Central Power Research Institute

Vol. 20(2)/167-175, December 2024
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v20i2.1183

Power Research

Design, Development, Testing and Analysis of a Termination Unit for A 1-ϕ, LN_2 Cooled Cold Dielectric HTS Power Cable Rated at 11 kV and 1 kA

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Abstract

Termination units serve as links between the incoming power supply (at ambient conditions) and the High-Temperature Superconducting power cable (at cryogenic temperature). These devices are electro-mechanical and therefore their design requires a multifaceted engineering approach which takes into account the electrical and mechanical aspects together. The focus of the present work is to design, develop and test a termination unit for a 1-ϕ LN_2 cooled HTS power cable rated at 11 kV and 1 kA. The design steps and fabrication procedure are shared in detail and the device has been analyzed structurally. Finally, key test results related to the leak test, high voltage test, cooldown and performance of the current lead of the termination unit are discussed.

Keywords: HTS Power Cable, Termination Unit

1. Introduction

High Temperature Superconducting (HTS) power cables are being developed and installed in girds across the world[1,2]. After having developed India's first 1-ϕ, 1.5-m long cold dielectric HTS power cable rated at 10 V and 1 kA[3], the Indian Institute of Technology (IIT), Kharagpur sponsored by Central Power Research Institute (CPRI), Bangalore developed another 5-m long 1-ϕ liquid nitrogen cooled cold dielectric HTS power cable rated at 11 kV and 1 kA. The first 1.5-m long cable, a newly developed 5-m long cable and another 0.5-m long cable were joined to make a 7-m long HTS cable[4].

One of the main issues faced in the development of the 1.5-m long cable was that of frosting at the ends of the cable as shown in Figure 1. Though undesirable, the frosting was not a major issue as the operating voltage level was ~10 V. However, when developing a cable at high voltage levels, like the 5-m long cable (rated at 11 kV and 1 kA), frosting is not permissible. The termination unit is a device that prevents and tackles the issue of frosting, especially near the excited conductor.

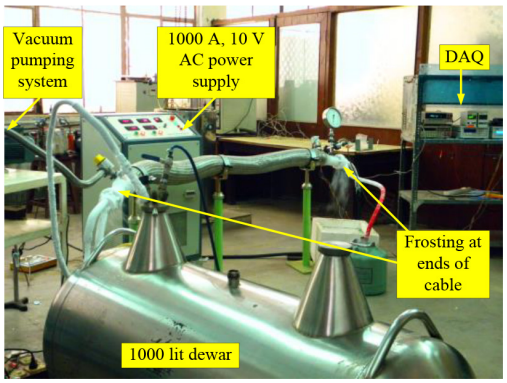


Figure 1. Photograph of 1.5-m long HTS cable with the issue of frosting observed at ends of the cable[3].

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The termination unit includes a current lead which connects the power supply (at ambient temperature -300 K) and the HTS power cable (at cryogenic temperature – 77 K). The current lead is positioned inside a double walled vacuum insulated cryostat which is flooded with pressurized LN_2. A combination of a bushing and PolyPropylene Laminated Paper (PPLP) serves as the dielectric material. Another function of the current lead is to carry the rated current with a minimum contribution of heat-in-leaks to the LN_2 inside the termination unit. According to the Wiedemann Franz law, good electrical conductors are also good thermal conductors. This presents a challenge in designing end terminals. The terminations have to handle the flow of LN_2 passing through the cable[5]. Existing literature reports termination units installed over the globe for HTS cables and the problems associated[6-10].

The primary objective of this work is to design, develop and test a termination unit for the 5-m long HTS power cable developed by IIT Kharagpur and funded by CPRI Bangalore. A detailed design procedure highlighting the design factors and necessary analysis is shared in Section 2. Section 3 provides the fabrication details, key dimensions, Material of Construction (MoC) and assembly. Finally, Section 4 summarises the test results. The present work can serve as a guideline to be followed when designing and developing termination units for future HTS power cables with similar or higher power ratings.

2. Design Details

The design of a termination unit for HTS power cables is not solely an electrical problem; rather, an electro-mechanical design approach has to be undertaken. Thus, the design requires an interdisciplinary engineering approach which takes into account the electrical and mechanical aspects together. Additionally, design parameters are linked thus requiring an iterative approach. The requirements of a termination unit are:

1. The current lead has to carry the rated current with minimum heat-in leaks into the device via the current lead.
2. Withstand the rated high voltage between the current leads (and conducting parts) and the cryostat body which is at ground potential.
3. The device has to be compatible with the operating temperature and pressure of the cryogen flowing through the cable.
4. The device needs to be thermally insulated to minimize heat-in-leaks from the ambient at 300 K (outside) to the cryogen at 77 K (inside) to minimize the boil-off of the cryogen.

The specifications of the HTS power cable are shown in Table 1. Figure 2 summarizes the design procedure followed to develop the termination unit.

Table 1. Specifications of HTS power cable developed at IIT Kharagpur

Parameter	Value
Rated Current	1 kA
Rated Voltage	11 kV
Cryogen	LN_2
Temperature of cryogen	~77 K
Pressure of cryogen	3 bara
Thermal insulation	Vacuum insulation (~10^{-5} mbar)

The termination unit is designed based on the rating of the HTS power cable, such as operating current, voltage, temperature, pressure and thermal insulation. The design of the current lead is dependent on the operating current, temperature conditions at either end and the material of construction. Though the current lead is the major source of heat-in-leak into the device[11], it is unavoidable and thus has to be optimized to minimize the heat-in-leaks.

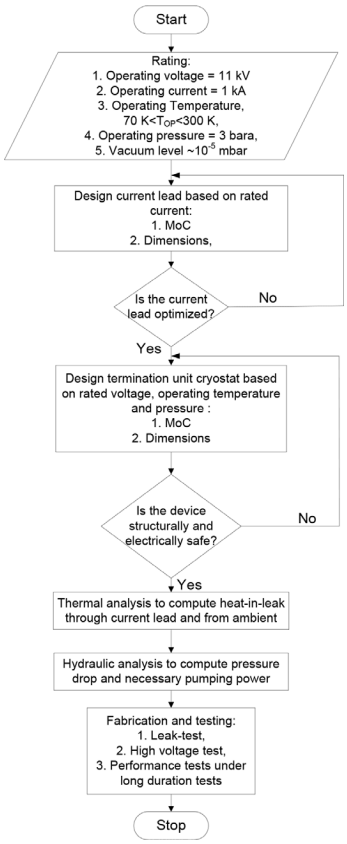


Figure 2. Flowchart for design, analysis and testing of termination unit for HTS power cable.

The design of the termination unit cryostat depends on the operating pressure and the voltage levels. Again, an iterative design approach is essential to ensure that the device is safe for operation due to high voltage and high operating pressure.

2.1 Electrical Aspects

The design parameters include the operating current and voltage.

2.1.1 Current

The termination includes a current lead[12] connecting the HTS cable conductor through an electrically insulated bushing to the power source at ambient temperature. The large temperature gradient across the current lead creates thermal stresses and this gradient is the reason for the current lead being the primary source of heat leakage from room temperature to low temperature. This heat-in-leak determines the operating costs of the superconducting power cable[4]. An ideal current lead should have low thermal conductivity to minimize heat-in-leak via thermal conduction, and high electrical conductivity to minimize joule heating. Usually, copper is used as the MoC for current leads. The optimum dimensions of the current lead can be estimated by Xiao *et al.*[13].

$$\left(\frac{1}{A}\right)=\frac{\bar{\lambda}}{I\sqrt{L_0}}\cos^{-1}\frac{T_1}{T_h} \quad (1)$$

where, l is the length of the current lead which is to be determined, A is the circular cross-section area of the current lead corresponding to a diameter of 20 mm, is the average thermal conductivity (420 W/mK), T_l and T_h are the temperatures at the cold and warm end respectively (77 and 300 K), L_0 *is the* Lorenz number (=2.35×10^{-8} W.Ω/K^2) and I is the operating current (=1000 A). The optimum length was determined to be 1.13 m.

2.1.2 Voltage

The operating voltage primarily influences the dimensions of the termination unit cryostat. Figure 3 shows the modes of breakdown and electrical discharge between the current lead at high electric potential and cryostat body at ground potential and denotes the distances for five basic modes of discharge namely:

A: Surface flashover distance along the Teflon surface in the air.

B.: Surface flashover distance along Teflon-LN$_2$ interface.

C.: Dielectric breakdown/puncture along bulk PTFE.

D.: Dielectric breakdown of LN$_2$ bulk.

E.: Arcing distance between current lead and cryostat through the air.

1. A: The flashover along A occurs due to the presence of surface roughness of the PTFE-air interface. The pollutants and moisture in the surroundings adhere to the surface of Teflon, decreasing the local dielectric strength. This distance can be determined using conventional design methods for electrical bushings. From Ren *et al.*,[14] we get this distance as:

$$A = d_{cs} \times U_m \times k_d \quad (2)$$

where, d_{cs} is the minimum flashover distance per 1000 volts, based on pollution strength. For our design, d_{cs} is considered as 25 mm/kV. U_m is the maximum operating voltage. Here, the rated line voltage is 11kV resulting in a peak voltage of about 16 kV. Considering a factor of safety of 1.1, U_m becomes 17.6 kV. k_d is the correction factor related to the average diameter of busing (k_d = 1 when the average diameter is less than 300 mm). Thus, the minimum value of A is 440 mm.

2. B: The flashover along B occurs at the interface of Teflon and LN$_2$. The discharge occurs due to surface roughness induced while machining the Teflon. Additionally, the bushing acts as a heat source resulting in bubble formation at the PTFE- LN$_2$ interface, leading to degradation in the insulation property of either Teflon or LN$_2$[15]. From[16,17], the flashover distance for gradual AC or impulse excitations in the 20-30 kV range is 5 mm, which is the minimum value of B.
3. C: The breakdown along this distance in the Teflon bulk is dependent on its dielectric properties. From[18], PTFE has a dielectric strength of 24 kV/mm resulting in a required thickness of 1 mm.
4. D: From[19], for LN$_2$ at 77 K and 1 bara, the calculated minimum thickness (in radial direction) of LN$_2$ is 1 mm.
5. E: Air has a dielectric breakdown strength of 3 kV/mm. Therefore, for a design voltage of 11 kV, the required thickness to prevent arcing between the conductor and cryostat body, the minimum air gap required is 4 mm.

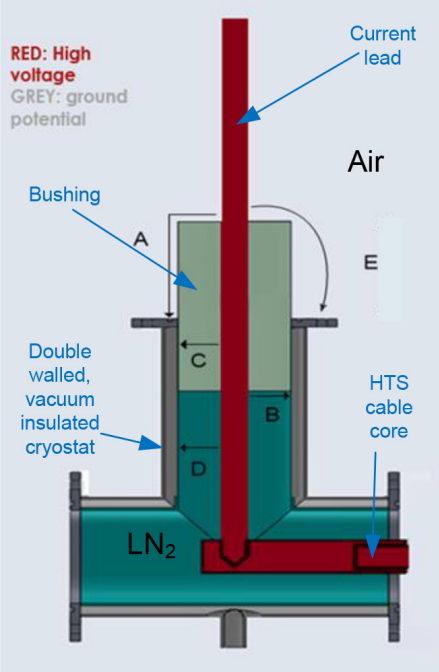


Figure 3. Sectional view of conceptual termination unit and modes of electric discharge.

Further, the Teflon bushing in this design also has to support the current lead of 1.16 m with a 12 TPI thread along 50% length of the lead. Also, the Teflon seals the top of the termination unit cryostat, thus facing the entire design pressure of 3 bara. Taking into consideration all the electro-mechanical constraints and manufacturing tolerances, the distances A, B, C, D and E were selected as shown in Table 2.

Table 2. Basic insulation distances

A (mm)	B (mm)	C (mm)	D (mm)	E (mm)
500	25	25	25	300

In conventional HV towers, ceramic insulators are employed. However, ceramic is brittle, particularly at cryogenic temperatures and hence cannot be employed for electrical bushings in termination units for HTS power cables. Other alternatives include Glass Fibre-Reinforced Plastic (GFRP) and Teflon. Because of prior experience with working with Teflon at cryogenic temperature, Teflon was selected as the material for the electrical bushing.

In the case of normal termination units, the ground termination is provided with stress control materials. Similar stress cones were reported for HTS terminations as well[20,21]. However, the rated voltage was of the order of 35 kV. Since the present work deals with an 11 kV termination unit, it was decided to analyse the electric field distribution around the current lead of the termination unit using Finite Element Method (FEM) to study the electric field distribution. Comsol Multiphysics was the software tool used. The electric field distribution around the current lead is shown in Figure 4. Case (a) corresponds to the electric field distribution around the current lead when it is bare; that is, exposed directly to LN_2 (which itself is a dielectric). Case (b) corresponds to the case wherein layers of PolyPropylene Laminated Paper (PPLP) were wrapped around the current lead; thereby confining the electric field. Since PPLP is used for the design of the HTS power cable, it was decided to use the same around the current lead as well. Therefore, for the present design 10 layers of PPLP (each layer having a thickness of 120 μm) were wrapped around the current lead and no additional stress cone was provided. However, stress concentration points were observed at the edges near the T-shaped cryostat and also near the edges of the horizontal copper lead. Further investigation needs to be carried out to address the stress points and to develop stress cones capable of operating in the LN_2 environment.

Table 3. Relative permittivity (ε_r) of materials[22]

Material	ε_r
Copper former	1
PPLP	2.25
LN_2	1.43
SS304	1
Teflon	2

2.2 Mechanical Aspects

As the termination unit will be flooded with LN_2 (77 K), it has to be well insulated (thermally) from the ambient temperature (300 K). Thus, there is a need for effective thermal insulation. Additionally, it also has to withstand the pressure (which may rise on account of boil-off of LN_2). The termination box will have to sustain many cycles of cooling and warming up back to ambient temperature. LN_2 entering should sufficiently cool the current leads. The flow of the LN_2 should be such that it is circulated throughout the termination box, cooling the current leads sufficiently.

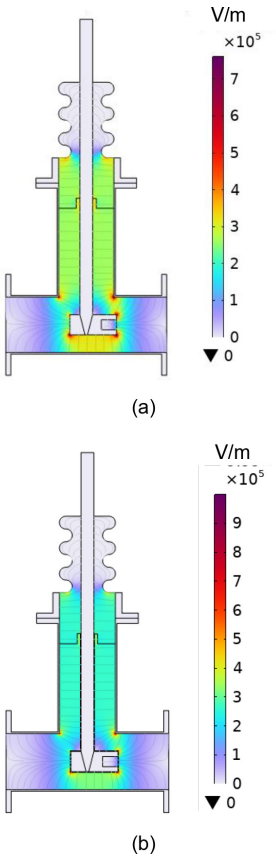


Figure 4. Electric field contour **(a)** without PPLP **(b)** with 10 layers of PPLP.

2.2.1 Temperature and Pressure

The inner vessel houses the current lead (solid copper cylindrical rods) and the joint between the current lead and the HTS cable core. Since this vessel will be flooded with LN_2, it will have to sustain a number of cycles of cooling from 300 K to 77 K and warming up from 77 K to 300 K. Thus, the inner vessel (SS 304) will expand and contract for every cooling and warming cycle. To realize the stresses endured by the vessel, the inner vessel was numerically analyzed in SOLIDWORKS. Figure 5 (a) shows a 3D CAD model of the vessel and the boundary conditions applied to the faces. The inner faces of the vessel are kept at 77 K, while the initial temperature of the body is 300 K. Similarly, an internal pressure of 3 bara is applied to the inner face while the pressure acting on the outer face is 0 bara (since it is exposed to vacuum pressure). The three edges are fixed since they are welded to the flanges which in turn are welded to the outer vessel. The geometry was meshed and the following equations were solved to determine the deformation, strain and stress endured due to the applied differential pressure[23].

$$\nabla \cdot \mathbf{S} + \mathbf{F}_V = 0 \quad (3)$$

where, $\mathbf{S}$ is the stress and $\mathbf{F}_V$ is the volumetric force.

For studying the effect of shrinkage due to chill down (from ambient to cryogenic temperature) the following equation is solved,

$$\Delta l = L\alpha\Delta T \quad (4)$$

where, Δl is the change in length (shrinkage) to be computed, α is the thermal expansion coefficient, L is the original length (at T=300 K) and ΔT is the change in temperature. It was observed that the stresses endured were beyond the yield stress for SS304 resulting in permanent plastic deformation as shown in Figure 5 (c). This issue was addressed by providing bellow/corrugated pipe sections at two of the three ends of the inner vessel as shown in Figure 5 (d). Additionally, for safety due to a break in the vacuum or sudden boil-off, a safety relief valve may be added to protect the device.

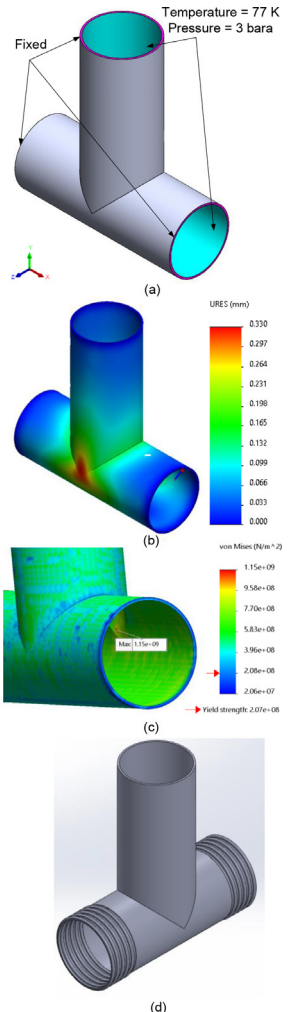


Figure 5. **(a)** Boundary conditions **(b)** Resultant deformation **(c)** Stress endured by inner vessel and **(d)** Corrugation portion added at either side to accommodate shrinkage and stress.

In the present case, however, due to the short length of the HTS cable and because the end terminal unit is open to atmospheric pressure, no pressure relief valve was provided.

2.2.2 Heat-In-Leaks

To minimize the heat-in-leaks from the outside ambient (300 K) to the cryogen inside (77 K), thermal insulation in the form of vacuum insulation was provided. The cryostat is, therefore, a double-walled vessel wherein the annular space between the inner and outer shells is evacuated to a vacuum pressure of the order of 10^{-5} mbar. The heat-in-leaks may further be reduced by employing Multi-Layer Super Insulation (MLSI)[24]. However, in the present case, MLI was not used in the annular space.

2.2.3 Supporting Structures for Current Leads

The current lead is a solid copper rod that weighs ~4 kg. Also, since they are at a high electric potential compared to the cryostat body, they have to be positioned concentrically with respect to the body of the cryostat. For this reason, spacers (Teflon) were provided as shown in Figure 6.

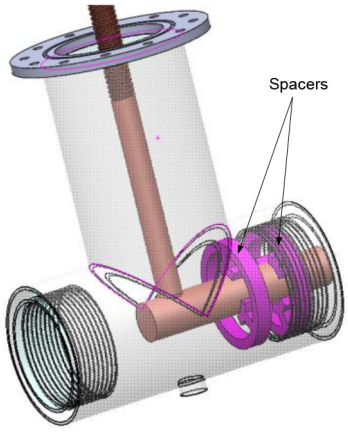


Figure 6. 3D CAD model of modified termination unit with Teflon spacers.

An important point to note is that these supporting structures, while they fulfil their purpose of positioning the current leads, must not hinder the flow of LN_2 through the termination. Additionally, to bear a portion of the mass and to limit the leak of cryogen between the bushing and current lead (at the top of the termination unit), matching threading is provided on both the vertical current lead and the Teflon bushing. A 3D CAD model and exploded view of the developed termination unit is shown in Figure 7. The list of components and materials of construction is shown in Table 4.

3. Fabrication Details

A photograph of the fabricated termination unit is shown in Figure 8. A KF 25 vacuum port was provided at the bottom of the unit. The assembly procedure may be realized by observing Figure 7. The cryostat, with the inner and outer vessels, is a single body. The core of the HTS cable is inserted into the axial bore of the horizontal copper rod. This is a soldered joint. Next, the current lead is threaded into the bushing which in turn is threaded to the top collared flange. The spacers are inserted to position the horizontal rod.

The horizontal and vertical current lead connection is a bolted joint for ease of assembly and disassembly. Initially, a cup and cone arrangement was planned. However, due to high contact resistance, the cup and cone arrangement was replaced by a bolted joint as shown in Figure 9. Finally, the Teflon bushing is inserted followed by bolting of the end flange. Teflon rope was used in the O ring grooves for sealing between the flanges.

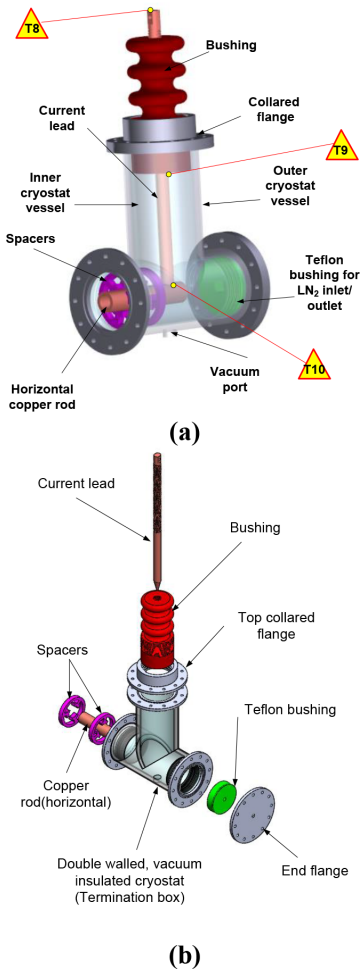


Figure 7. 3D CAD model of **(a)** modified termination unit, **(b)** exploded view.

Table 4. Components and Material of Construction (MoC)

Component	MoC
Current lead	Copper
Current lead bushing	Teflon
Inner vessel	SS304
Outer vessel	SS304
Spacers, Teflon bushing	Teflon
End flange	SS304
Horizontal rod	Copper
Top collared flange	SS304

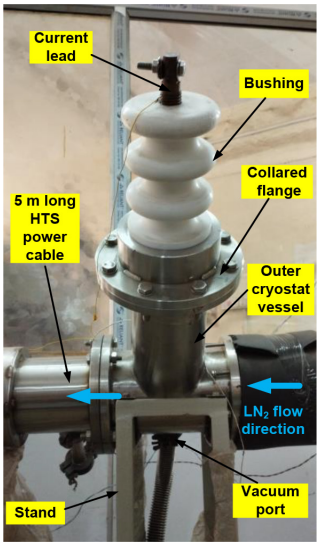
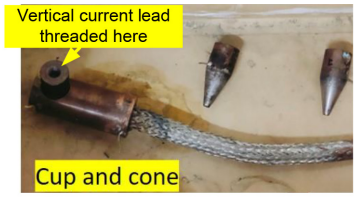
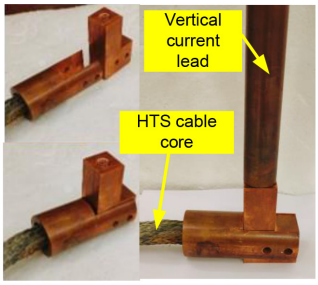


Figure 8. Photograph of fabricated termination unit.



(a) Initial design – Cup and cone arrangment



(b) Modified design – Bolted joint

Figure 9. Photograph of the initial and modified joint between the current lead and HTS cable core.

4. Results and Discussions

Once the termination unit was fabricated the following tests were performed.

4.1 Leakage Tests

Initially, during the cooldown of the cable with LN_2, due to shrinkage, leaks (LN_2 drops) were observed at multiple locations. For the flanged connections, it was observed that the Teflon O-rings were not suitable and hence the Teflon O-rings (circular cross-section) were replaced by asbestos Teflon (PTFE) ropes (rectangular cross-section). For the top collared flange joint and Teflon bushing, the threads were wrapped with Teflon tape and no leakage was observed. This may be on account of the pressure drop along the threads resulting in sealing. Similarly, no leaks were observed between the copper current lead and Teflon bushing.

4.2 High Voltage Test

For the high-voltage tests, a separate cable prototype was developed and the breakdown voltage was determined at different locations of the termination unit. The results of the HV test are summarized in Table 5. Additionally, a long-duration test was conducted wherein the current lead and cable core were charged and held at 15 kV (140% of rated voltage) for a period of ~6 h as shown in Figure 10. During this period, the leakage current was observed to be less than 0.01 mA.

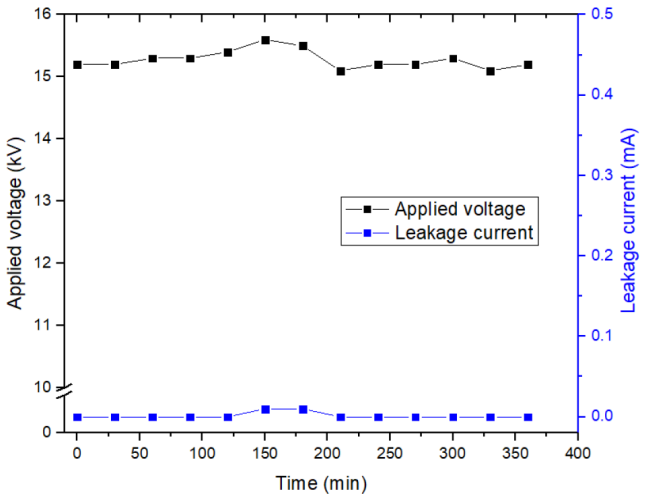


Figure 10. Plot for long-duration HV test.

Table 5. Results of high voltage test

Location	Breakdown voltage (Leakage current > 0.01 mA)
Current lead joint (inside termination unit)	25.09 kV
The outer surface of the Teflon bushing	26.12 kV

4.3 Cooldown and Performance Test of Current Lead

The developed termination units along with the HTS power cable were tested under varying operating currents. The plot of temperature, flow rate and current with time when excited with an AC power supply is shown in Figure 11. The location of the RTDs T8, T9 and T10 are shown in Figure 7 highlighted by yellow triangles.

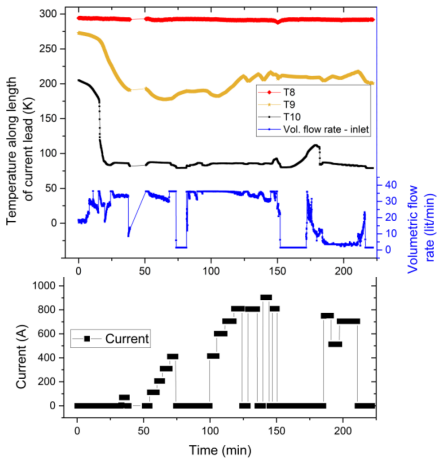


Figure 11. Plot of temperature, volumetric flow rate and current vs time for developed termination unit.

The volumetric flow rate corresponds to the flow rate at the entry of the power cable. Similarly, the HTS power cable along with the termination unit was tested with a DC power supply separately and the performance was found to improve. This may be attributed to the skin effect due to AC excitation.

The issue of stress concentration needs to be addressed by the provision of stress cones which are compatible with cryogenic temperatures.

5. Conclusion

A termination unit for an HTS power cable rated at 11 kV and 1 kA was designed, developed and tested. A detailed design procedure is shared. The dimensions of the device, material of construction and structural analysis procedure required to analyse the termination unit are summarized. The developed termination unit was successfully tested and is presently part of the functioning HTS power cable at IIT Kharagpur. This paper can serve as a template to be followed when designing and developing termination units for future HTS power cables with similar or higher power ratings.

6. Acknowledgement

The authors would like to thank Central Power Research Institute, Bangalore for their funding towards the project on HTS power cable.

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