are drastically reduced down to  $0.5U_0$ . The reason is that the final dielectric strength of these cables is not available yet in the factory but will be achieved only after installation and pressurising with N<sub>2</sub>-gas of 12 to 15 bars in the steel pipes at site.

In principle, this configuration is comparable with lapped HTS CD cables, which will reach their final dielectric strength only after impregnation with LN at site in the cryostat, too.

In both cases, it seems not practical to bring each shipping length for routine tests to its final pressure or impregnation state.

As a consequence, it is recommended here to widely abandon the conventional routine test procedures from HTS CD cables.

Sample tests, as described under § 4.2.2), could be considered an alternative to cope with the legitimate desire of manufacturers and customers for confirmation that cables comply with the agreed levels.

### 4.2.2 **Sample test**

Sample tests are made by the manufacturer on samples taken from complete cables at a specified frequency depending on the total volume of the contract.

For electrical tests at conventional not-fully impregnated cables with lapped insulation, a piece of cable is installed with suitable terminations and the gas pressure is adjusted to the minimum value declared by the manufacturer.

Applying this approach to HTS CD cables results in a full size installation of a HTS cable sample in a laboratory cryostat with cooling down and impregnating with LN. The length of the sample is to be discussed further, but a length of ~10 m seems reasonable for all sample tests. Even if the length will be much shorter than for a routine test, the test of a sample will remain costly. The test terminations will have to be very similar to final terminations due to the cryogenic needs whereas provisional terminations for conventional cable testing mostly are much simpler. Furthermore, an adequate cooling unit is needed. Provided that a suitable test set including appropriate terminations is available at the

manufacturer's, most of the basic tests required by conventional specifications for routine and sample tests could be performed at nominal conditions, i.e.,

- conductor resistance test,
- capacitance test
- $\tan \delta$  measurement
- high voltage power frequency test
- impulse voltage test

Though complete shipping length could not be tested as in conventional routine tests, these tests would at least confirm the principle characteristics of the cables of his contract to the customer.

#### 4.2.3 Type test

Type tests are made before supplying on a general commercial basis a type of cable system in order to demonstrate satisfactory performance characteristics to meet the specified requirements and the intended application, respectively. For this purpose, a full size test installation including cables and accessories is erected to simulate service conditions.

Type tests for fluid filled paper insulated cables (LPFF) typically consist of

- $\tan \delta$  measurement/temperature test
- dielectric security test
- lightning impulse voltage test

Type tests for internal gas pressure cables are not explicitly specified, however in Part 2 of HD 634 some equivalent tests are proposed.

For HTS CD cables this would mean to install the various system components with suitable cryostats and to cool down and impregnate the complete circuit with LN as designed for normal operation.

Apart from electrical withstand tests with power frequency, lightning or switching impulses and proof of the main electrical characteristics (resistance, capacitance, loss factor etc.), specific test procedures and requirements for HTS cable systems must still be discussed, such as

- kind and duration of load cycles (currents)
- thermal cycles (cooling down and heating up)
- mechanical aspects due to temperature changes (shrinkage)
- performance of cooling circuit and cryostat
- proof of losses (electrical, thermal)
- etc.

#### 4.2.4 Prequalification test

Prequalification tests are made before supplying on a general commercial basis a type of cable system in order to demonstrate satisfactory long-term performance under simulated field conditions of the complete cable system.

With regard to HTS CD cable systems the prequalification test is still an open issue:

- on one side, prequalification tests on a HTS cable would not bring any relevant information about thermo-mechanical ageing of accessories and cable.
- on the other side, a customer that would buy for the first time a HTS cable system, would strongly ask for a kind of "prequalification test", mainly to get experience with the whole operating system, especially on cryogenic and cooling unit part, on which the customer was not yet used.

#### 4.2.5 After laying test

Electrical tests after installation are made to demonstrate the integrity of the cable system as installed. For HTS CD cables this will be the first time that the fully impregnated insulation and the HTS conductors are available for electrical test at operating, i.e. LN temperature. In addition, it is the first time that the auxiliary equipment, e.g. the cooling plant, the cryostats and the measuring and control systems are ready for testing.

Possible tests could include:

- $\Delta P$  measurement for LN
- $\Delta T$  measurement for LN with voltage and load
- Measurement of total losses without voltage and load
- Measurement of total losses with voltage and load

#### 4.2.6 Summary

The special features of HTS cables with lapped cold dielectric (CD) insulation do not allow to apply unchanged the usual test procedures and requirements as specified for conventional cables. The reason

is that the design electrical strength of the CD insulation is only achieved after impregnation with LN. Therefore measurements and tests of electrical properties at the not-impregnated cable dielectric with room temperature will not give much information, even if this is still an open issue because of lack of feed-back experiment (see § 4.3.3).

To cope with this problem at the manufacturers, shorter samples could be installed in specially designed HTS test plants and tested with regard to their principle compliance with the specified requirements.

The confirmation, however, that the complete set of components of a HTS cable contract is without defects, will only be possible during the commissioning test after completion of the whole installation.



### 4.3 Description of tests

In the following chapter an analysis is made of the main characteristics specific to HTS CD cables under the aspect of being appropriately covered by different test procedures. Depending on the test objectives three main configurations are considered:

- *Complete cable* = cable with cryostat
- *Complete cable system* = complete cable + terminations + joints, all filled with LN ( + trifurcation box for CD configuration with 3 phases in 1 cryostat)
- *Complete operating system* = complete cable system + cooling unit

#### 4.3.1 HTS tapes and conductors: $I_c$ and AC loss measurements

Purpose: to check that the superconductivity of the HTS tapes in the core and screen conductors, respectively, comply with the specified data.

Description: for sample test, a length of a cable is put in a cryogenic vessel filled with LN<sup>5</sup>,  $I_c$  is set with  $1\mu\text{V}/\text{cm}$ . For type tests, the measurements are made with complete operating system. Voltage sensors have to be provided.

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	No test at 77 K, only check at room temperature	Yes : 77 K	Yes ( at ~ 77K)	No
<b>Why test is put here (or not)</b>	If any damage during handling has decreased $I_c$ and if no test is made earlier, the damage will be visible only after laying. On the other side, routine tests at LN temperature present high difficulties and expenses and are therefore not recommended. →So we suggest only to check the electrical continuity at room temperature	To check that $I_c$ is $\geq$ and AC losses are $\leq$ specified data. (no need to make measurements at other temperature, whereas the law $I_c(T)$ is intrinsic and does not rely on handling).	To check that $I_c$ is $\geq$ and AC losses are $\leq$ specified data (to be done after bending and cooling cycle tests). The type test might be conducted at some temperature between 67 and 80 K.	It is practically not possible to apply for test reasons the critical current to a complete HTS cable system.
<b>Difficulties</b>	For rigid cryostat configuration, tests of HTS cable conductors at LN temperature require a circular testing cryostat with a high radius; with flexible cryostat, filling of LN could be done with cable on a mandrel, but this requires a long time to cool down and warm up. Therefore not recommended.	No significant difficulties (needs only a LN bath)	This requires a cooling unit or a LN tank with pumps to get a flow-rate of LN in cable circuit; needs much time to cool down and warm up. Measurements will be made at average temperature (between input and output temperature permitted by the cooling circuit)	Voltage sensors are difficult to put in a real-life cable

Comments: except measurements of  $V(I)$  on some samples, no tests about HTS tapes are proposed here, provided that a standard will exist on HTS material qualification

<sup>5</sup> LN = liquid nitrogen

### 4.3.2 Global loss measurements

Purpose: firstly to measure flow-rate of LN and  $\Delta T$  output/input and deduce thermal loss and secondly to measure electrical power consumed by the complete cooling system, especially for after laying tests.

Description: the measurements are made with complete operating system for type and after laying tests; the cryostat is filled with LN that is circulated by a pump

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	No	open issue	Yes (~ 77K )	Yes
<b>Why test is put here (or not)</b>	Same as for $I_c$ measurements	Try to check that the thermal insulation of the cryogenic jacket is correct.	To record losses and electrical consumption with and without voltage and a set of currents from 0 to $I_{nom}$ , then check that these values are $\leq$ specified values. There is no real need to make measurements at other temperatures, because $I_c(T)$ and AC losses (T) are known; thermal losses are quite constant whereas the average operating temperature will be close to 77 K.	To record losses and electrical consumption with and without voltage and a set of currents from 0 to the max. current available by the network at the testing time; then check that these values are $\leq$ specified values.
<b>Difficulties</b>		Same as for $I_c$ measurements. In the case of a short sample, the evaluation of the thermal losses is difficult because of great influence from the terminations.	Same as for $I_c$ measurements. In the case of a short sample, the evaluation of the thermal losses is difficult because of great influence from the terminations; this test might be conducted on several 10 m of cable.	No significant difficulties.

### 4.3.3 Capacitance C and tan $\delta$ measurements

Purpose: to check that actual values are in compliance with specified data.

Description: for sample test, a length of a cable is put in a cryogenic vessel filled with LN; for type test, the measurements are made with complete operating system. Voltage sensors have to be provided.

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	open issue	Yes : ( 77 K)	Yes (~ 77K)	No
<b>Why test is put here (or not)</b>	See comments below	To check that C and tan $\delta$ are $\leq$ specified data.	To check that C and tan $\delta$ are $\leq$ specified data (test to be done after bending and heating cycle tests).	
<b>Difficulties</b>	See comments below	This requires a pressurised vessel with LN at ~ 77K and needs to provide suitable provisional terminations.	This requires a cooling unit and needs much time to cool down and warm up	

Comments on routine tests: this is still an open issue, as more feed back data are needed. Arguments “for” and “against” this test are summarised below:

*"for"*: - capacitance measurement can detect large defects (relation between voltage breakdown at non impregnated insulation at room temperature and with impregnation at LN temperature could be collected in future and could possibly indicate a value of test voltage at room temperature).

*"against"*: - because of air-filled gaps and moisture inside the lapped insulation, measured values do not give relevant information to extrapolate at LN temperature; application of test voltages could result in PD in the non impregnated insulation with the risk of pre-damage due to electrical trees.

#### 4.3.4 Bending test

Purpose: to check that the HTS tapes and the cable insulation withstand mechanical stresses due to handling of cable.

Description: complete cable for flexible cryostat and only cable for rigid cryostat is bent 3 times on a mandrel, without LN.

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	No	Yes	Yes	No
<b>Why test is put here (or not)</b>		To prove that the handling occurring during manufacture, transport and laying on site will not damage the insulation and HTS tapes. Checking is made by visual inspection.	To check that the handling occurring during manufacture, transport and laying on site will not damage the insulation and HTS tapes. $I_c$ measurements will have to be made before and after bending for comparison. Bending has to be made before voltage and impulse tests.	
<b>Difficulties</b>		No significant	No significant	

#### 4.3.5 Cooling cycle test

Purpose: to simulate the consequence of warming up and cooling down that could happen to the whole cable due to a LN leak in the event of a failure in a point of the link during a 30 to 40 years life.

Description: cooling down and warming up of the complete cable system is made at least 2 times. No need to stay a long time at LN temperature between the two cooling cycles (1 day seems sufficient, as no ageing is expected on HTS cable parts, if level of temperature keeps constant).

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	No	No	Yes (~77K)	No
<b>Why test is put here (or not)</b>	Same as for $I_c$ measurements		To check the thermomechanical strength of the complete system during cooling down and warming up including the insulation and HTS tapes. Cooling cycle test has to be done before $I_c$ measurements and voltage and impulse tests. Make visual inspection of cryostat (leakage) and check thermal losses degradation.	
<b>Difficulties</b>			Same as for capacitance measurements	

#### 4.3.6 Voltage test

Purpose: to ensure that the cable insulation withstands the network voltage during cable life.

Description: Tests are made with a complete cable system for sample and with complete operating system for type and after laying test. Tests are done after bending. The sample test is similar to the dielectric safety test of an oil cable.

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	open issue	Open issue	Yes (~77K)	Yes
<b>Why test is put here (or not)</b>	Same comments as for capacitance and tan $\delta$ tests.	To check that insulation manufacturing is reliable. This test must be conducted according to agreed frequency, e.g. one sample on each lot.	To check the good design and manufacture of lapped insulation; to be done after bending and cooling cycle tests. Time and voltage level in AC or DC to be specified in the future <sup>6</sup> .	To check the good manufacture and handling of lapped insulation and primarily the integrity of the complete system. Time and voltage level in AC or DC to be specified in the future <sup>3</sup> .
<b>Difficulties</b>	Same comments as for capacitance and tan $\delta$ tests.	Same as for capacitance measurements; this will cause <b>high cost</b> because of need to provide suitable provisional terminations.	Same as for capacitance measurements.	Same as for XPLE or oil cables.

#### 4.3.7 Impulse voltage test

Purpose: to ensure that the cable insulation withstands the network lightning voltage during cable life.

Description: Tests are made with a complete operating system for type tests. Tests are made after bending.

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	No	No	Yes (~77K)	No
<b>Why test is put here (or not)</b>			To check the good design, manufacture and handling availability of lapped insulation; to be done after bending and cooling cycle tests. Impulse voltage level to be taken from IEC 60071-1 (insulation co-ordination standard).	
<b>Difficulties</b>			Same as for capacitance measurements.	

#### 4.3.8 Partial discharge test

Open issue

<sup>6</sup> We can start from existing values in oil cables, but need to have a task force on this issue.

#### 4.3.9 Short circuit current test

Purpose: to check that the HTS core and screen configuration withstands the short-circuit currents in the network.

Description: Test is made with a complete operating system for type tests. Test is made after bending.

	<b>Routine</b>	<b>Sample</b>	<b>Type</b>	<b>After laying</b>
	No	No	Yes (~77K)	No
<b>Why test is put here (or not)</b>	Same as for $I_c$ measurements.		To check that design and manufacture of core and screen are sound <sup>7</sup> . To check the cable behaviour towards electro-dynamic forces(time and current level in AC to be specified by customers).	
<b>Difficulties</b>			Same as for capacitance measurements.	

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#### 4.3.10 Cryostat pressure test

The cryostat has to be certified according to local rules on pressurised apparatus. In some countries, tests could be avoided with high safety margin design. This is a pending issue that will have to be addressed in future installation.

#### 4.3.11 Cooling unit test

At first glance, we suggest to follow the rules existing in the cooling unit market (especially for commissioning tests), but this issue is not in the framework of this document.

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<sup>7</sup> Right now, we don't know whether the simple analytic calculations of short-circuit are correct, especially because they do not represent the transient phenomena; so, we recommend such a test, but in the future we can cancel it if an improved model of short-circuit will prove reliable with experience.

## 5 TESTS AT HTS POWER CABLES WITH EXTRUDED OR LAPPED WARM DIELECTRIC (WD) INSULATION

As explained in chapter 2 of this document, HTS cables with warm dielectric are different from conventional cables mainly with their inner conductor and cryostat whereas the outer components, especially the electrical insulation and screens are in principal identical to those of fluid filled or synthetic cables. Accordingly, most of the usual test procedures and requirements seem to be applicable unchanged to HTS WD cables, too.

So, we only emphasize hereinafter, what should have to be changed for HTS cable with extruded or lapped warm dielectric, compared to conventional cable.

### 5.1 Routine tests

All tests usually done for conventional cable should be kept unchanged with regard to usual standards for lapped or extruded insulation (high voltage, ionisation,  $\tan \delta$  and C, electric sheath test, partial discharges, etc...), except conductor resistance measurements.

Regarding HTS tapes, two choices are possible:

- To check the level of resistance at room temperature and compare it to the expected resistance of the cable core at room temperature; this permits to detect only a significant break in the core, i.e. HTS conductor + cryogenic jacket, but damage or break of a few tapes will not be detectable. Therefore, if any damage during handling has decreased  $I_c$ , the damage will be visible only at site after installation.
- To cool down the HTS core with LN and make measurements of  $I_c$ . For WD cable, cooling down is less time-consuming and complicated than in a CD cable, as there is no need to wait for insulation impregnation; but this test will, however, stay costly for each shipping length.

We suggest to wait for further feed back experiment before making such a choice.

Note : except core resistance issue, all routine tests do not require to cool down the SC core.

### 5.2 Sample tests

Most of tests usually done for conventional cable should be kept unchanged with regard to usual standards for lapped or extruded insulation (mechanical integrity, delamination, bending and high voltage test, dielectric power loss and power factor tests, ionisation, etc...), **with the exception that all tests are achieved only at room temperature**; furthermore, the need to achieve ageing testing, hot set tests and so on, is not obvious or at least must be reviewed. The reason is that, due to its design, the core of a WD cable will always operate quite at room temperature in real life.

Note : all sample tests above do not require to cool down the SC core.

➔ Besides, a measurement of critical current and AC losses at  $\sim 77$  K should be added to check that  $I_c$  is  $\geq$  and AC losses are  $\leq$  specified data (there is no need to make measurements at other temperature, as the law  $I_c(T)$  is intrinsic of the HTS material and does not rely on handling).

### 5.3 Type test

All tests usually done for conventional cable should be kept unchanged with regard to usual standards for lapped or extruded insulation (bending, impulse and voltage test, partial discharges,  $\tan \delta$ , heating cycle voltage test, etc ...), **with the exception that all tests are achieved only at room temperature for the same reason as for sample tests**. Therefore, for example, the “heating cycle voltage test” of IEC would become “20 days voltage test”.

Note : all type tests above do not require to cool down the SC core.

➔ Besides, specific tests related to superconductive features should be added:

- Critical current and AC losses have to be measured at  $\sim 77$  K after bending and cooling cycle test to check that the superconductivity of the HTS tapes comply with the specified data.
- Cooling cycle tests have to be done to check that the manufacture of HTS core is reliable with simulating the consequence of warming up and cooling down that could happen to the whole cable due to a LN leak in the event of a failure in a point of the link during its life.
- Short circuit tests have to be done to check the HTS core's behaviour towards the electro-dynamic forces.

#### **5.4 Test after installation**

The tests usually done for conventional cable should be kept unchanged with regard to usual standards for lapped or extruded insulation (voltage test on insulation, sheath, etc ..).

*Additional tests could be considered taking into consideration a commercial plant (cable without monitoring), to check that the specified performances are reached:*

- $\Delta P$  measurement for LN
- $\Delta T$  measurement for LN with voltage and load
- Measurement of total losses without voltage and load
- Measurement of total losses with voltage and load

We add the same comments as for CD cable (see §4.3.10 and 4.3.11): the cryostat has to be certified according to local rules on pressurised apparatus. For cooling unit, we suggest to follow the rules existing in the cooling unit market (but these two issues are not in the framework of this document).

#### **5.5 Comments on prequalification tests**

This is still an open issue, as already written for CD cable (see detailed comments in § 4.2.4): on one side, prequalification test would not bring any relevant information when this type of cable will have reached a commercial maturity. On the other side, a customer who will buy for the first time a HTS system would strongly ask for such a test.

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## ANNEXES : DETAILED SPECIFICATIONS

### Annex 1: feasibility study

#### **Data to be provided by the customer to the supplier:**

- $U_0$  Rated Voltage phase to earth (kV)
- $U$  Rated Voltage phase to phase (kV)
- $U_m$  Highest Voltage phase to phase (kV)
- $U_p$  Lightning Impulse Voltage (kV)
- Nominal Power (MVA)
- $I_n$  Nominal Current (A)
- Short Circuits Characteristics:
  - o Current (kA)
  - o Duration (ms)
  - o Re-closure procedure
- Type of cable
  - o Warm Dielectric
  - o Cold Dielectric
    - Rigid or flexible cryostat
    - Single-phase or three-phase
- Possible applicable standard (*to be defined under a specific task*)
- N° of circuits
- Frequency (Hz)
- New installation or retrofit
- Route characteristics
  - o Length (km)
  - o Profile
  - o Particular route constraints
- Possible location for refrigeration units

*The technical contents of the study could be agreed or could be at the discretion of the supplier.*

## **Annex 2: rough quotation**

Data to be provided by the customer to the supplier

### **Electrical Data**

- $U_0$  Rated Voltage phase to earth (kV)
- U Rated Voltage phase to phase (kV)
- $U_m$  Highest Voltage phase to phase (kV)
- $U_p$  Lightning Impulse Voltage (kV)
- Nominal Power (MVA)
- $I_n$  Nominal Current (A)
- Frequency (Hz)
- Overload conditions
- Short Circuits Characteristics:
  - o Current (kA)
  - o Duration (ms)
  - o Re-closure procedure

### **System/Cable Data**

- N° of circuits
- Type of cable
  - o Warm Dielectric
  - o Cold Dielectric
    - Rigid or flexible cryostat
    - Single-phase or three-phase
- Possible applicable standard (*to be defined under a specific task*)

### **Installation Data**

- New installation
  - o Buried
  - o In tunnel
  - o In duct
  - o In pipe
- Retrofit
  - o In tunnel
  - o In duct
  - o In pipe
- Route characteristics
  - o Length (km)
  - o Profile
  - o Particular route constraints
- Possible location for refrigeration units

*The technical contents of the offer could be at the discretion of the supplier.*

### **Annex 3: binding tender**

For the sake of completeness we are dividing the data in three categories even if all this information will be collected in a single contractual document:

- Data to be provided by the customer to the supplier
- Data to be provided by the supplier when answering the tender
- Data to be provided by the supplier after the awarding of the contract

#### **1) Data to be provided by the customer to the supplier**

##### ***Electrical Data***

- $U_0$  Rated Voltage phase to earth (kV)
- U Rated Voltage phase to phase (kV)
- $U_m$  Highest Voltage phase to phase (kV)
- $U_P$  Lightning Impulse Voltage (kV)
- Nominal Power (MVA)
- $I_n$  Nominal Current (A)
- Frequency (Hz)
- Over-current (A) as a function of frequency and duration of over-current period [see note 1](\*)
- Short Circuits Characteristics: [see note 2]
  - o Current (kA)
  - o Duration (ms)
  - o Re-closure procedure

(\*) All notes are listed in **Annex 4**

##### ***Cable Data***

- Type of insulation for WD cable only
  - o Lapped
  - o Extruded
- Components
  - o Tape
    - Material
- Applicable standard [see note 3]
- Tests [see note 5]
  - o Type tests
  - o Factory - Routine tests
  - o Sample tests

##### ***Cryostat Data***

- Applicable Standards (design, manufacturing, testing, safety)
- Maintenance
  - o Allowed time between maintenance
  - o Maximum time for maintenance
- Maximum thermal efficiency degradation between maintenance intervals

##### ***Accessories Data***

- Applicable standard [see note 3]
- Tests
  - o Type tests
  - o Factory - Routine tests

##### ***Installation Data***

- Environmental conditions (min. and max. temperature, altitude, etc.) [see note 8]
- New installation
  - o Buried
  - o In tunnel
  - o In duct
  - o In pipe

- Retrofit
  - o In tunnel
  - o In duct
  - o In pipe
- Route characteristics
  - o Length (km)
  - o Profile
  - o Inaccessible sections along the cable route (n° and relative length)
  - o Manhole distribution and dimensions
  - o Possible location for joints
- Possible location for refrigeration units
  - o Available space
  - o Available voltage and power supply
  - o Available pressure and flow water supply
- Environmental requirement
- Environmental constrains (e.g. presence of water)
- Accessories
  - o Available space for installation
  - o Terminations (warm part)
    - connecting conditions: drawing of customer's connecting parts
    - pollution level of installation area (according to standard IEC 60815 article 3)
    - Temperature min and max on upper connections part
- Drawing of trench, duct bank etc.

#### **System Data**

- N° of circuits
- Electrical scheme
- Cable screen connection (for Warm Dielectric only)
  - o Single point bonding or cross bonding system [see note 9]
  - o Applicable standard [see note 3]
- Tests [see note 5]
  - o Pre-qualification tests
  - o After-laying tests

#### **Refrigeration plant**

- Applicable Standards (design, manufacturing, testing, safety)
  - o Operational + Maintenance Limit
  - o Permitted time of outage (n° of outage per unit of time(years)) for warming up, repair and cooling down
  - o Allowance for using back system based on LN delivery on site
  - o Time allowed for repair
  - o Minimum current flow guarantee during repair as a function of the repair duration
  - o Time allowed for maintenance
- Control and monitoring
  - o Information required to be seen by the operator

#### **Cable marking and identifications**

- reference to the future standard [see note 3]
- name of manufacturer
- identification of superconducting material tapes
- assigned voltage  $U_0/U(U_m)$
- assigned current  $I_0$
- manufacturing year and batch

### **2) Data to be provided by the supplier when answering the tender**

#### **Cable Data**

- Type of cable
  - o Warm Dielectric
  - o Cold Dielectric
    - Rigid or flexible cryostat

- Single-phase or three-phase
- Cross-sectional drawing (main dimension, cable outer diameter with tolerances)
- Tape Material
- Electrical characteristics
  - Capacitance ( $\mu\text{F}/\text{km}$ )
  - Inductance ( $\text{mH}/\text{km}$ )
- N° of shipping length
- Dimensions and weight of shipping reels
- Cable pulling strength per cable length

#### ***Cryostat Data***

- Size
- Weight
- Maintenance
  - General maintenance procedure
  - Foreseen time between maintenance
  - Foreseen time for maintenance

#### ***Accessories Data***

- Terminations [see note 6]
  - Overall dimensional drawings (without tolerances)
  - Overall thermal losses
- Joints [see note 7]
  - Overall dimensional drawings (without tolerances)
  - Space requirement for the joint bay
  - Overall thermal losses

#### ***Installation Data***

- Refrigeration units
  - Space needed
  - Voltage and power supply requirements
  - Pressure and flow water supply requirements
- General description of the installation procedure
- Time required for installation
- General description of the cooling down procedure
- Time required for cooling down
- General description of the warming up procedure
- Time required for warming up
- General description of the repair procedure
- Time required for repair

#### ***System Data***

- Hydraulic scheme (n° of refrigerators, LN path, etc.)
- Service and emergency (overload, short circuit) conditions (flow rate, temperature and pressure) for the coolant
- Overall cold losses ( $\text{W}/\text{m}$ ) at different operating conditions:
  - System cold
  - System energised
  - System in operation at 50% of the nominal power
  - System in operation at the nominal power

#### ***Refrigeration plant***

- Scheme and General technical description
  - Electrical scheme
  - Hydraulic scheme
  - Type of cooling cycle
  - Electrical requirements
  - Water supply requirements
  - Overall dimensions. Drawing for main sub-assemblies
  - Range of temperature LN input and output from cooling unit

- Evolution of cold power versus output LN temperature
- Operational + Maintenance Limit
  - Maintenance interval
  - Mean Time between Failure (MTBF)
  - Safety guard against cooling liquid or gas (pressure relief valve, space for cooling liquid relief)
- Control and monitoring
  - Scheme
  - Technical description

### 3) Data to be provided by the supplier after the awarding of the contract

#### *Cable Data*

- Description (see attached Data Sheet samples)
- Components [see note 4]
  - Tape
    - $J_c$  : critical current density ( see § 2.1) of the superconducting part of the HTS tapes (at 77K ; self field)
    - $J_e$  : effective critical current density, that takes into account the overall section of the HTS tapes (for example, OPIT tapes contains more than 60% of silver alloy - see §2.2).
    - $I_c (A_{dc})$ : critical current of HTS tapes as a function of temperature for the operating range +20 K
    - Curves  $V (\mu V/cm)$  as a function of  $I (A_{dc})$  of the HTS tapes for the temperature operating range +20 K
- Conductor
  - “n” value : with ac current , the voltage’s evolution of the HTS conductor is roughly as follows :  $V_{ac} \approx I_{ac}^n$  , insofar  $I_{peak}$  does not reach critical current; n value is generally around 2

#### *Cryostat Data*

- Maintenance: detailed procedures

#### *Accessories Data*

- Terminations [see note 6]
  - Space requirement
  - Detailed dimensional drawings
  - Scaffolding and/or supporting structure
- Joints [see note 7]
  - Space requirement
  - Detailed dimensional drawings
  - Supporting and/or fixing structure

#### *Installation Data*

- Installation procedure
- Cooling down procedure
- Warming up procedure
- Repair procedure

#### *Refrigeration plant*

- Scheme and detailed technical description
  - Electrical scheme
  - Hydraulic scheme
  - Type of cooling cycle
  - Electrical requirements
  - Water supply requirements
  - Overall dimensions. Drawing for main sub-assemblies
  - Book for all running, maintaining and emergency operations.

**Annex 4: notes**

- **note 1:** Overcurrent could be specified by indicating for example:

<i>Event</i>	<i>Frequency</i>	<i>Duration</i>	<i>Overcurrent</i>
<i>1</i>	<i>1 day</i>	<i>10 s</i>	<i>n1* In</i>
<i>2</i>	<i>1 month</i>	<i>10 min</i>	<i>n2* In</i>
<i>3</i>	<i>1 year</i>	<i>10 days</i>	<i>n3* In</i>

- **note 2:** The particular electrical characteristics of HTS cables require that the short-circuit level must be verified with a network power flow analysis.
- **note 3:** To be defined under a specific task.
- **note 4:** Apart from the overall performances for system, cable and accessories it is very difficult, at this stage, to determine which type of data can be disclosed to the customer avoiding any infringement of IPR.

*On the cable components side, for example, the following parameters could be provided as additional technical information to be used for differentiating between different manufacturers.*

Example of data sheet for CD cable description to be provided by the supplier after the awarding of the contract

<b><i>Element/Material</i></b>	<b><i>nom. thick. (mm)</i></b>	<b><i>width (mm)</i></b>	<b><i>nom. diam. (mm)</i></b>	<b><i>net. Weig ht (kg/m)</i></b>	<b><i>Technical data</i></b>
<i>LN duct (if present)</i>					
<i>HTS tape support</i>					
<i>HTS conductor:</i>					
<i>Semiconducting screen</i>					
<i>Insulation</i>					
<i>Semiconducting screen</i>					
<i>HTS return conductor:</i>					
<i>External screen and protection</i>					
<i>LN channel</i>					
<i>Cold cryostat wall</i>					
<i>Spacer</i>					
<i>Thermal insulation</i>					
<i>Warm cryostat wall</i>					
<i>Protection</i>					

Example of data sheet for WD cable description to be provided by the supplier after the awarding of the contract

<i>Element/Material</i>	<i>nom. thick. (mm)</i>	<i>width (mm)</i>	<i>nom. diam. (mm)</i>	<i>net. weig ht (kg/m)</i>	<i>Technical data</i>
<i>LN duct</i>					
<i>HTS tape support</i>					
<i>HTS conductor:</i>					
<i>Cold cryostat wall</i>					
<i>Spacer</i>					
<i>Thermal insulation</i>					
<i>Warm cryostat wall</i>					
<i>Semiconducting screen</i>					
<i>Insulation</i>					
<i>Semiconducting screen</i>					
<i>External screen and protection</i>					

- **note 5:** *This item should be covered in the applicable standard to be defined under a specific task. Customer will provide reference to future standards for SC cable which would correspond to those for impregnated paper (IEC 60055-1 and 2,) oil filled and gas-pressure (IEC 60141-1,2 and 3), or for extruded cable ( i.e. IEC 60502, 60840 or 62067), especially for test voltages. These standards will have to be completed, especially for pre-qualification or type tests, with overcurrent and short-circuit tests, long term tests etc.*
- **note 6:** *At present only terminations for outdoor or indoor installation are under development. These components will be taken into consideration for the definition of the relevant testing procedure.*
- **note 7:** *At present feeding joints are not taken into consideration.*
- **note 8:** *The contractor should generally acquire all the information related to the installation condition (pipe/duct conditions, bending radii, space availability etc.) by means of a route survey.*
- **note 9:** *Taking into account the very high level of current considered for HTS cables a solid bonding system seems not to be applicable.*