

Design of conduction cooling system for a high current HTS DC reactor

Van Quan Dao, Taekue Kim, Thang Le Tat, Haejin Sung, Jongho Choi, Kwangmin Kim, Chul-Sang Hwang, Minwon Park, and In-Keun Yu

Changwon National University, 20 Changwondaehak-ro, Changwon 51140, Rep. of Korea

yuik@cwnu.ac.kr

Abstract. A DC reactor using a high temperature superconducting (HTS) magnet reduces the reactor's size, weight, flux leakage, and electrical losses. An HTS magnet needs cryogenic cooling to achieve and maintain its superconducting state. There are two methods for doing this: one is pool boiling and the other is conduction cooling. The conduction cooling method is more effective than the pool boiling method in terms of smaller size and lighter weight. This paper discusses a design of conduction cooling system for a high current, high temperature superconducting DC reactor. Dimensions of the conduction cooling system parts including HTS magnets, bobbin structures, current leads, support bars, and thermal exchangers were calculated and drawn using a 3D CAD program. A finite element method model was built for determining the optimal design parameters and analyzing the thermo-mechanical characteristics. The operating current and inductance of the reactor magnet were 1,500 A, 400 mH, respectively. The thermal load of the HTS DC reactor was analyzed for determining the cooling capacity of the cryo-cooler. The study results can be effectively utilized for the design and fabrication of a commercial HTS DC reactor.

1. Introduction

Large electric power systems, such as high voltage direct current (HVDC) transmission systems, need a DC reactor with high inductance and high transport current. However, systems typically experience a lot of electrical losses due to the resistance of the metal winding. HTS magnet has zero electric resistance under DC current conditions and it is possible to increase the capacity of the transport current, hence, reduce the reactor's size, weight, and electrical losses [1]-[4].

An HTS DC reactor magnet needs cryogenic cooling to achieve and maintain its superconducting state. There are two cooling methods; the one is pool boiling the HTS magnet in cryogen, and the other is conduction cooling by connecting the HTS magnet to a cryo-cooler directly or indirectly in a vacuum chamber. The conduction cooling system is more effective, smaller, and lighter than the pool boiling method [5]-[7]. An optimal design of the conduction cooling system is an important factor to operate the reactor stably and effectively.

This paper discusses a design of conduction cooling system for a high-current HTS DC reactor. The inductance and the operating current of the HTS DC reactor were 400 mH and 1500 A, respectively. Dimensions of conduction cooling system parts including HTS magnets, bobbin structures, current leads, support bars, and thermal exchangers were calculated and drawn using a 3D CAD program. A finite element



method model was developed for determining the optimal design parameters and analyzing the thermal characteristics. For the heat load calculation, the temperatures of the 1st stage, 2nd stage, and radiation shield were 38 K, 7.4 K and 77 K, respectively. The simulation results were analyzed and are described in detail. This study results can be effectively utilized for the design and fabrication of a commercial HTS DC reactor.

2. Design of a 1,500 A, 400 mH class HTS DC reactor

2.1. Structure design of the HTS DC reactor magnet

Figure 1 shows the structure and size of a toroid-type HTS DC reactor magnet. The D-shape HTS double package coil (DPC) was applied to the reactor magnet. The toroid-type magnet consists of 30 DPCs. The inner diameter and outer diameter of the reactor magnet are 439.24 mm and 933.81 mm, respectively. The D-shape DPCs are arranged at an angle of 12° from each other based on the central axis of the toroid-type magnet. That is, all coils constituting the toroid-type magnet are arranged at identical intervals. The wire length of one D-shape DPC is 101.8 m, and the total wire length of the toroid-type HTS DC reactor magnet is about 3,054 m. The basic structure was referred to the previous research [2], and the major dimensions of the HTS DC reactor were modified to minimize the cooling capacity of the cryo-coolers in this paper.

Two layered GdBCO HTS wires were used for the reactor magnet. The critical current (I_c) was 1,200 A at a temperature of 77 K. The wire width and thickness are 12 mm and 0.61 mm. The calculated inductance of the reactor magnet was 404.59 mH. The detailed specifications of the 1,500 A, 400 mH class toroid-type HTS DC reactor magnet are shown in table 1.

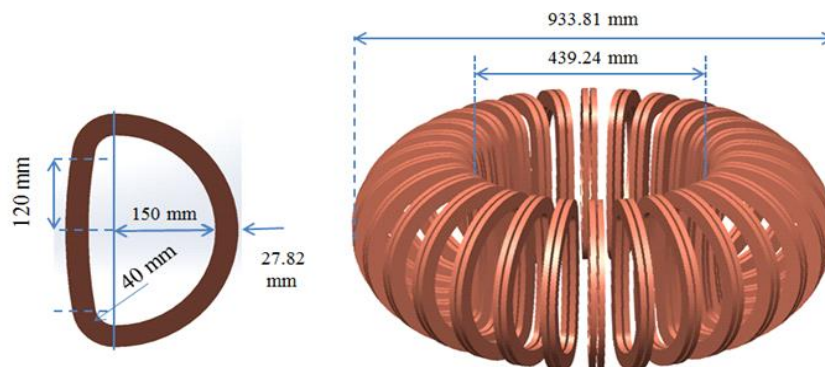


Figure 1. Detail size of the D-shape DPC and magnet structure

Table 1. Heat load of 1,500 A, 400 mH HTS DC reactor

Parameter	Value
Wire type	2G HTS wire
Thickness of wire	0.61 mm
Width of wire	12 mm
Operating current	1,500 A
Magnet inductance	404.59 mH
Length of wire (SPC/DPC)	50.9/101.8 m
Number of DPC	30 ea.
Total length of wire	3,054 m
Number of turns	57 turns
Width of magnet	933.81 mm
Height of magnet	370.76 mm

2.2. Electromagnetic analysis result of HTS DC reactor magnet

A 1/10 numerical model of the toroid-type DPC HTS DC reactor magnet was built in the Matlab program as shown in figure 2. The flux density of HTS DC reactor magnet was calculated by a numerical method based on Biot-Sawart law. The highest magnetic flux density area of the D-shape coil needs to be considered for determining the critical current of HTS coil. The magnetic flux density results were shown in figure 3. The maximum perpendicular and the parallel flux density were 1.57 T and 4.37 T, respectively. The values obtained by the numerical calculation were applied to all of the DPCs in order to determine the parameters of the magnet.

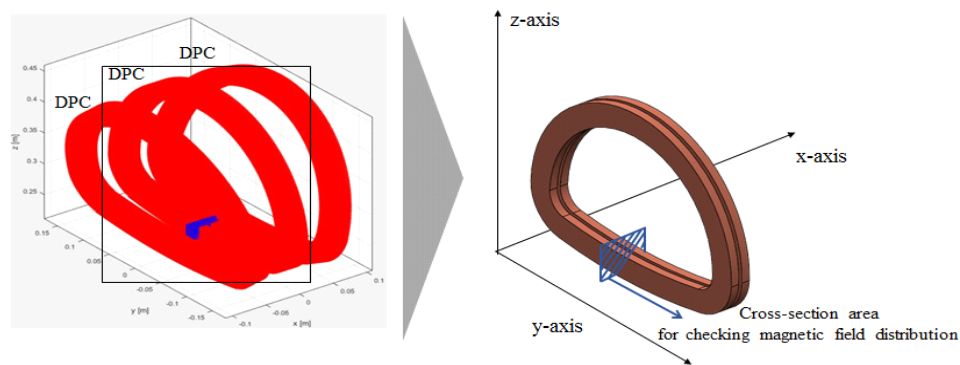


Figure 2. 1/10 numerical model of the toroid-type HTS DC reactor magnet

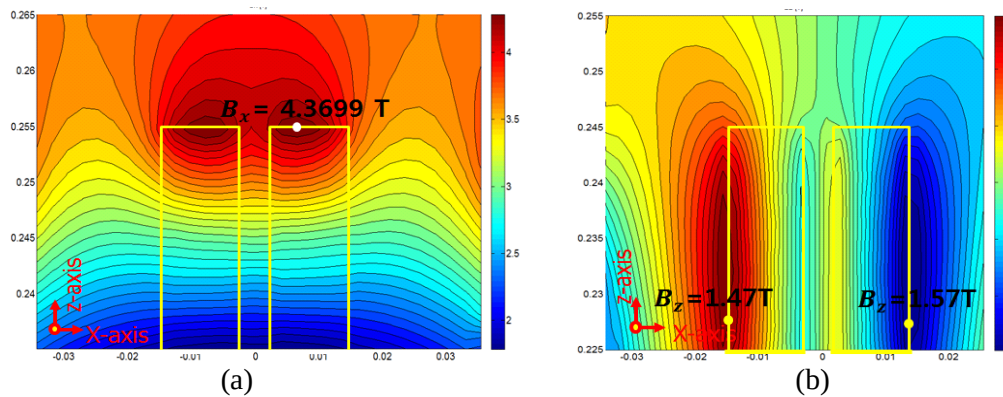


Figure 3. Magnetic flux density in D-shape DPC: (a) Parallel flux density, (b) Perpendicular flux density

2.3. Conduction cooling system design

In this study, a conduction cooling system was used for cooling the toroid-type HTS DC reactor magnet. In this cooling method, the single-stage (RDK-400) and two-stage (RDK-415D) type Gifford-McMahon (GM) cryo-cooler (Sumitomo Corp.) were adopted. The conduction cooling system of HTS DC reactor mainly consists of the 1st and 2nd stage areas as shown in figure 4.

The 1st stage area is structured to carry currents via the DC reactor magnet in the room temperature section. A current supplied from the outside into the inside of the cryostat through two 800 A class current feedthroughs and then a current is supplied to the reactor magnet through brass current lead, copper stick, and HTS current lead. The 2nd stage area cools HTS DC reactor magnet. 30 DPCs were arranged in a toroid shape through the heat exchanger located in the lower and upper side of the DPC.

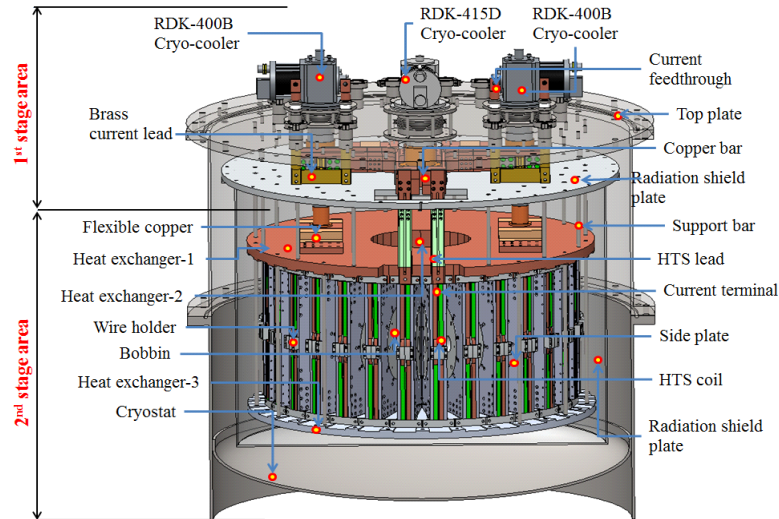


Figure 4. Configuration of the conduction cooling system of HTS DC reactor

2.3.1. Design of the 1st stage area. In the 1st stage area of the conduction cooling system, three cold heads of the GM cryo-coolers (single and two-stage) are responsible for the cooling of current leads and radiation shields.

Several important factors must be determined in order to design current leads, including the choice of materials and the lead geometry (length, cross section area, cooling surface area) [8, 9]. Figure 5 shows schematic layout of a conduction current lead with a length of L , a cross sectional area of A , and a carrying current of I . and represent the temperature of the warm and cold ends, respectively. Assume the lead has a uniform temperature distribution on the cross section, such that $k(T)$ and (T) are the thermal conductivity and the electric resistivity of the material. The minimum heat load can be written as (1), and the optimal length of the current lead can be determined by (2):

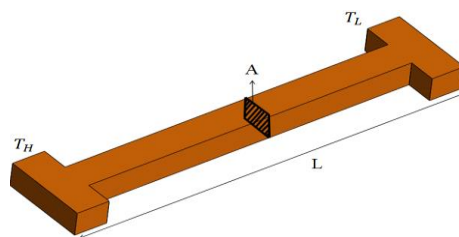


Figure 5. Schematic layout of a conduction current lead

$$Q_{op} = I \left(\frac{T_H}{2 \int_{T_L} \rho(T)k(T)dT} \right)^{1/2} \quad (1)$$

$$\frac{L}{A} = \frac{1}{I} \int_{T_L}^{T_H} k(T) \left(\frac{T_H}{2 \int_{T_L} \rho(T)k(T)dT} \right)^{-1/2} dT \quad (2)$$

For pure metals, $k(T)$ and (T) are inversely related, according to the Wiedemann-Franz law:

$$k(T)\rho(T) = L_0 T \quad (3)$$

Here, $L_0 = 2.45 \times 10^{-8} \text{ W}\Omega\text{K}^{-2}$. Hence, the equation (1) and (2) can be rewritten as:

$$Q_{op} = I \sqrt{L_0 (T_H^2 - T_L^2)} \quad (4)$$

$$\frac{L}{A} = \frac{1}{I} \int_{T_L}^{T_H} k(T) \left(L_0 (T_H^2 - T_L^2) \right)^{-1/2} dT \quad (5)$$

The current lead system, including current feedthroughs, brass loop current leads, copper bars and HTS leads was designed using a 3D CAD program using calculation results. Figure 6 shows the configuration the current lead system of the 1st stage area in the 1,500 A, 400 mH class HTS DC reactor.

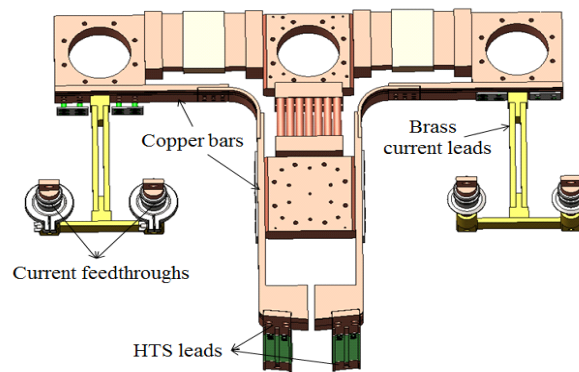


Figure 6. Configuration of the current lead system of the 1st stage area in HTS DC

2.3.2. Design of the 2nd stage area. The 2nd stage cold heads of two GM cryo-coolers (RDK-415D) are responsible for cooling of the toroid-type magnet. Figure 7 shows the detail configuration of the 2nd stage area. The coils are cooled by aluminum conducting bars assembled on the top and bottom of the coils. In addition, between each coil and the cryo-coolers, the heat exchangers made of oxygen free copper (OFCu), aluminum and a flexible copper blade are installed in order to support and cool the 30 double pancake coils simultaneously.

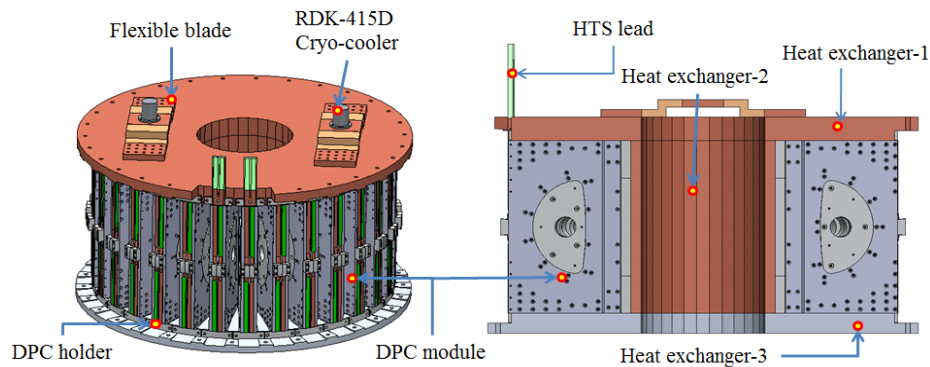


Figure 7. Detail configuration of the 2nd stage area

The bobbin structures and the shape of DPC module are described in detail in figure 8. The DPC module for an HTS DC reactor magnet is composed of two D-shape coils, two bobbins, two side plates and joint parts (joint plate, wire holder).

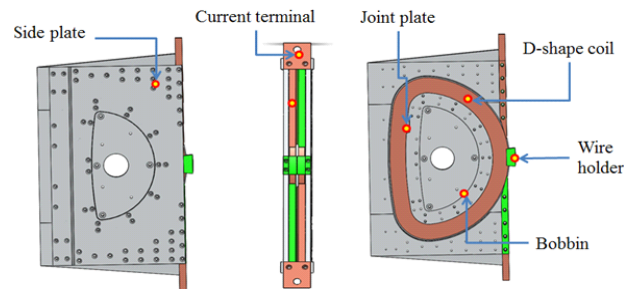


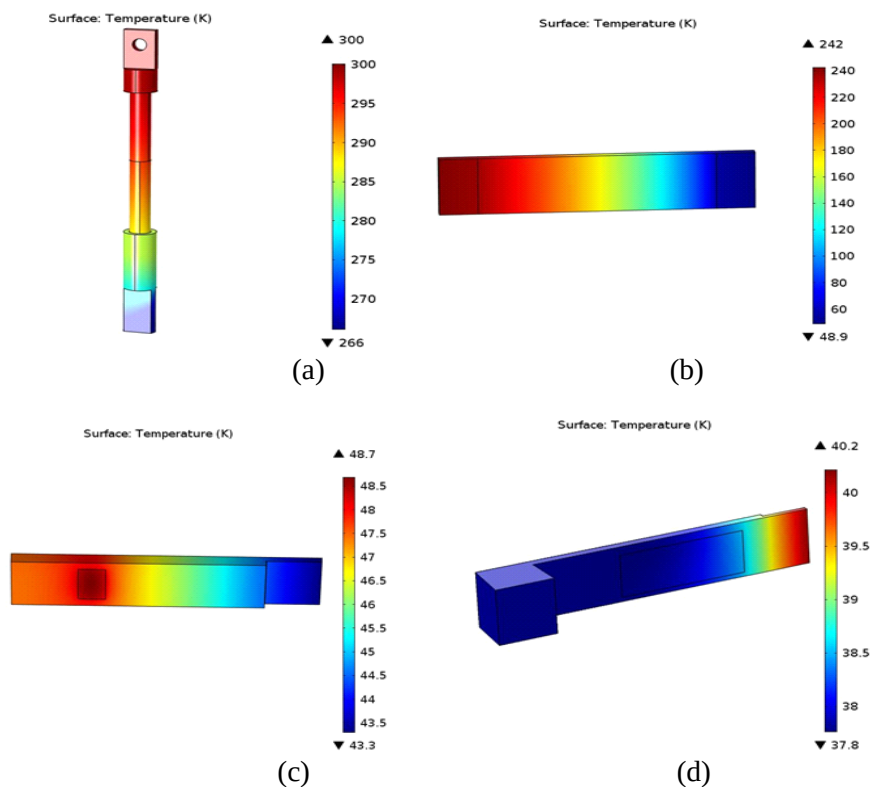
Figure 8. Bobbin structures and the shape of DPC module

3. Thermal analysis and optimal design of the conduction cooling system

3.1. FEM simulation

From the 3D CAD design, the thermal analysis for the 1,500 A, 400 mH HTS DC reactor was implemented. For basic heat load, the 1st stage, 2nd stage, radiation shield, and room temperatures were 40 K, 7 K, 77 K, and 300 K, respectively.

In the 1st stage area, the operating currents in each current feedthroughs were 750 A in the analysis of Joule heating. In order to reduce the Joule heat, the HTS current leads were connected to copper bars. The total heat load of the current leads includes Joule heat and heat invasion at room temperature. Here, the heat invasion at room temperature is conduction heat from outside into the current leads.



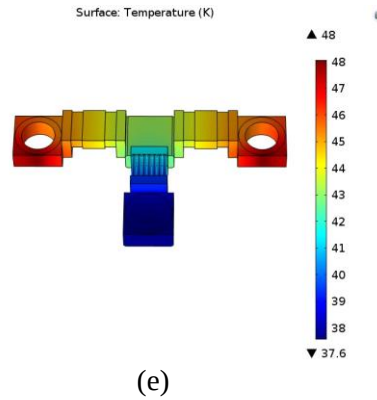


Figure 9. Thermal analysis results in the 1st stage area: (a) Current feedthrough, (b) Brass current lead, (c)-(d) Copper bars, (e) Cooling blocks

Figure 9 shows the temperature distribution analysis result of the optimal design for the 1st stage area. The temperatures in the copper bars connected to HTS leads and HTS wires were 38 K and 48 K, respectively.

In this paper, the minimized heat load of the current lead was 76 W. The total heat load includes the Joule heat and conduction heat load. To prevent heat transfer from outside to inside of the HTS DC reactor, the conduction heat load of the current lead should be 0 W which was obtained by changing the thickness of the current lead as depicted in figure 10 with major parameters of the current lead.

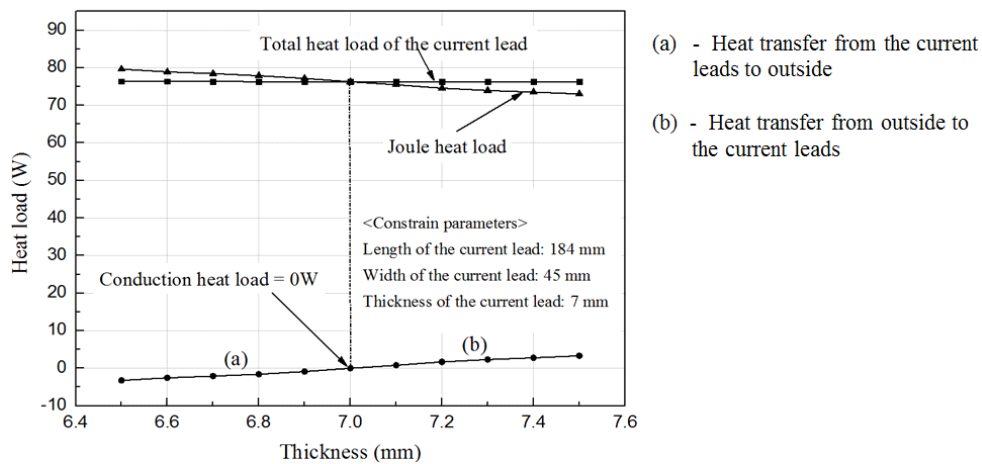


Figure 10. Conduction heat load depending on the thickness of the current lead

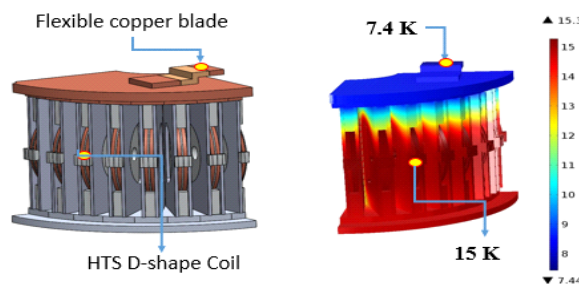


Figure 11. Temperature distribution of the 2nd stage area of HTS DC

In the 2nd stage area, the HTS magnet stably operates at the temperature of under 20 K. Figure 11 shows the temperature distribution analysis result of the 2nd stage area. The temperature in cold head of two-stage cryo-cooler (RDK-415D) is 7.4 K. In the D-shape coil, the temperature is 15 K.

3.2. Conduction cooling system design

In order to analyze the thermal characteristics of the HTS DC reactor, the basic heat load of the system was considered. Basic heat load can be divided into conduction heat and radiation heat. Conduction heat is transferred by the current lead and steel use stainless (SUS) support bars and cooler port. Multi-Layer Insulation (MLI) reduces the radiation heat transferred from outside to inside of the HTS DC reactor. The MLI was wrapped at the surface of the radiation shield. The thermal heat load of the HTS DC reactor in the 1st stage and 2nd stage is shown in detail in table 2.

Table 2. Heat load of 1,500 A, 400 mH HTS DC reactor

1 st stage heat load (W)		2 nd stage heat load (W)	
Current feedthroughs (4ea)	48.84 W	Conduction heat load from support	1.2 W
Brass current leads (4ea)	104 W	Conduction heat load from HTS lead	0.016 W
Radiation Shield	12.4 W	Magnet joint	6 W
Support bars	6 W	Current terminals	0.018 W
Total heat load	171.24 W	Total heat load	7.234 W

4. Conclusions

The authors designed a conduction cooling system for a toroid-type HTS DC reactor magnet and analyzed its thermal characteristics. The operating current and inductance of the reactor magnet were 1,500 A, 400 mH, respectively. The detailed structure design of conduction cooling system in the 1st stage area and 2nd stage area were described. The optimal heat load of HTS DC reactor was calculated and analyzed by FEM simulation. The minimized heat load of the current lead was 76 W. The conduction heat load of the current lead was 0 W with thickness of 7 mm of the current lead. The temperature at the 1st stage area for the operation of HTS leads and the 2nd stage area for the magnet were 42 K, and 7 K. The heat load of the HTS DC reactor can determine the optimal cooling capacity of the cryo-coolers. The study results can be effectively utilized for the design and fabrication of a commercial HTS DC reactor.

Acknowledgement

This work was supported by the Power Generation & Electricity Delivery Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No.2013T100200094)

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