Two-Stage Cryocooling Design for Hybrid Superconducting Fault Current Limiter

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***Abstract*—New concept of two-stage cryogenic cooling system for full-scale hybrid superconducting fault current limiter (SFCL) is proposed and designed with an objective to significantly reduce the capital and operational costs. Even though we have developed and successfully tested a cryocooling system for 300 A level, it is not easy to scale up the same technology to $3\phi/22.9\ \mathrm{kV}/2.5\ \mathrm{kA}$ level, mainly because of the heavy cost of GM or Stirling cycle coolers to cover the increased thermal load. It is proposed in this study to employ a large capacity of JT cooler for heat intercept at an intermediate location of current leads. The JT coolers with mixed refrigerant are very reliable and commercially available at an inexpensive price. Detailed cryogenic design of cryostat and heat intercept components is carried out in consideration of thermal characteristics of cryocoolers and electrical insulation. It may be concluded that the two-stage cooling with a JT cooler at 130 K and a GM cooler at 77 K is feasible in practice, and can significantly reduce the capital cost and power consumption.**

***Index Terms*—Cooling, cryogenics, fault current limiters, high-temperature superconductors.**

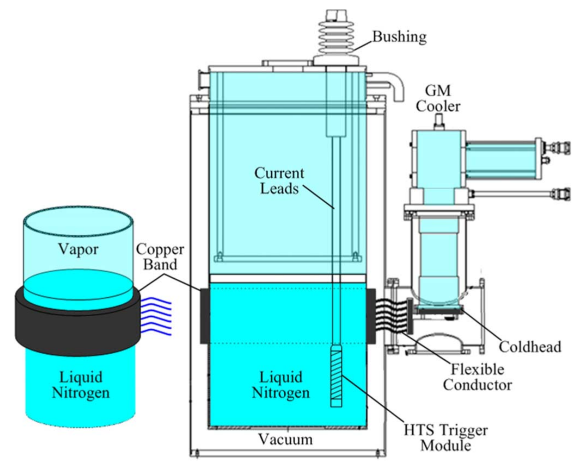

Fig. 1. Cryogenic cooling system developed and successfully tested for prototype of 22.9 kV/300 A hybrid SFCL.

I. Introduction

CRYOGENIC refrigeration with a closed-cycle cryocooler is one of the key techniques required for practical use of superconducting fault current limiters (SFCL) in transmission grid [1]–[4]. An unmanned operation without periodical supply of liquid nitrogen may be realized only with reliable and efficient cryocooling system. In addition, the cryocooler is an effective tool to keep liquid nitrogen under boiling temperature. The subcooled state plays a crucial role of suppressing bubbles to improve the electrical insulation, the spatial temperature uniformity of HTS elements, and the rapid recovery after a quench [5], [6].

An excellent cryocooling system [4] has been developed for our prototype of 22.9 kV/300 A hybrid SFCL [7], [8], as shown in Fig. 1. The HTS trigger modules are immersed in a pool of subcooled liquid nitrogen at 77 K and 300 kPa, where the boiling temperature is 87.7 K. A circular copper band is brazed around the exterior sidewall of liquid cylinder at a vertical location just under liquid level for the purpose of peripherally uniform cooling by a GM cooler. The cooling capacity of the cryocooler is 220 W @ 77 K. The vapor space above liquid nitrogen provides a fully open room for current leads and supports. Heat is removed by natural convection of liquid nitrogen [9] to the cold sidewall. A temperature control system is implemented with a heater attached on the coldhead of cryocooler, As a result, the entire liquid pool was maintained at 77 ± 0.45 K for over 3 days with or without current load.

The next step of our efforts is a scale-up of the cryogenic design to $3\phi/22.9\ \mathrm{kV}/2.5\ \mathrm{kA}$ level. A serious obstacle to this scale-up is the high cost of cyrocoolers. Since an estimated full load is nearly 800 W at 65 K, the cooler cost could be as high as $200,000 [10], which is definitely unaffordable. Furthermore, the commercially available coolers for this application are based on a regenerative (GM or Stirling) cycle [11], which is essentially inappropriate for the heavy load, because the cold surface is limited to its coldhead.

In order to jump this obstacle, a new concept of two-stage cooling is proposed and designed in this paper. A large capacity of JT cryocooler with mixed refrigerant is employed for heat intercept at an intermediate axial location of current leads. A variety of those JT coolers are commercially available at an inexpensive price [12]. In addition, the JT cycle is recuperative type [11], which is more suitable for larger scale applications, because a large cold surface is provided as cooling coil. On the other hand, the heat intercept with electric insulation is a tough

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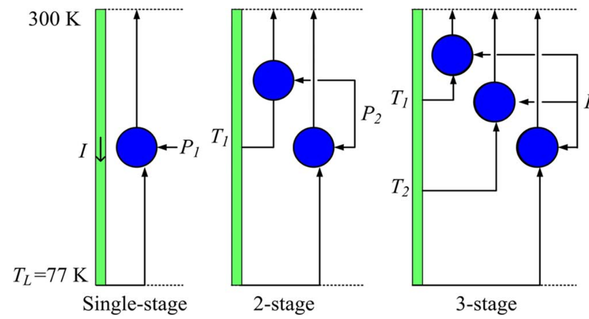

Fig. 2. Concept of multi-stage cooling of current leads.

design challenge. Some theoretical background and details for the two-stage design are presented in this paper.

II. Thermodynamic Background

According to thermodynamic theory, an efficient cryogenic cooling of SFCL is achieved by the minimization of cooling load and the reversible refrigeration to remove the load. In a cryogenic system of hybrid SFCL, the current leads are the dominant source of cooling load, as conduction and radiation loads may be technically reduced to a certain level, and the dissipation (as loss) is negligible in HTS elements. Thus, the minimum power per unit current (W/kA) required for cryocooling at temperature T_L can be estimated by

$$\left(\frac{P_1}{I}\right)_{\min} = \sqrt{L_0\left(300^2 - T_L^2\right)}\left(\frac{300}{T_L} - 1\right) \quad (1)$$

where the square root term is the minimum thermal load per unit current ($L_0 = \text{Lorentz constant} = 2.45 \times 10^{-8}\ \mathrm{W\ \Omega/K^2}$) [13]–[15] and the next term is the minimum input power per unit refrigeration [11]. For $T_L = 77$ K, the required minimum power is 131.4 W/kA per conductor, or 1.971 kW in 3ϕ 2.5 kA SFCL. This value is the strict minimum that can be obtained when the current leads are exactly optimized and the cryocooler is thermodynamically reversible.

There exists only one way to reduce the required power below the minimum, which is heat intercept or multi-stage cooling [1], [16]. As shown in Fig. 2, heat may be intercepted at an intermediate location of current leads, which results in a great reduction of cooling load at the cold end. For two-stage cooling at T_I and T_L, the minimum power is expressed as

$$\left(\frac{P_2}{I}\right)_{\min} = \sqrt{L_0\left(300^2 - T_1^2\right)}\left(\frac{300}{T_1} - 1\right) + \sqrt{L_0\left(T_1^2 - T_L^2\right)}\left(\frac{300}{T_L} - 1\right) \quad (2)$$

Since the intermediate cooling temperature can be analytically optimized, the minimum power for two-stage cooling is found as 98.2 W/kA, as listed in Table I. A similar procedure may be repeated for more stages, and a general expression for minimum power with N-stage cooling is

$$\left(\frac{P_N}{I}\right)_{\min} = \sum_{i=1}^{N}\sqrt{L_0\left(T_{i+1}^2 - T_i^2\right)}\left(\frac{300}{T_i} - 1\right) \quad (3)$$

where $T_0 = 300$ K and $T_N = T_L$.

TABLE I
Theoretical Minimum Power for Multi-Stage Cryocooling of a 77 K Lead

Number of stages	1	2	3	∞
Optimized thermal load (W/kA)			28.8 @237K	
		39.1 @166K	29.1 @147K	-
	45.4 @ 77K	23.0 @ 77K	19.6 @ 77K	
Minimum power (W/kA)	131.4	98.2	94.7	82.0

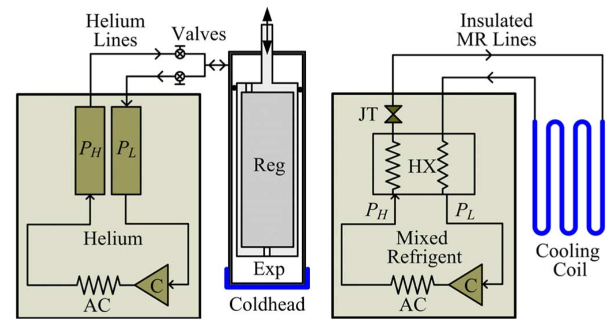

Fig. 3. Structure of GM and JT cryocoolers.

The absolute minimum of power for the cooling is achieved with an infinite number of optimized stages [14], [17].

$$\left(\frac{P}{I}\right)_{\min} = 300\int_{T_L}^{300}\sqrt{\frac{L_0}{T}\left(\frac{1}{T} - \frac{1}{300}\right)}dT \quad (4)$$

This value is also listed in Table I as a thermodynamic limit. It is obvious that as the number of stages increases, the required power decreases gradually towards the limit. It should be noted that the saving of two-stage cooling over single-stage is dominant. Even though the number of stages in practical system should be determined by economics, the heat intercept is expected to make a considerable improvement in cooling efficiency for our full-scale SFCL. On the contrary, it should be also pointed that this discussion is not applicable to HTS transmission cables or transformers, because the main cooling load is dissipative (ac loss) or widely dispersed so that the heat intercept is not so helpful.

III. Cryocoolers and Cryostat Design

A. GM and JT Cryocoolers

The cooling requirement of a few hundred watts at 77 K can be easily met with a single-stage GM cooler. On the other hand, the best choice for over one kilowatt of cooling at 120 ∼ 150 K appears to be a JT cooler. The structure of the two cycles is schematically shown in Fig. 3, and brief specifications of commercial GM and JT coolers considered for the system are listed in Table II. It is difficult to increase the capacity of GM cooler at liquid-nitrogen temperature, because the cold surface area is limited to coldhead. The JT cooler is more appropriate for the heavy load above 110 K, because the efficiency is higher and a larger cold surface is provided as cooling coil.

TABLE II
SPECIFICATIONS OF COMMERCIAL GM AND JT CRYOCOOLERS CONSIDERED FOR THE SYSTEM

	GM Cooler [10]		JT Cooler [12]	
Refrigerant (phase)	Helium (gas)		Mixture (2 phase)	
Cooling temperature	25 K	77 K	113 K	150 K
Cooling capacity	0 W	300 W	0 W	1100 W
Cold surface	Coldhead cylinder		Cooling coil	
Power consumption	7.5 kW		11.8 kW	

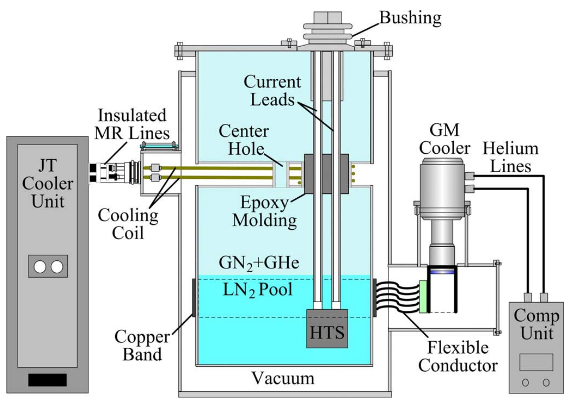

Fig. 4. Schematic overview of two-stage cooling system with a unit of GM cooler and a unit of JT cooler.

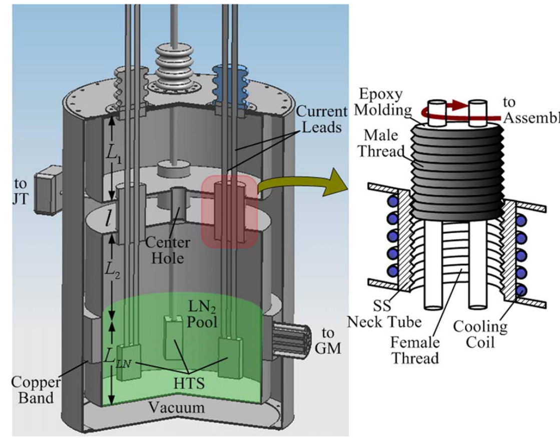

Fig. 5. Graphic representation of inner vessel of cryostat and detailed heat intercept design with epoxy molding, neck tube and cooling coil.

B. Cryostat

The overall cryogenic system is schematically shown in Fig. 4. The cryostat has two cooling station, one at liquid-nitrogen (LN_2) level and the other at an intermediate height between the top plate and LN_2. The lower station is basically similar to the proven single-stage system shown in Fig. 1. The inner vessel of vacuum cryostat is composed of two cylindrical containers, which are vertically connected with three "neck" tubes for three pairs of current leads to pass through. The three neck tubes are evenly spaced around the axis for electric insulation. The cooling coil of JT cooler is wound and brazed on the exterior surface of the neck tubes for heat intercept. Thermal load by conduction and radiation as well as by the leads may be effectively removed at the intermediate station.

In order to subcool LN_2 at 77 K and, 300 kPa, the vapor space is pressurized with helium gas [3]–[6], [9]. Another neck tube is installed at the center for a uniform pressure distribution and a rapid vent in case of boil-off.

C. Heat Intercept Design

The core of this two-stage cooling is the heat intercept design to satisfy the effective cooling and electrical insulation at the same time. Fig. 5 is a graphic representation of designed cryostat with an enlarged highlight of the intermediate cooling station. The current lead assembly is made with a pair of conductors, an HTS trigger element at the cold end, a room- temperature bushing for top plate, and an epoxy molding for heat intercept. For repeated assembly and good thermal contact, male and female threads are machined on the external surface of the epoxy molding and the internal surface of the neck tube, respectively. The distance between conductors and the diameter of epoxy molding are determined for safe electric insulation. Thermal contact between two threaded surfaces is improved by cryogenic thermal grease.

The temperature and vertical location of the intermediate cooling station are determined as following. If refrigeration is ideal, there exists a unique optimum for intercept temperature (T_I) to minimize the total power input, as listed in Table I. In practice, however, the JT cooler is thermodynamically more efficient than the GM cooler, which implies that the actual T_I should be lower than 166 K. In addition, the cooling capacity of commercially available JT cooler is much greater as listed in Table II. It is thus reasonable to select T_I in the range of 130 $\sim$ 140 K, as discussed in the following section.

Once T_I is given, the next step to determine the vertical height of upper vessel (L_1), neck tube (l), and lower vessel (L_2) is straightforward. The upper and lower sections of current leads can be separately optimized [13]–[15] such that

$$\frac{I(L_1 + l/2)}{A_1} \approx \frac{k}{\sqrt{L_0}} \cos^{-1} \frac{T_I}{300} \tag{5}$$

$$\frac{I(L_2 + l/2)}{A_2} \approx \frac{k}{\sqrt{L_0}} \cos^{-1} \frac{77}{T_I} \tag{6}$$

where A_1 and A_2 are the cross-sectional area of conductor for the upper and lower sections, respectively, and k is thermal conductivity of conductor at room temperature. Since $A_1 = A_2$, (5) and (6) are added to yield the optimal cross-sectional area for given values of current level and total height of vapor space above liquid.

$$A_1 = A_2 = \frac{I(L_1 + l + L_2)\sqrt{L_0}}{k\left[\cos^{-1}(T_I/300) + \cos^{-1}(77/T_I)\right]} \tag{7}$$

Next, the height of neck tube (l) is determined so that enough cooling surface area is provided. Typically, this requirement is imposed by overall heat transfer coefficient and temperature difference between the cooling coil and conductor. Finally, the decided values of $A_1 = A_2$ and l are substituted back into (5) and (6) to determine the optimal values of L_1 and L_2.

In preparation for thermal stress due to axial contraction, the conductor length of upper section needs to be slightly greater

TABLE III
SELECTED DIMENSIONS AND ESTIMATED COOLING LOAD

Inner vessel	Upper	1000 mm OD, L_1=460 mm	
	Neck	3 ea, 250 mm OD, l =60 mm	
	Lower	1000 mm OD, L_2=480 mm, L_{LN}=500 mm	
Current leads	OF Cu	6 ea, A = 184 mm^2, 1050 mm long	
Thermal load @ 130 K	684 W	Current leads (3ϕ, 2.5 kA)	635 W
		Conduction (wall+gas)	21 W
		Thermal radiation	28 W
Thermal load @ 77 K	262 W	Current leads (3ϕ, 2.5 kA)	246 W
		Conduction (wall+gas)	6 W
		Thermal radiation	1 W
		Dissipation in LN_2 pool	9 W

TABLE IV
ECONOMICAL EVALUATION OF TWO-STAGE COOLING DESIGN

	Single-Stage	Two-Stage	
Cryocooler	GM (62 K)	GM (62 K)	JT (120 K)
Thermal load	760 W	262 W	684 W
Cryocooler Cost[a]	$190,000	$65,500	$34,200
		Total $99,700	
Power consumption[b]	22.8 kW	7.9 kW	10.3 kW
		Total 18.2 kW	

than L_1, and the bolt-joints of bushing on the top plate should be tightened after initial cool-down. It should be noted that the intercept stations works also as mechanical supports, especially against horizontal displacement.

IV. DESIGN SUMMARY AND EVALUATION

Selected dimensions of cryostat and current leads for the designed two-stage cooling system are listed in Table III. The thermal load at each stage is estimated from the dimensions and also listed in the same table. The most significant source of thermal load is the current leads for both stages, even though the size of conductors has been optimized.

The listed cooling load at each stage can be compared with the cooling capacity of coolers in Table II. But, we must be careful in the comparison, because the cryocooler temperature is practically lower than the cooling object. The temperature difference strongly depends on the heat transfer media, such as flexible conductor, copper band, neck tube, or epoxy molding. With our experience and a short heat transfer analysis, the JT cooling temperature is assumed $\sim$120 K (10 K lower) and the GM coldhead temperature is assumed $\sim$62 K (15 K lower). It is noted that the 130 K load is lower than the JT capacity at 120 K, and the 77 K load is also lower than the GM capacity at 62 K. This implies that the proposed cryogenic system for 2.5 kA hybrid SFCL is feasible with one unit of GM cooler and one unit of JT cooler.

Table IV is an economic evaluation of the two-stage design in comparison with a similar size of single-stage system. The cryocooler cost and power consumption are roughly predicted with given values of "price per unit cooling" ($/W) and "power per unit cooling" (W/W), respectively, as listed at footnote of Table IV. These values are rough estimates from product information of a few commercial coolers. Obviously, an enormous saving in capital cost is expected with two-stage cooling, basically thanks to the inexpensive JT cooler for temperatures over 110 K. The power consumption for cooling can be saved approximately by 20%, which is comparable with the theoretical saving of ideal refrigeration listed in Table I. The enhanced cooling efficiency is, of course, a valuable outcome of our thermodynamic efforts on two-stage cooling. A hardware construction of the designed cooling system is underway for a full-scale hybrid SFCL.

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