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Analysis of terminal heat loss of 10kV/6000A high temperature superconducting cable

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Abstract: HTS power cable terminal is an afflux unit of transition from superconducting cable operating at low temperature to high voltage bus and outlet of refrigerant in normal temperature. In order to obtain the low-temperature environment for the stable operation of 10kV/6000A superconducting cables, we designed a terminal system. The terminal is refrigerated by circulating liquid nitrogen, and the heat loss of the terminal is calculated to obtain. The current leads in the terminal are optimized and the optimal structure lead dimensions are obtained and finally it is verified by experiments. The results show that the leakage heat value of the terminal is about 590W, and the current lead is the most important leakage heat source. The calculation results provide a basis for the design and further optimization of the HTS cable terminal cryogenic system.

1. Introduction

The discovery of high temperature superconducting materials with zero resistance at liquid nitrogen temperature in 1986 laid the foundation for the industrial application of superconducting materials in the field of electric power. Superconducting cable is the most practical and rapidly developing superconducting power device in the application of superconducting power, which embodies the technical advantages of superconductors. Superconducting cable has the outstanding advantages of high current carrying capacity, low loss, small volume and light weight. Its transmission capacity can be 3-5 times higher than conventional cable, and the heat loss of cable body is close to zero. Therefore, the development and research of HTS cables is of great significance for the current situation in China.

HTS cable system is generally composed of superconducting cable, vacuum Dewar pipeline, terminal, on-line monitoring system and cryogenic refrigeration system. The terminal is a very important part of the superconducting cable system, and it is also the most important source of the thermal loss of the superconducting cable system. It usually accounts for more than 90% of the thermal loss of the system, which requires it not only to reduce the heat loss as much as possible, in order to reduce operating costs. In addition, a large number of measurement signal lines need to be drawn from the terminal of HTS cables, which complicates the structure and increases the difficulty of design and manufacture. Therefore, on the one hand, the design of HTS cable terminal needs to optimize its structure, size, insulation mode, etc. to reduce the heat loss from the internal low temperature environment to the external room temperature environment and improve its economy. On the other hand, it needs to realize with vacuum Dewar pipeline, cryogenic refrigeration system, on-line monitoring system, and the connection of external conventional electrical system of HTS cable.

The purpose of this paper is to design a suitable terminal system for 10 kV/6000A superconducting DC cable of the same grade developed by the Research Center of Applied Superconducting

Technology of Beijing Jiaotong University. The optimization design will be carried out mainly from the aspect of system heat loss, and the rationality and economy of the structure will be taken into account. The terminal is easy to install and operate, and meets the requirements of demonstration engineering technology. It lays a good foundation for the long-term stable operation of HTS DC cable system.

2. Terminal system construction

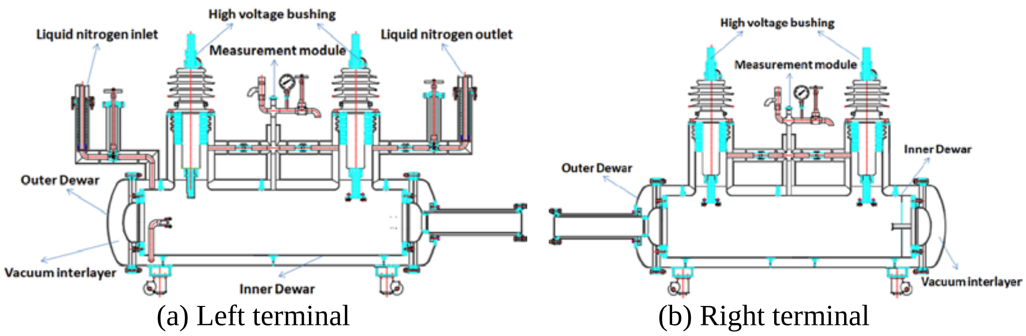
The following Fig.1 is a schematic diagram of the HTS cable termination in this design. It is divided into two terminal structures, consisting of internal and external Dewar, high voltage bushing, liquid nitrogen inlet and outlet, etc. The superconducting cable is located inside the inner dewar and immersed in liquid nitrogen. The liquid nitrogen flows into the inner Dewar from the liquid nitrogen inlet. After circulation, the temperature-rising liquid nitrogen is discharged through the liquid nitrogen outlet for refrigeration. The vacuum interlayer between the inside and outside Dewar can reduce the heat loss of the whole system. The superconducting cable is connected to the external power system through a high-voltage bushing. The temperature, liquid level, quench and other parameters that need to be monitored during the operation of superconducting cable can be monitored by measuring module. The key components and functions of the terminal system are introduced below.

2.1. Inner/Outer Dewar

Inner Dewar is in the low temperature environment, and the outer Dewar is in room temperature, at room temperature. There is enough insulation distance between them, and space is left for the laying of multi-layer insulation materials and the installation of support mechanism. Two high voltage bushing outlets are left in the upper part of the inner and outer Dewar. Because of the great temperature difference between the inner and outer Dewar, the cold shrinkage of the inner and outer Dewar will be very different. A corrugated pipe structure is installed at the outlet of the inner Dewar high voltage bushing to counteract the effect of cold shrinkage and prevent the cylinder from destroying when the cold shrinkage deformation occurs at low temperature. There is a complex thermodynamic relationship between the inner and outer Dewar, and choosing an appropriate adiabatic way can reduce the overall heat leakage of the system.

2.2. High voltage bushing

The high voltage bushing consists of an external capacitance shield and an internal current lead. Capacitance shield ensures insulation between bushing and Dewar, while current leads form a path between superconducting cables and external circuits. The upper part of the current leads is at room temperature and the lower part is connected to the superconducting layer and the quench protection layer of the superconducting cable, and is immersed in liquid nitrogen. Because of the huge temperature difference between the two ends of the current lead, the current lead is also called the most important heat loss source in the terminal structure. This paper will also focus on the optimization of the current lead structure in order to achieve the purpose of reducing the heat loss of the system.

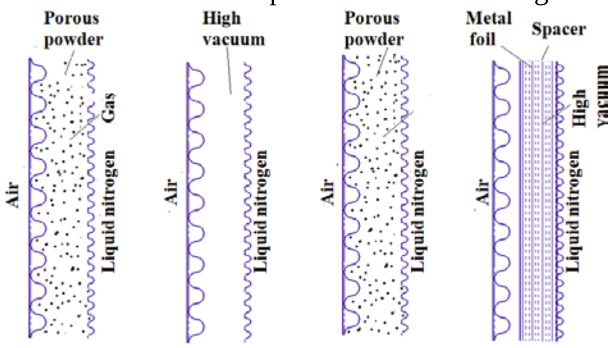


(a) Left terminal (b) Right terminal

Figure 1 Schematic diagram of terminal structure

3. Selection of heat insulation mode

Due to the limitations of liquid nitrogen storage, installation space and so on, the general structure size of the superconducting cable terminal is basically determined and there is no room for modification. Therefore, the heat loss of the system can be reduced only by choosing the appropriate heat insulation way. Considering convection, conduction and radiation, the heat transfer from the room temperature to the inner Dewar is minimized and the insulation effect is improved. The insulation structure between the inner Dewar and the outer Dewar can be adopted as shown in the figure below[1].



(a) Accumulation insulation (b) High vacuum multilayer insulation

(c) Vacuum porous insulation (d) High vacuum multilayer insulation with spacers

Figure 2. Multiple insulation structures.

3.1. Accumulation insulation

This is a non vacuum insulation, as shown in Fig.2 (a). Solid heat conduction and gas conduction account for about 90% of the heat flux of this type of insulation structure. In order to reduce solid heat conduction, small insulation materials, such as expanded perlite (pearlescent sand), aerogel, ultra-fine glass wool, polystyrene and foam plastics, are usually selected. In order to prevent the deterioration of insulation performance caused by the condensation of gases in insulation materials, packed materials are filled with gases whose condensation temperature is lower than the surface temperature of the inner tube, such as hydrogen or helium. The insulation structure has the advantages of simple fabrication process and low cost, but has the fatal defects of poor insulation performance and thick insulation layer.

3.2. High vacuum multilayer insulation

This is a simple vacuum insulation, as shown in Fig.2 (b). For achieving good insulation effect, the vacuum degree of adiabatic interlayer is less than 1.3×10^{-3}Pa. Radiation heat loss is the main heat loss source of the structure. In order to reduce radiation heat loss, copper, aluminum and other materials with low emissivity are usually used for high vacuum wall surface finish treatment. Simple vacuum insulation has the advantages of simple structure, compact, small thermal capacity, convenient manufacturing, etc. The disadvantages are limited radiation heat loss. For long-term engineering applications of superconducting cable, the thermal loss is too large and maintenance is more frequent.

3.3. Vacuum porous insulation

The insulation method is to fill the insulation space with porous insulation material and then pump the insulation space to a low vacuum of 1-10Pa, as shown in Fig. 2 (c). Commonly used porous insulation materials include aerogels, vermiculite, pearlescent sand and microsphere insulation materials. Vacuum porous insulation requires low vacuum, and its insulation performance is 2 orders of magnitude better than stacking insulation, and 1 order better than high vacuum insulation, but it has the disadvantages of large interlayer spacing, complex structure and bulky.

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3.4. High vacuum multilayer insulation with spacers

This type of insulation is a highly insulated structure with multiple layers of metal foil (such as aluminum foil) wrapped in an insulating space to substantially reduce radiation heat loss. It is the best insulation structure at present, also known as super insulation. It is also the most widely used insulation method at present. Its structure is shown in Fig. 2 (d).

The two layers of metal foil are separated by spacers, called super insulation. The radiant heat flux of the n-layer insulation is obtained when the outer tube temperature is T_1, the inner tube temperature is T_2 and the Stephen-Boltzmann constant is $5.67 \times 10^{-8} W/(m^2.K^4)$ [2].

$$Q = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}(\frac{1}{\varepsilon_2} - 1) + \sum_{i=1}^{n}\left(\frac{A_1}{A_{si}}\right)\left(\frac{1}{\varepsilon_{i1}} + \frac{1}{\varepsilon_{i2}} - 1\right)} \quad (1)$$

If the emissivity of each insulation screen is the same, the upper form becomes:

$$Q = \frac{1}{n+1}\frac{\varepsilon}{2-\varepsilon}\sigma A(T_1^4 - T_2^4) \quad (2)$$

It can be seen that after radiating the N layer between the inner and outer tubes, the radiant heat flux decreases to 1/ (n+1).

Considering various insulation methods, we find that high vacuum multilayer insulation is the most suitable choice. For high voltage bushing, the gap between capacitor screen and current leads is too small to fill the insulation material. Therefore, the use of high vacuum insulation, to ensure that the gap vacuum is less than 10^{-3} will have a good insulation effect.

4. Leakage heat analysis of various parts

The thermal load sources of HTS cable terminals are: conduction of superconducting cable current leads and Joule heat leakage, radiation heat leakage in vacuum layer, convective heat leakage of residual gases in vacuum environment. In the HTS cable terminal system, the leakage of current leads is the main source of heat load, followed by the conduction and radiation leakage of supporting and connecting pipe fittings between inner and outer Dewar.

4.1. Current lead leakage heat

HTS cables operate in the low temperature environment of liquid nitrogen. Current leads are needed to connect the power system. Temperature spans from liquid nitrogen temperature zone to room temperature. The current lead itself has a large conduction heat leakage, the Joule heat generated by the current through the wire is the main source of heat leakage load, is the largest heat leakage source of the superconducting cable terminal system, and plays a decisive role in the operation cost of the cable.

When the current lead material is selected, the smaller the cross-sectional area of the current lead, the smaller the conduction heat leakage, but the Joule heat will increase; otherwise, the larger the cross-sectional area of the current lead, the greater the conduction heat leakage, but the Joule heat will decrease. At this time, there is a ratio between lead length and sectional area L/A, so that the leakage heat of the lead to the low temperature end is minimal[3]. Conduction cooling is selected for the design of current leads in the terminal system of high temperature superconducting cable with (+10kV/6kA). The heat conduction model of the leads is shown below.

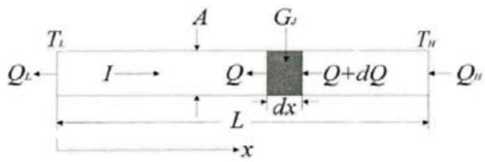

Figure 3. Heat conduction model of lead

The relationship between the current lead length and the sectional area is as follows:

$$(\frac{IL}{A})_{opt}=\int_{T_L}^{T_H}\frac{k(T)}{\sqrt{2\int_{T}^{T_H}k(T)\rho(T)dt}} \tag{3}$$

Current lead unit current minimum leakage heat is：

$$\frac{(Q_L)\min}{I})=\sqrt{2\int_{T}^{T_H}k(T)\rho(T)dt} \tag{4}$$

In the formula, *k(T)* is the thermal conductivity of metals, and $\rho(T)$ is the resistivity of metallic materials. The above two expressions can be transformed into:

$$(\frac{IL}{A})_{opt}=\int_{T_L}^{T_H}\frac{k(T)}{\sqrt{2\int_{T}^{T_H}L_0(T)Tdt}}dt \tag{5}$$

$$\frac{(Q_L)\min}{I})=\sqrt{2\int_{T}^{T_H}L_0(T)T\,dt} \tag{6}$$

L_0 *(T)* is the Loren constant in the equation. It is generally taken as L_0 = 2.45x10 $^{-8}$W.Ω.K^{-2}. But in fact, L_0 from liquid nitrogen temperature to room temperature is not a constant, but increases with temperature. The following is a curve of Loren constant versus temperature for three metal materials, copper, aluminum and silver[4] . Because of the complexity of the expression, the average value of Loren constant in a certain temperature range is usually taken in practical calculation. In this design, current leads consist of soft copper wires drawn from superconducting strips and connected red copper wires. The temperature range is from 77K to 300K. Loren constant L_0 is taken as 2.17x10^{-8}W.Ω.K^{-2}, and the result is L/A=360m^{-1}.

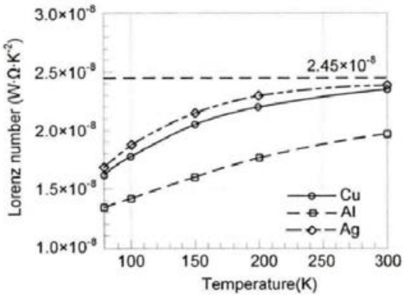

Figure 4. Loren constant

The maximum current of the cable design is 6kA. The current leads are made of red copper and the cross-sectional area of the current leads is 2000 mm^2 when the current density is 1.2A/mm^2 at 6 kA, so the diameter of the copper terminal should be 50 mm. According to L/A, the total length of current leads from liquid nitrogen temperature to room temperature should be 0.8m. Taking the data into the formula (6), the unit loss of the current leads can be obtained as *(QL) min/I*=42.7W/kA. Therefore, the total loss of single current leads is 42.7 x 6=256.2W.

4.2. Inner/Outerl Dewar leakage heat

The outer layer of inner Dewar is wrapped with multilayer insulation, and the outside temperature of outer Dewar can be regarded as room temperature. Heat is transmitted between the inner and outer Dewar by means of thermal radiation and gas conduction. These factors will influence each other in the process of heat transfer. Several factors are considered in engineering calculation and their comprehensive effects are characterized by an apparent thermal conductivity which combines all the factors. The leakage heat can be expressed as follows:

$$\Phi_1 = \lambda_{eff} A_1 \frac{\Delta T}{\delta_1} \tag{7}$$

Among them, the apparent thermal conductivity of λ_{eff} is high vacuum multilayer insulation. It is advisable to be 1.5×10^{-4}W/(m.K). T_1 is inner Dewar temperature and T_2 is outer Dewar temperature. $A_1 = \sqrt{A_{in} A_{out}}$ is the heat transfer area. δ is the total thickness of insulation. The calculated leakage heat is about 15.2W.

4.3 Leakage of connecting fittings

The liquid nitrogen circulating flow in the HTS cable terminal system, the extraction of the measurement signal and the connection of the safety valve all need to be connected with the Dewar through the sealed neck tube. It is difficult to accurately calculate the heat transfer through the neck of a cryogenic vessel because the flow in the neck is unstable and the specific heat capacity of the gas and the thermal conductivity of the wall material are both functions of temperature.

In the design of this system, the heat conduction of the tube wall caused by the temperature difference between the two ends, the heat transfer between the insulation layer outside the tube and the surrounding medium, and the heat transfer between the inner surface of the tube and the steam escaping from the tube are mainly considered. Under the assumption that the evaporated gas has no cooling effect on the neck tube, the maximum heat flux through the neck tube can be calculated by the following heat transfer formula：

$$\Phi_2 = n\psi \frac{\lambda_2}{L_2} A_2 \left(T_4 - T_3\right) \tag{8}$$

In this formula, L_2 is the length of the neck tube, λ_2 is the thermal conductivity, A_2 is the cross-sectional area, T_4 and T_3 refer to the upper and lower temperatures, respectively. Ψ is a correction factor, usually 0.5. The calculated leakage heat of the neck tube is 30.2W. Therefore, the total leakage heat of the system is 557.8W.

5. Experimental verification

In order to verify the theoretical results, we assembled the terminal system and measured the liquid nitrogen loss of the system under the normal operation of the cable, and then calculated the heat loss of the system. The following is a scene map of the cable system after assembly. We injected liquid nitrogen into the terminal, cooled it for 24 hours, and recorded the loss of liquid nitrogen for 7 hours.

(a) Terminal (b) Superconducting cable system

Figure 5. Experimental scene

Table 1. Liquid nitrogen consumption

Time(hour)	Nitrogen volume(L)
0	46185
1	55230
2	64100
3	73310
4	82390
5	91300
6	100312
7	109481

From the experimental results, it can be seen that in 7 hours, a single terminal emits about 9000L of nitrogen gas per hour, converted into liquid nitrogen about 13.5L. The heat required for vaporizing a liter of liquid nitrogen is 160 kJ, and the heat required for vaporizing 9000 L of nitrogen is 2150 kJ. The heat loss of a single terminal can be calculated to be about 590 W, which is basically consistent with the calculated values before.

6. Conclusion

Terminals are the most important source of thermal loss in superconducting cable systems. The thermal stability of the whole system will be directly affected by choosing a reasonable adiabatic mode and optimizing the structure. In this paper, the thermal load of the 10kV/6000A thermostat terminal thermostat is calculated in detail.

In the leakage heat source of the system, the leakage current of the current leads is the largest. The relationship between the size of the lead and the current is obtained through optimization. The radiation and conduction heat leakage of the thermostat are calculated, and the main heat load of the thermostat is given. The calculation results and experimental results show that under the existing design structure, the total heat load of the cryostat is about 590W. From the analysis of thermal load distribution, the leakage of current leads is the main heat leakage, accounting for 86.8%; the inner and outer Dewar heat leakage accounts for about 13% of the total heat leakage of the system. The determination of the thermal load of the terminal cryostat provides a basis for further optimization of the system.

Acknowledgments

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