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Design of Electrical Terminals for High Temperature Superconducting (HTS) Power Cable

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Abstract

HTS cables are designed to carry bulk power with high ampacity in superconducting state. These cables require terminal connectors of same ampacity to transfer power from source to load via HTS cable. This paper deals with thermal analysis of 2 kA, 220V DC terminal connector for HTS cable. The ohmic losses were computed and were used as an input for steady state thermal analysis of HTS terminal connector. Based on thermal analysis optimal location of feed through is estimated for thermal stability of HTS cable.

Keywords: Cryogenics, End Termination, Heat Transfer, HTS Cable, FEM

1. Introduction

Superconducting power cable has the ability to carry large amount of current with negligible joule loss and requires lesser space when compared with conventional power cables for the same rating. HTS cable specification varies with the operating conditions like number of phases, ampacity, operating voltage[1,2]. The designed cable should be able to comply with electrical, mechanical, structural, vacuum and cryogenic standards and requirements for operation of complete system. One of the challenges in the development of superconducting cable system is to design its end terminations. End terminations are used to connect the power source and load which are kept at room temperature (300 K) to the superconducting cable which is operating at cryogenic temperature (below 77 K).

The end terminal design of superconducting cable is more complicated and difficult to fabricate when compared to the conventional copper cable of same rating[3,4]. This is because HTS cable is operated using cryogen at 77K and below which has vacuum jacket as a thermal insulator to reduce boil off of cryogen. In order to connect the load, the cable has to be brought out of this multi-chamber cryostat using copper conductor. Copper being good conductor provides less electrical resistance but introduces heat in leak conduction path into cryostat which causes boil off of cryogen. Longer the length of copper conductor higher will be electrical resistance as well as heat in leak. On other hand, reduction of length of copper conductor will result in reduction of dielectric strength of cable. Thus, selection of optimum conductor length and cross-sectional area will help in no frost formation and reduced heat in leak due to end termination.

This paper focuses on design of 2 kA, 220 Volt DC terminal connector for HTS power cable. Initially, ohmic losses in the copper terminal were computed analytically based on the cable ampacity for assumed dimensions of current leads. The computed ohmic losses were then used as an input for the thermal modeling of the end terminals. A detailed analysis on thermal and electrical aspects of end terminals is discussed using Ansys software. Heat transfer simulation was carried out for fixed conductor length in liquid nitrogen (LN2) with varied vacuum feed through positions and the distance between copper conductor end and vacuum end joint to obtain the temperature gradient profile across the current lead with current excitations.

2. HTS DC Cable Description

Figure 1 shows a detailed view of HTS cable. It comprises of HTS wire wounded over supporting tube and surrounded by electrical insulation material enclosed inside a liquid nitrogen cryostat. The liquid nitrogen cryostat is thermal

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insulated by vacuum jacket and nonmetallic jacket as shown in Figure 1. HTS cable, LN2 cryostat and vacuum vessel are concentrating to each other using spacers.

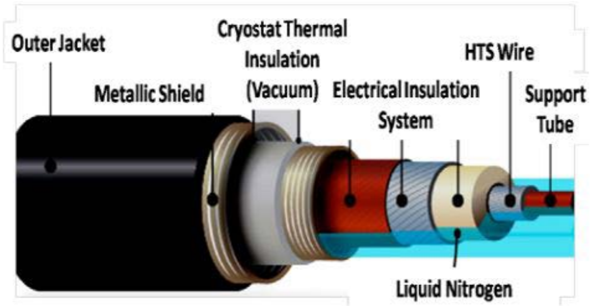

Figure 1. The detailed view of HTS cable[5].

3. Design Consideration of HTS Cable Termination

There are two important design considerations for HTS cable terminal namely, electrical and thermal. The electrical specification includes ampacity (which decides size and material of conductor) and operating voltage (size and type of dielectric material). Thermal specification includes thermal conductivity of material used as conductor as well as insulator[6]. This solid rod can be considered as conduction cooled conductor. Figure 2 shows schematic of the conductor along with the heat loads.

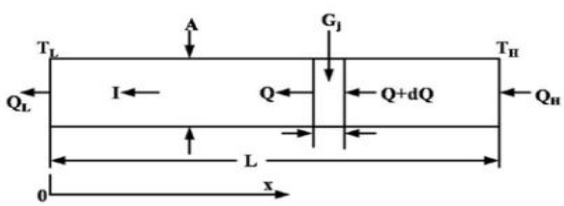

Figure 2. Schematic of conduction cooled conductor[6].

Eq. 1 defines heat flow in a conduction cooled conductor.

$$\frac{d}{dx}\left[k(T)A\frac{dT}{dx}\right]+\frac{\rho(T)I^2}{A} \qquad (1)$$

The first term of Eq. 1 corresponds to conduction heat load and second term corresponds to joule heat produced by the current flowing through the conductor. Heat conduction per unit length is given by Fourier's law of thermal conduction Eq. 2.

$$\frac{dx}{kA}=\frac{dT}{Q} \qquad (2)$$

Combining Eq. 1 and Eq. 2, the net heat load at a given temperature (T) is given by

$$Q(T)=\sqrt{Q_L{}^2-2I^2\int_{T_L}^{T}k\rho dT} \qquad (3)$$

The ratio of length to cross-section is given by Eq. 4.

$$\frac{L}{A}=\int_{T_L}^{T_H}\frac{k}{\sqrt{Q_L{}^2-2I^2\int_{T_L}^{T}k\rho dT}} \qquad (4)$$

When the conductor is conducting a current I, the minimum heat leakage Q_L to cryostat can be achieved by taking the minimum of Eq. 3 given by Eq. 5.

$$(\llbracket Q_L)\rrbracket_{min}=I\sqrt{2\int_{T_L}^{T_H}k\rho dT} \qquad (5)$$

By substituting Eq. 5 in Eq. 4, an optimized operating current Iopt can be obtained.

$$\left(\frac{IL}{A}\right)_{opt}=\int_{T_L}^{T_H}\frac{k}{2\int_{T_L}^{T_H}k\rho dT}dT \qquad (6)$$

$$or, I_{opt}=\frac{A}{L}\int_{T_L}^{T_H}\frac{k}{2\int_{T_L}^{T_H}k\rho dT}dT \qquad (7)$$

When the transport current I is I_{opt}, the heat leakage from the conductor to the cryostat is minimal. The analytical solution of the above equation is not straight forward to calculate as the thermal conductivity of material is a function of temperature as well as of material itself. This involves the use of FEM based solution to determine the temperature rise for the applied heat.

4. Design Specification and Simulation

An FEM simulation for the HTS cable terminal was carried out using Ansys thermal steady state simulation. The terminal was designed with an ampacity of 2 kA and operating voltage of 220 V. Figure 3 shows sectional of 2-D drawing of HTS cable terminal. HTS cable and copper conductor were joined by soldering. Copper conductor was directly connected with power supply. Vacuum and LN2 feed through consists of teflon as an insulating material with tight fitted SS ring at the ID and OD of the teflon ring. The inner SS ring of both the feed throughs has the ID same as that of the OD of copper conductor. These joints were brazed using silver brazing to have sufficient strength as well as LN2 and vacuum leak proof. On the other hand the outer SS ring of LN2 and vacuum feed throughs were brazed with the SS LN2 cryostat and vacuum jacket respectively. Liquid nitrogen was entered into the LN_2 chamber through LN_2 port as shown in Figure 3.

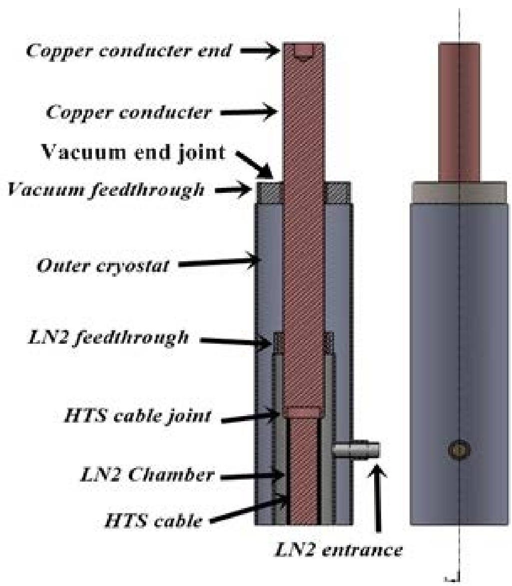

Figure 3. Sectional 2 D drawing of HTS cable terminal.

Ohmic losses for the copper conductor were calculated as 250 Watts based on the cable specifications for assumed dimensions of current leads from Eq. 8.

$$P = I^2 \rho \frac{l}{A} \quad (8)$$

where, P is the Ohmic losses in the conductor in watts, I is the current flow through the conductor in amperes, ρ is the resistivity of copper at 300 K in ohm-m, l is the length of the conductor in m and A is the cross-sectional area of the conductor in m^2.

The simulations were carried out for fixed conductor length in LN_2 with varied vacuum feed through position to obtain the temperature gradient profile for calculated heat loads for three different lengths (200mm, 250mm and 300mm) between vacuum end joint and copper conductor end. The boundary conditions and parameters used for the simulation are listed in the Table 1.

Table 1. The boundary conditions and parameters

Boundary Conditions & Parameters	Values
Heat load	250W
Uniform initial temperature	300K
Liquid nitrogen temperature inside the chamber	77K
Vacuum chamber, feed through	Perfectly insulated (only heat transfer carried out by radiation)

5. Results and Discussions

Figure 4 shows the thermal steady state FEM simulation for HTS cable terminal. The input heat load of 250 W was given at the conductor end. The distance between the LN2 and vacuum feed through was 450 mm. Distance between copper conductor end and vacuum end joint was 200mm. The maximum temperature obtained at the end of conductor was 398.68K. The vacuum end joint temperature was found to be 313.24 K.

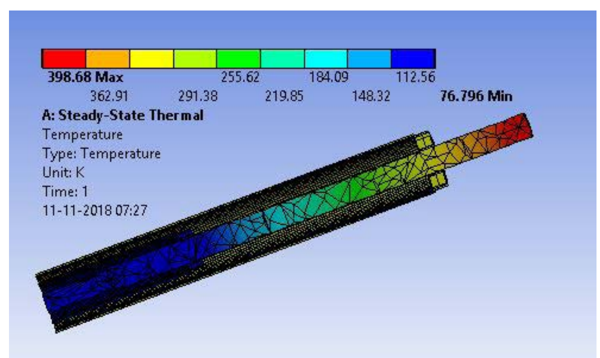

Figure 4. Temperature distribution profile for distance between vacuum and LN2 feed through of 450mm and distance between copper conductorend and vacuum end joint of 200mm.

Figure 5 shows the variation of maximum temperature along the conductor for same heat load of 250W. The distance between vacuum and LN2 feed through were varied. Conductor length inside LN2 was fixed to 100 mm. Based on the above condition the simulation were carried out for three different distance of copper conductor between vacuum end joint and copper conductor end.

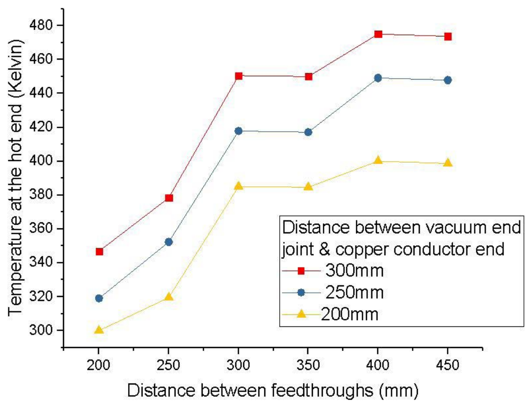

Figure 5. Maximum temperature of copper conductor end for varied FT position and distance between copper conductor end and vacuum end joint.

Frost formation is one of the major problem in HTS cable terminal. At this location temperature of vacuum end joint should be greater than the due point temperature of water for the surrounding. Figure 6 shows the variation of minimum temperature at the vacuum end joint in the radial direction.

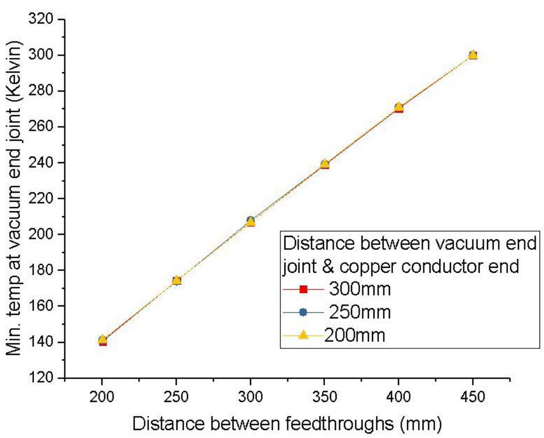

Figure 6. Minimum temperature at vacuum end joint in radial direction for varied FT position and distance between copper conductor end and vacuum end joint.

Based on the discussion, it was found that the suitable configuration for 2kA, 220 V HTS cable terminal is listed in Table 2.

Table 2. Configuration details of HTS cable

Length of copper conductor at LN2 chamber	100mm
Distance between two feed throughs	450mm
Distance between copper conductor end and vacuum end joint	200mm

For the mentioned configuration temperature at the vacuum end joint configuration (313.24 K) is well above atmospheric temperature hence frost formation cannot occur and on the other hand temperature at copper conductor end was found to be 398.68 K which is a nominal temperature for the cable and terminal for the specified rating. Temperature distribution between two feed through and along cryostat seal in radial is shown in Figures 7 and 8 respectively.

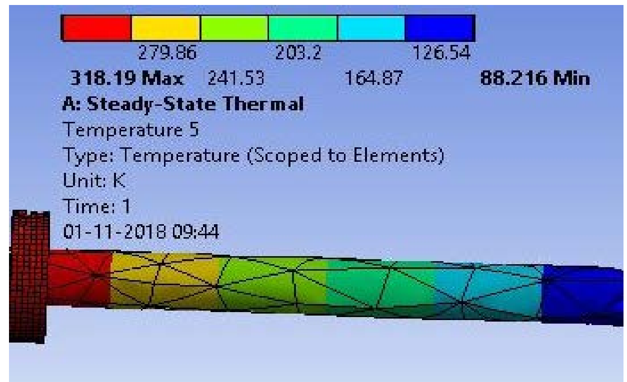

Figure 7. Temperature distribution between two feedthroughs for final configuration.

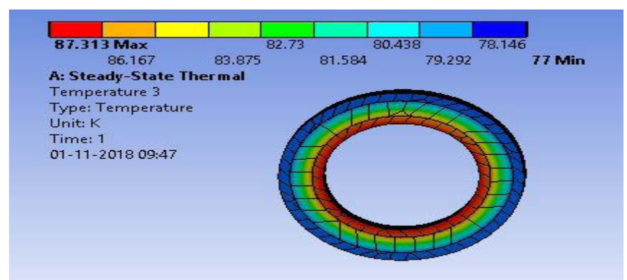

Figure 8. Temperature distribution along cryostat seal in radial direction for final configuration.

6. Conclusions

The thermal analysis 2kA, 220V DC terminal connector for HTS cable was carried out. The ohmic losses were computed and were used as heat load input for the FEM simulation. The position of the LN2, vacuum feed through, length of the cable conductor and distance between cable conductor and vacuum end joint were optimized to have maximum temperature of 398.68 K and 313.24 K at copper conductor end and vacuum end joint temperature respectively. The maximum temperature obtained was well within the nominal operating values of a cable terminal which indicates the cable terminal is optimally designed.

7. References

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