Cryogenic Cooling Temperature of HTS Transformers for Compactness and Efficiency

Ho-Myung Chang, Yeon Suk Choi, Steven W. Van Sciver, and Thomas L. Baldwin, *Member, IEEE*

***Abstract*—A comprehensive thermal design to optimize the cryogenic cooling temperature of HTS transformer is presented, aiming simultaneously at compactness and efficiency. As small size and low power consumption are conflicting in determining the operating temperature, we develop a general and systematic model to quantify the effects of the temperature on compactness and efficiency. The procedure includes modeling of the critical property of HTS and the winding size, a heat transfer analysis for cooling load estimate, and a thermodynamic evaluation for cryogenic refrigeration. We demonstrate that there exists an optimum for the operating temperature that minimizes the overall power consumption, while taking into account the size effect of HTS windings. The optimal temperature turns out to be slightly above 77 K for two specific systems considered here: liquid-cooled pancake and conduction-cooled solenoid. The operation at temperatures well below 77 K can be justified, if the amount of ac loss is substantially reduced or the saving in capital investment earned by the compactness is significant in comparison with the operational cost.**

***Index Terms*—Cryocooler, cryogenic temperature, HTS, thermal optimization, transformer.**

I. Introduction

MAIN advantages of HTS power transformers are the small size and the low power consumption. Several prototypes have been constructed to date and successfully demonstrated the feasibility of compactness and efficiency with Bi-2223 windings and liquid-nitrogen cooling at around 77 K [1]. Toward the practical applications, an operation of HTS transformers at temperatures well below 77 K has been investigated, in order to take advantage of a greater critical current density of HTS and considerably reduce the size and weight of the system. As the operating temperature decreases, however, the required power for cooling increases dramatically, and the degraded overall efficiency could seriously affect its competitiveness with the existing technology. Thus, the optimization of the cooling temperature aiming simultaneously at compactness and efficiency is one of the critical issues in the commercialization of the HTS transformers.

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H.-M. Chang is with the National High Magnetic Field Laboratory, Tallahassee, FL 32310 USA, on leave from Hong Ik University, Seoul, Korea (e-mail: chang@magnet.fsu.edu).

Y. S. Choi and S. W. Van Sciver are with the National High Magnetic Field Laboratory and the FAMU-FSU College of Engineering, Tallahassee, FL 32310 USA.

T. L. Baldwin is with the Center for Advance Power Systems and the FAMU-FSU College of Engineering, Tallahassee, FL 32310 USA.

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In spite of the significance, only a few studies have been performed concerning the operating temperature of HTS power devices. Recently, Iwakuma *et al.* [2] and Funaki *et al.* [3] reported on the feasibility of an HTS transformer in subcooled liquid nitrogen at around 65 K and the measurement of the ac loss for Bi-2223 windings. An economic analysis to exploit the capital investment and the operational cost for different sizes and operating temperatures was presented by Oomen *et al.* [4]. Still these reports have neglected the principal thermal characteristics of the HTS material and the cryogenic refrigeration.

An international collaborative research program involving the cryogenics for HTS power transformers is underway at the National High Magnetic Field Laboratory. The objective of the project is the design of compact and efficient cryogenic systems for both the Korean power industry and shipboard applications for the US Navy. As a first step, we have introduced a general design concept to optimize the operating temperature of cryocooled HTS magnets [5]. The preliminary work is a thermodynamic investigation for the ideal refrigeration of HTS windings, revealing that there exists a unique optimum in the operating temperature for efficiency and compactness. In this paper, we present the next step toward the practical design of HTS transformer cryostats, with an emphasis on the interface between the HTS windings and the cryocooler. We pursue a versatile optimization scheme that is applicable to different winding types (pancake or solenoid) and cooling media (liquid cryogen and/or thermal conductive metal).

II. Modeling for Optimization

Two configurations of the HTS transformer system to be considered here are schematically shown in Fig. 1. The HTS windings may be immersed in a bath of subcooled (or compressed) liquid nitrogen (or neon) continuously refrigerated by a closed-cycle cryocooler (a) or it may be directly conduction-cooled without any liquid (b). In both cases, thermal conductive sheets (made of copper) or so-called thermal buses are placed in order to augment the axial heat conduction of the windings. In (a), heat from the HTS windings is removed primarily to the metal sheets by natural convection of liquid, and then transferred to the coldhead of cryocooler by conduction. Thus, the liquid works only as a heat transfer medium, like the conductive metal.

A flowchart given in Fig. 2 depicts how the operating temperature of an HTS transformer affects the winding size, the cooling load, and finally the power consumption in the proposed modeling. As identified in the left side, the four design factors—the HTS materials, the winding types, the cooling media, and the cryocoolers—should be provided at the corresponding steps of

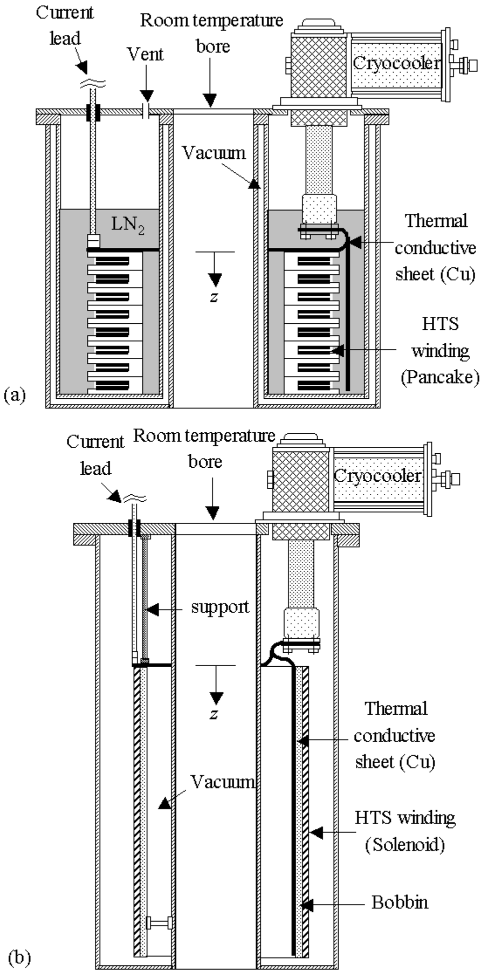

Fig. 1. Schematic configurations of cryocooled HTS transformer (a) liquid-cooled double-pancake (b) conduction-cooled solenoid.

the procedure. The entire process can be repeated with various input values of the operating temperature, to find its optimum for the least power consumption.

A. Operating Temperature and HTS Winding Size

Even in steady state, the temperature may not be spatially uniform over the HTS windings because of the dissipated heat (ac loss) and the thermal radiation on the surface. Since the highest temperature of the windings is important for a conservative HTS design, we define the operating temperature (T_L) as the temperature at the farthest point from the coldhead of cryocooler. The left top of Fig. 2 indicates the critical current density (J_C) of Bi-2223/Ag tape as a function of T_L.

In practice, it is not easy to determine how much we can reduce the size of HTS windings if the operating temperature is lowered to a particular level. It is reasonable, however, to assume that the amount of required HTS conductor for a specified transformer rating is inversely proportional to the critical current density at the operating temperature, if the operating current density is designed at a certain fraction (e.g., 50%) of J_C at the temperature. Therefore, we may well take a simple model that the winding size (i.e., mass M or volume V) is inversely proportional to J_C of HTS, as shown in Fig. 2. From a dimensional consideration for similar shapes, we further assume that the external surface area (A) and the axial length (L) of the HTS windings have the two-third and the one-third power of the volume, respectively.

B. Cooling Media and Temperature Distribution

In order to maintain the operating temperature at the designed level, the coldhead temperature of cryocooler (T_C) must be lower so that heat may be removed from the HTS windings. Since T_C is significant in determining the power consumption at the cryocooler, the difference between T_L and T_C should be carefully estimated by taking into account the effects of the cooling media, the winding size, the magnitude of ac loss and thermal radiation as indicated in Fig. 2.

The temperatures of the HTS winding (subscript *HTS*) and the thermal conductive sheet (subscript *Cu*) can be determined by the one-dimensional heat conduction equations, because heat is transported principally in the axial direction

$$(kA_c)_{\rm HTS}\frac{d^2T_{\rm HTS}}{dz^2} - PU(T_{\rm HTS} - T_{Cu}) + Q'_{ac} + Q'_r = 0 \quad (1)$$

$$(kA_c)_{Cu}\frac{d^2T_{Cu}}{dz^2} + PU(T_{\rm HTS} - T_{Cu}) + Q'_r = 0 \quad (2)$$

where the axial coordinate, z, is defined as the distance from the cold end of windings, and k, A_c, and P denote the thermal conductivity (averaged for composite conductor [6]), the axial cross-sectional area, and the perimeter between *HTS* and *Cu*, respectively. U is the overall heat transfer coefficient, which is determined by the natural convection of the gap liquid in the liquid-cooled system, and by conduction and mechanical contact in the conduction-cooled system. In (1) and (2), Q'_{ac} and Q'_r are the ac loss and the thermal radiation per unit axial length, respectively. In the liquid-cooled systems as Fig. 1(a), the radiation from room-temperature surfaces is received first by the walls of the liquid container, and then transferred to the metallic sheets. The boundary conditions and the energy balance at the two ends are given by

$$\begin{aligned} T_{\rm HTS}(L) &= T_L, \frac{dT_{\rm HTS}(L)}{dz} = \frac{dT_{Cu}(L)}{dz} = 0, \\ T_{Cu}(0) &= T_c \\ Q_{ac} + Q_r &= (kA)_{\rm HTS}\frac{dT_{\rm HTS}(0)}{dz} + (kA)_{Cu}\frac{dT_{Cu}(0)}{dz}. \end{aligned} \quad (3)$$

C. Cryogenic Load and Power Consumption

There are four different sources of cryogenic load in the HTS transformers—ac loss, thermal radiation, conduction through supports or walls, and current leads—as indicated in Fig. 2.

$$Q_C = Q_{ac} + Q_r + Q_k + Q_l. \quad (4)$$

The magnitude of ac loss can be roughly estimated according to the so-called critical state model. Since the model predicts that ac loss per unit volume of conductor is proportional to the critical current density if the magnetic field is greater than the penetration field, we assume that the total ac loss is independent

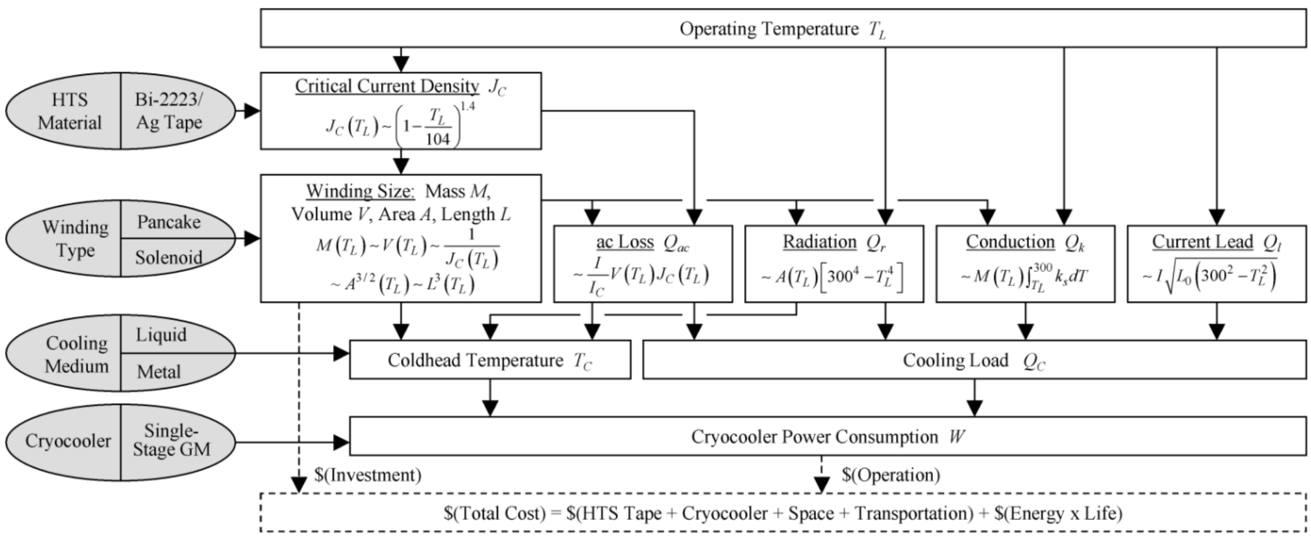

Fig. 2. Flowchart to estimate the power consumption from a given HTS operating temperature (solid lines indicate the present investigation).

of temperature. The thermal radiation is proportional to the external surface area and the difference of the fourth-powers of temperature as indicated in Fig. 2. The heat conduction is proportional to the cross-sectional area of the wall or the mechanical supports and the temperature-integration of thermal conductivity. We assume here that the cross-sectional area is proportional to the mass of HTS windings from the viewpoint of safe design in mechanical components. The cooling load due to a current lead is proportional to the operating current and $\sqrt{300^2 - T_L^2}$, assuming a Wiedemann-Franz material and no boil- off gas. The lead is independent of the winding size.

The power consumption of a cryocooler that absorbs Q_C at T_C and rejects the heat at 300 K can be generally expressed as

$$W = \frac{Q_C}{FOM}\left(\frac{300}{T_C} - 1\right) \tag{5}$$

where *FOM* is the figure of merit [7] or Carnot efficiency of the cryocooler. The *FOM* of a specific cryocooler varies with T_C to a certain extent, but depends more significantly upon the thermodynamic cycle and the refrigeration capacity. Typical GM or Stirling coolers eligible for hundreds of watts at 77 K have an *FOM* value between 0.1 and 0.2. We take $FOM = 0.15$ in present study.

III. Results and Discussion

An immediate goal of this study is the cryogenic design of both the utility transformer developed by the Korea Polytechnic University (KPU) and the shipboard transformer developed by the Center for Advanced Power Systems (CAPS). Preliminary design parameters for the two systems are summarized in Table I. They consider the same HTS material and the same type of cryocooler, but different designs in HTS winding and cooling medium, as shown in Fig. 1. The given parameters about the windings are based upon the operation at 77 K, and may vary at different temperatures. The presented optimization method is now applied to the two specifics systems for a quantitative discussion.

TABLE I
Preliminary Design Parameters of KPU and CAPS Transformers

	KPU	CAPS
Coil Rating	1 MVA / 60Hz 22.9 kV / 6.6 kV 44 A / 152 A	1.17 MVA [a] / 60Hz 2400 V / 450 V 486 A / 2593 A
HTS Material	Bi-2223 / Ag Tape	
Winding Type	Double Pancake	Solenoid
Turns [b]	888 / 256	96 / 18
Parallel Tapes [b]	1 / 4	12 / 64
Tape Length [b]	1212 m / 333 m	135 m / 34 m
Inner Diameter [b]	378 mm	448 mm / 580 mm
Outer Diameter [b]	450 mm	452 mm / 584 mm
Height [b]	182 mm / 182 mm	1250 mm
Cooling Medium	Liquid Nitrogen	Conductive Metal
Cryocooler	Single-Stage GM Cooler	

[a] Transformer rating is 3.5 MVA with 3 phase.
[b] Based on the operation at 77 K.

Fig. 3 shows the calculated axial temperature distributions along the *HTS* winding and the *Cu* sheet for the two systems, when $T_L = 77$ K. The curves are convex upward because of the heat input by ac loss and radiation. In spite of the short axial length (height) in the KPU transformer, we observe not a small temperature difference (3.6 K) between the two axial ends of winding, because the average thermal conductivity of the pancake is relatively small due to the insulating material (such as GFRP). The end-to-end temperature difference is even larger in the CAPS transformer, since it has a greater surface area exposed to thermal radiation. The winding-to-sheet temperature difference is estimated around 1.5 K with the natural convection of liquid nitrogen and less than 1 K for the most region of the contact and conduction. The key point of these results is that the coldhead temperature of the cryocooler must be lower than the operating temperature by 3.6 K for the KPU system and by 11.8 K for the CAPS system. This coldhead temperature is especially important in liquid-cooling, because the failure to maintain the low temperature may cause the generation of bubbles in the liquid, deteriorating the electrical insulation.

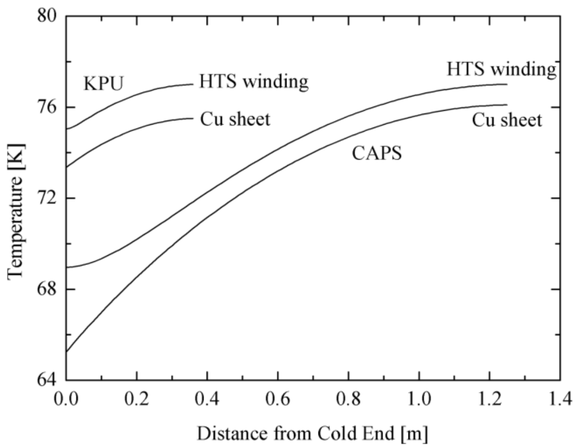

Fig. 3. Calculated axial temperature distributions along HTS windings and metal sheets for the KPU and CAPS transformers.

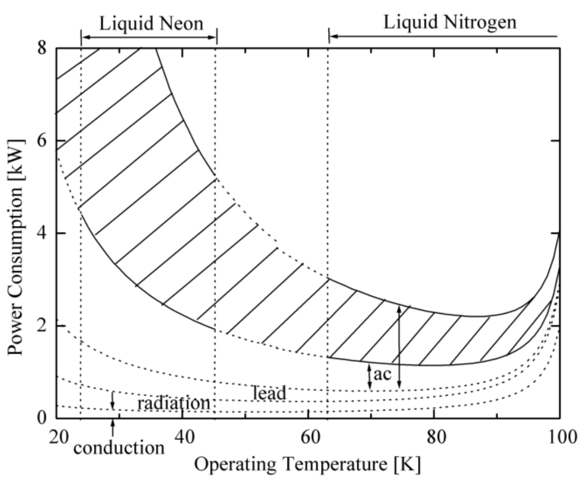

Fig. 4. Power consumption as a function of operating temperature for KPU transformer.

The estimated power consumption as a function of operating temperature is shown in Figs. 4 and 5, for the KPU and the CAPS transformers, respectively. The sum of the power is subdivided into the four portions, indicating the contributions of individual load. Since the most uncertain quantity in the estimate is the ac loss, the total power is presented as a range (shaded area). We take the minimum of ac loss as 0.25 W/(kA-m) in both cases [1], but the maximum as 0.75 W/(kA-m) for the KPU and 0.5 W/(kA-m) for the CAPS, because the former may be more affected by the perpendicular magnetic field than the latter.

In Fig. 4, only the solid curve at temperatures above 63 K or below 44 K represents the viable liquid cooling, as nitrogen or neon can exist as liquid in those temperature ranges. In the KPU transformer, the minimum power consumption is predicted at 1.2–2.2 kW when the operating temperature is around 79–87 K, depending on the magnitude of ac loss. We can notice that the optimal operating temperature shifts down as the ac loss decreases. At any higher temperatures, more power would be required due to oversized HTS winding for the same rating. At any lower temperatures, on the other hand, more power would be required too, mainly by the excessive penalty of the ac loss.

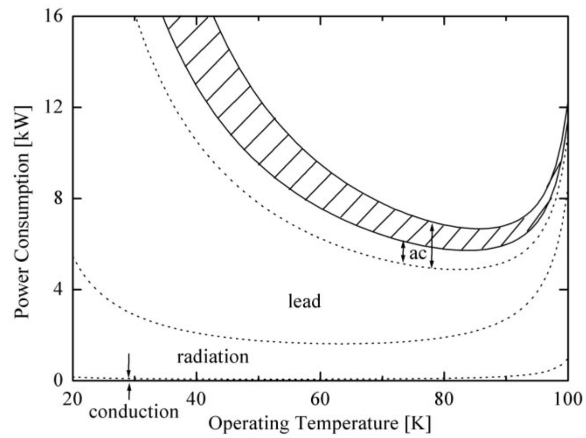

Fig. 5. Power consumption as a function of operating temperature for CAPS transformer.

Fig. 5 predicts that the minimum power consumption for the CAPS transformer will be as large as 5.6– 6.6 kW when the operating temperature is 84– 86 K. The main reason for the increased power is the current leads with higher operating currents. In addition, the extended surface area makes the radiation load higher and the required coldhead temperature lower. In spite of various differences between the two transformers, a very similar behavior on the optimal operating temperature is predicted, because there is a trade-off of the load from ac loss and conduction with the load from leads and radiation.

Finally, we mention an economic aspect in optimizing the operating temperature. The present study is primarily focused on the power consumption in steady state, which will essentially determine the operational cost and the transformer efficiency. The small size of HTS windings can provide us additional economic merits, such as the saving in HTS conductor costs and the easiness in transportation or installation. As indicated by dotted lines in Fig. 2, a complete economic analysis including the capital investment and the operational cost should be performed, in order to justify the operation of HTS transformers at temperatures well below 77 K.

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