Design and Performance Testing of a 1.2 kA Peltier Current Lead

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Abstract. Peltier current lead (PCL) is a device based on Seeback effects. PCL can reduce the leakage heat of the high-temperature superconducting (HTS) cable, which could improve the overall operating efficiency of the HTS cable. The numerical calculation and simulation analysis model of the PCL based on Bi₂Te₃ thermoelectric materials is established, and the optimized design method of PCL is obtained. Consequently, the design and manufacture of a kA-class PCL with 8 parallel connected Bi₂Te₃ thermoelectric elements is completed. The experimental results show that the maximum current deviation of the PCL under different transmission currents is less than 5 A, and the maximum temperature difference is less than 10 K, which is consistent with the designed value. At the same time, the heat leakage is approximately 32 W/kA at the rated current of 1200 A, which is about 25% lower than conventional copper current leads.

1. Introduction

High temperature superconducting (HTS) DC cable has the characteristics of large transmission capacity and low loss, so it has a broad application prospect in VSC-HVDC system and data center DC power grid. The superconducting conductor of the superconducting cable is connected with the external equipment through the copper current lead. The heat loss of the copper current lead after heat transfer optimization is 42.4 W/kA, which is one of the most important heat load of the HTS cable. Reducing the heat loss of the current lead can effectively improve the operation efficiency of the HTS cable.

Yamaguchi first proposed to reduce the leakage heat of current leads by using the Peltier effect. The leakage heat of current leads could be reduced to about 30 W/kA [1], and a 20 m long HTS cables using the Peltier current lead (PCL) was developed in 2007 [2]. In 2013, multiple Peltier elements are connected in parallel to increase the transport current. In 2016, the 5 kA and 2.5 kA PCLs were applied in the 500 m and 1000 m DC HTS cables in Ishikari, which effectively reduced the heat leakage of leads [4]. Wang have carried out research on PCL, and have successively developed various types of current leads using Bi₂Te₃ materials [5-6].
The structure and simulation analysis of PCL are presented in this paper. The design parameters and experimental results of 1.2 kA current lead are given. It is shown that the heat loss of PCL is close to 30 W/kA.

2. Design of the PCL

2.1. Structure of PCL

![Figure 1. Schematic diagram of the PCL.](image)

Figure 1 shows the structural diagram of PCL. The Peltier element used is Bi\textsubscript{2}Te\textsubscript{3} semiconductor thermoelectric block, which is fixed on the room temperature side of copper lead by copper heat sink on both sides. Among them, \( T_R \) is the room temperature end temperature of copper lead, which is generally 300 K in design; \( T_L \) is the low temperature end of copper lead, which is generally 77 K for superconducting cable. In addition, \( T_H \) and \( T_C \) represent the temperature on both sides of Bi\textsubscript{2}Te\textsubscript{3} block respectively. Therefore, the heat \( Q \) absorbed at the low temperature end of Bi\textsubscript{2}Te\textsubscript{3} block is:

\[
Q = \alpha T_c I - \frac{1}{2} I^2 R - \kappa (T_H - T_C)
\]  \( \text{(1)} \)

where, \( \alpha \) is Seebeck coefficient; \( I \) is the transport current of Bi\textsubscript{2}Te\textsubscript{3}; \( R \) is the resistance of the element, and \( \kappa \) is the thermal conductivity.

Let \( \zeta = IL/A \), where \( L \) and \( A \) are the length and cross-sectional area of the Bi\textsubscript{2}Te\textsubscript{3}. Thus,

\[
\frac{Q}{I} = \alpha T_c - \frac{\rho \zeta}{2} - \frac{\kappa (T_H - T_C)}{\zeta}
\]  \( \text{(2)} \)

where, \( \rho \) is the resistivity of the thermo element. Therefore, we could get the one dimension energy balance function:

\[
\frac{d}{dx} \left( \kappa A \frac{dT}{dx} \right) + \frac{I^2 \rho}{A} - f C_p \frac{dT}{dx} = 0
\]  \( \text{(3)} \)

where, \( f \) denotes the heat conductivity. For conduction cooling current lead \( f=0 \); \( C_p \) is the Specific heat at constant gas pressure.

![Figure 2. Heat leakage of the PCL with different \( \zeta \).](image)
Figure 2 shows the relationship between the minimum heat leakage $Q_{min}/I$ and shape factor $\zeta$, where the thermo element is Bi$_2$Te$_3$ and the conventional current lead is made of copper. According to the calculation results, the minimum heat leakage $Q_{min}$ is 29.7 W/kA, while $\zeta_{B}$ of the Bi$_2$Te$_3$ is 5000 A/m and $\zeta_{Cu}$ of the copper is $2.73 \times 10^6$ A/m.

2.2. Simulation of the PCL

A simulation model of a PCL with rated current of 100 A is developed, and the length of the PCL is 600 mm.

![Temperature distribution of PCL with different current](image1)

**Figure 3.** Temperature distribution of PCL with different current

Figure 3 shows the temperature distribution of the PCL with different current. When the transport current of the PCL is 100A, the temperature rises at the low temperature (LT) terminal. This is due to the Joule heat generated by the PCL. However, at the room temperature (RT) end, the heat from the LT side is pumped to the RT end due to the thermoelectric effect of the Bi$_2$Te$_3$ element. Thus, the temperature of the copper at RT end does not increase due to Joule heat. Consequently, the temperature gradient at both ends of the copper lead could be reduced as well as heat leakage.

![Heat leakage of the PCL with different current](image2)

**Figure 4.** Heat leakage of the PCL with different current.

Since the PCL cannot always work at the rated current in actual applications, the axial temperature distribution and heat leakage of the PCL under different currents are calculated in figure...
4. According to calculation results, the heat leakage at the rated current is about 30 W/kA. However, the heat leakage at other currents increases, especially when the transmission current is small.

3. Experiments of the PCL

The HTS DC cables for data center applications require multiple terminals, and the current from a single outlet port is approximately kA. Therefore, based on the aforementioned simulation analysis, a kA-class PCL current lead was developed, and the rated transmission current was designed to be 1200 A. 8 Bi$_2$Te$_3$ elements of the same structure with rated current of 150 A were implemented in parallel.

![Figure 5. Structure of the kA class PCL](image)

The single Bi$_2$Te$_3$ element is completed according to the aforementioned simulation analysis method. The conventional conductor is copper, and the Bi$_2$Te$_3$ element is placed between the copper leads. Copper lead and Bi$_2$Te$_3$ are welded with indium metal to reduce the interface thermal resistance. Since the interface is relatively easy to break when using metal indium welding, four insulation posts are used to enhance the structure stability of the PCL. The transmission current test of the 1200 A current lead is carried out, including the current sharing of each parallel lead under steady state conditions, the temperature difference between the leads, and heat leakage.

![Figure 6. Current distribution of the parallel element of the PCLs.](image)

Figure 6 shows the distribution of 8 PCLs’ current in parallel under different transmission currents. It can be seen that the current values transmitted by each PCL are almost the same, and the overall deviation is less than 5 A.
Figure 7. Terminal temperature of the parallel Bi$_2$Te$_3$ of the PCLs.

Figure 7 shows the terminal temperature of the 8 parallel Bi$_2$Te$_3$ of the PCL. Due to the heat pump effect of the thermoelectric element, if the parameters of the elements do not match, the temperature change between the parallel elements may be inconsistent, and the temperature will affect the current transmission performance of the thermoelectric element. Therefore, the temperature distribution at the two ends of the 8 thermoelectric elements connected in parallel shows that the temperature distribution of the LT end and RT end of each element are similar, and the maximum temperature difference under the same transmission current is less than 10 K.

Figure 8. Heat leakage of the PCL.

Figure 7 shows the heat leakage of the developed PCL, where the heat leakage is calculated by the temperature fitting method. Compared with the previous simulation results, the experimental heat leakage is slightly larger. It is caused by the welding resistance between the Bi$_2$Te$_3$ elements and the copper leads at both ends. According to the test results, the leakage heat at the rated transmission current of 1200 A is about 32 W/kA, which is higher than the calculated 30 W/kA, but also lower than the pure copper lead.

4. Conclusion

By analyzing the structure of Peltier current leads, a simulation analysis model based on Bi$_2$Te$_3$ elements is established, and a PCL using 8 Bi$_2$Te$_3$ elements in parallel is developed. The experimental
results show that the developed PCL has good current sharing characteristics, which ensures that the integrated transmission current of the lead can reach the rated value, and also ensures the uniformity of the temperature distribution during the steady-state transmission current. Finally, the heat leakage at the rated current of 1200 A is approximately 32 W/kA, which reduces heat leakage by approximately 25% compared to traditional copper current leads.

5. Acknowledgments

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References

[1] K. Sato, H. Okumura, S. Yamaguchi. Numerical calculations for Peltier current lead designing[J]. Cryogenics, 2001, 41(7): 497-503.
[2] S. Yamaguchi, M. Hamabe, I. Yamamoto, et al. Research activities of DC superconducting power transmission line in Chubu University[J]. Journal of Physics: Conference Series, 2008, 97(1): 012290.
[3] H. Sugane, Y. Hikichi, M. Minowa, et al. Development of 1 kA-class PCL for superconducting applications[J]. Physics Procedia, 2013, 45(3): 317-320.
[4] M. Seiki, Y. Yukio, W. Hirofumi, et al. Evaluation of thermoelectric performance of Peltier current leads designed for superconducting direct-current transmission cable systems[J]. IEEE Transactions on Applied Superconductivity, 2016, 26(3):5401604.
[5] G. Chen, Y. Wang, W. Pi, et al. Experimental investigation on 100 A-Class PCL for DC HTS devices[J]. IEEE Transactions on Applied Superconductivity, 2016, 26(4): 4800805.
[6] M. Liu, T. Ma, S. Mo, et al. Analysis of interfacial heat-leakage characteristics of Peltier current lead[J]. Cryogenics & Superconductivity, 2019, 47(5): 27-32.