Choice and justification of the optimum cooling temperature for HTS cable

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Abstract. At the first stage of designing a high-temperature superconducting (HTS) cable and its cryogenic refrigeration system (CRS), it is necessary to choose the optimum cooling temperature. The operating temperature is selected not only according to the critical parameters of the HTS conductor, but also taking into account other design and operational characteristics - geometry, length, operating current and the need to have subcooled nitrogen to prevent the occurrence of steam inclusions. Normally the range of cooling temperatures is limited by the critical temperature of the HTS conductor ($T_{HTS} \leq 104$K) and the triple point temperature of nitrogen ($T_{LN} \geq 63.15$K). The choice of a certain temperature value will enable us to approximately evaluate the parameters of the CRS and overall characteristics of the cable. The article presents an analysis of the dependence of the electric power magnitude consumed by the CRS on the choice of the cooling temperature value and cable geometry. The analysis may be useful for determining the characteristics of the HTS cable operating at different temperature levels.

1. Introduction

To use superconducting equipment, the effective and reliable CRS is required which can maintain the superconductor temperature at a given level. The complexity and high price of effective CRS prevent the widespread use of high-temperature superconducting (HTS) cable line (CL) in the power grid. As a rule, the CRS use liquid nitrogen as a coolant due to its properties: high dielectric strength, wide range of operating temperatures (especially at elevated pressure), high specific heat capacity, low cost and fire safety.

Replacement of liquid nitrogen in a saturation condition (77 K) by subcooled liquid nitrogen with a temperature below 77 K increases the permissible density of critical current [1]. An increased current density makes it possible to reduce the cost and weight of the cable. However, as the operating temperature level decreases, the thermal load on the CRS and the energy consumption for cooling of the HTS CL increase. Excessive power consumption in the CRS due to relatively low temperature level of heat removal from the subcooled nitrogen can seriously impair the competitive ability of the HTS CL in comparison with alternative technologies of energy transmission. The choice and justification of the optimum cooling temperature of the HTS CL, taking into account the compactness
and effectiveness of the CRS, are one of the most important scientific and technical problems of HTS cable commercialization.

Today, subcooled liquid nitrogen is used for cooling in most HTS cables. The nitrogen temperature at the inlet to the cryostat is lowered to \( T_{\text{LN}} = 65 \text{ K} \) [2]. The choice of this temperature range is determined by the fact that it provides high current density of HTS tapes and reduces the cost of cable manufacture. At the same time, capital and operating costs associated with the CRS are increased.

The wider use of the HTS tapes forms a tendency of gradual reduction in their price. In the future it will be possible to increase the specific consumption of HTS material and, thus, to rise the cooling temperature and simplify the CRS.

2. HTS cable model description
In this investigation, an attempt was made to analyze the dependence of the cryostat size and the power used by CRS on the choice of the cooling temperature. It is necessary to determine the cooling temperature at which the minimum energy consumption in the CRS will be achieved. The size of a cryostat affects the energy efficiency of the CRS (see Figure 1).

![Figure 1. HTS cable model.](image)

To select the CRS parameters, the design of a power cable with a cold dielectric described in the literature [3] was used. Sumitomo’s 1st generation DI-BSCCO Type HT tape with a width of 4.5 mm and a thickness of 0.34 mm is used as a current-carrying element. The flow part of the cable is defined by an annular channel (See Figure 1). It is assumed that the temperature of the HTS cable varies along its length. The temperature gradient (\( \Delta T \)) along the cable length is taken equal to 10 K. The critical current density of the HTS tape decreases with increasing temperature. The number of tapes in layers of the cable increases, so the diameter and weight of the cable also depend on the choice of the operating temperature of the CRS. In this case, a HTS cable with two layers is considered. Two layers of the HTS tapes ensure an even current distribution [4]. The HTS cable diameter is made up of the former diameter \( (D_f) \), the thickness of the power HTS layer, the insulation and the thickness of the HTS shield, which are proportional to the cryostat temperature. The required number of tapes is determined by the current density in the HTS cable and the critical current of the HTS conductor. The former diameter is selected for laying two HTS layers. The tapes are placed evenly across the layers. The diameter is selected based on the possibility of placing the tapes of the first layer along the perimeter of the cable without gaps.

The cryostat diameter \( (D_{cr}) \) is selected based on the condition of minimizing hydraulic losses and ensuring a given temperature gradient (\( \Delta T \)) along the cable length.

3. Thermal load on the cryogenic refrigeration system
The thermal load on the cryogenic system of the HTS cable consists of the following components:

- Thermal leak through current leads.
• Thermal leak through thermal insulation.
• AC losses.
• Dielectric losses.
• Hydraulic losses.
• Pumping losses.
• Losses in contacts.

3.1. Thermal leak through current leads
Current leads - devices to transfer electric energy to the low temperature zone. One end of the current lead is in contact with the electric power source at ambient temperature, the other is connected to the HTS cable. The design of Current leads should provide a minimum thermal load \(q_{\text{load}}\) on the CRS. To calculate the intensity of thermal leak through current leads, you can use the expression [5]:

\[
q_{\text{lead}}^n = I \cdot (2 \cdot \lambda \cdot \Delta T_{\text{in}} \cdot \rho)^{1/2}, \quad q_{\text{lead}}^o = I \cdot (2 \cdot \lambda \cdot \Delta T_{\text{out}} \cdot \rho)^{1/2}
\]

\[
q_{\text{lead}} = q_{\text{lead}}^n + q_{\text{lead}}^o
\]

where \(\Delta T_{\text{in}}, \Delta T_{\text{out}}\) - temperature difference at the initial and final sections of the current lead, respectively, K;
\(\rho=f(T)\) - average integral resistivity of copper in the temperature range, Om\(\cdot\)m;
\(\lambda=f(T)\) - average integral thermal conductivity of copper in the temperature range, W/(m\(\cdot\)K);
\(I\) - operating current, A.

3.2. Thermal leak through thermal insulation
Thermal leak through insulation \(q_{\text{ins}}\) mainly provides thermal radiation. For modern flexible cryostats, this type of thermal load is from 1 to 3 W/m [6]. The amount of thermal leak through the insulation varies in length since there is a gradient \(\Delta T\) between the input and output of the cable. The temperature gradient shall be taken into account when calculating the value of \(q_{\text{ins}}\). The thermal leak from heat transfer by radiation is proportional to the diameter and length of the cable. It is shown that the cable diameter depends on the operating temperature of the cable. The thermal leak by radiation can be described by the following expression:

\[
q_{\text{in}} = \varepsilon \cdot \sigma \cdot (T_R^4 - T_{\text{in}}^4) \cdot S_{cr}, \quad q_{\text{out}} = \varepsilon \cdot \sigma \cdot (T_R^4 - T_{\text{out}}^4) \cdot S_{cr}
\]

\(q_{\text{in}}\) and \(q_{\text{out}}\) are thermal leaks to the cryostat at the initial temperature \(T_{\text{in}}\) and \(T_{\text{out}}\) respectively, where \(\varepsilon\) - Emissivity of the surfaces; \(\sigma\) - Stefan-Boltzmann Constant, \(5.67 \times 10^{-8}\) W/m\(^2\)K\(^4\); \(T_R\) - Room temperature, K; \(S_{cr}\) - the area of the inner pipe of the cryostat, m\(^2\). The traditional way to reduce thermal leak from radiation is to use multilayer insulation (MLI) with high reflectivity [7]. In a first approximation, the average thermal leak to the cryostat can be calculated as the arithmetic mean between the thermal leak determined for the initial and final temperature:

\[
q_{\text{ins}} = \left(\frac{q_{\text{in}} + q_{\text{out}}}{2}\right) \cdot (n+1)^{-1}
\]

where \(n\) is the number of layers MLI.

3.3. AC and dielectric losses
AC losses are converted into heat and distributed along the entire length of the cable. This heat is to be diverted by the CRS. The sum of the specific energy losses during AC transmission in one phase can vary from 0.1 to 5 W/m, depending on the operating current. The AC losses in a superconductor are usually much lower than resistive losses in a normal conductor with the same operating current. However, minimization of thermal load associated with the movement of alternating current is technically important, since thermal energy is dissipated in the low-temperature zone of the cable. Complete loss modeling in the HTS cable requires consideration of the method of winding HTS tapes.
onto the former. In a simplified model, this conductor can be described as a superconducting tube. This is the so-called monoblock model [8]. It takes into account neither the method of tape winding nor changes in the properties of HTS tapes during cable manufacturing. In this case, the energy loss in the current-carrying layer can be calculated by the formula:

\[
q_{ac} = \frac{f \cdot \mu_0 \cdot I_c^2}{2\pi \cdot b^2} \left(2 - R \cdot b \cdot R \cdot b + 2 \cdot (1 - R \cdot b) \cdot \ln(1 - R \cdot b)\right) \text{[W/m]}
\]

where \(R = I_p / I_c\) is the ratio of the transport to the critical current; \(\mu_o\) is the magnetic constant; \(f\) is the frequency of the electric current.

The AC losses for HTS shield \((q_{sh})\) are calculated similarly. Dielectric losses depend on the operating voltage of the cable and are usually insignificant; therefore they are not taken into account in this analysis.

3.4. Hydraulic and pumping losses
The heat dissipation \((q_f)\) in the cable path due to irreversible energy losses (friction of the coolant along the channel walls) is determined by: flow rate, coolant temperature, design features of the cooling channel (roughness of the channel wall, turbulence of the flow due to swirling), the presence of local hydraulic resistances. For a given temperature gradient along the cable length, the corresponding coolant flow rate \((G_v)\) is determined and the optimal external diameter \((D_{cr})\) is selected. With this diameter, \(q_f\) will be minimal. The pressure head \((\Delta p)\) created by the cryogenic pump is converted into thermal energy. Additional heating of the liquid in the pump path \((q_{pump})\) occurs because the pump coefficient of performance \((COP_{pump})\) usually does not exceed 70%. The thermal load from hydraulic and pumping losses can be calculated using the following formulas:

\[
q_f + q_{pump} = \frac{\Delta p \cdot G_v}{COP_{pump}}
\]

\[
q_f = \Delta p \cdot G_v
\]

3.5. Actual Performance of cryogenic refrigeration system
The thermal load of the HTS cable shall be removed using a cryogenic refrigerator. The ratio between the thermal load and the power consumed determines the coefficient of performance, which shows the relationship between the power consumed and the temperature cooling level:

\[
\sum q = q_{lead} + q_{ins} + q_{ac} + q_{sh} + q_{pump} + q_f
\]

\[
COP = \frac{\sum q}{W}.
\]

The minimum value of the power consumed by the refrigerator can be determined using the Carnot cycle [9]:

\[
COP_{car} = \frac{T_s}{T_0 - T_s}, \quad W_{min} = \frac{\sum q}{COP_{car}}.
\]

To compare the performance of real cryogenic refrigerator with the Carnot refrigerator, it is possible to use a figure of merit \((FOM)\):

\[
FOM = \frac{COP}{COP_{car}}.
\]

For the modern cryogenic refrigerator, this indicator is within 25% [10].
4. Thermal analysis of HTS cable

A model for finding the optimal operating temperature with minimized power consumption for the HTS cable is presented in the previous section. The analysis was based on the cable with an operating current of 2500 A and a length of 2.5 km. The results of thermal analysis of the HTS cable are presented in Figures 2 and 3. As you can see in Figure 2, minimum power consumption in the CRS is at an average cable temperature of 88 K. Figure 3 illustrates the individual contribution of each type of thermal load. At low temperatures, the influence of AC losses is great. As the cooling temperature of the HTS cable increases, the thermal load on the CRS decreases. But at higher temperatures, the proportion of thermal leak by radiation increases, since the calculated dimensions of the cryostat are enlarged at the increased cable cooling temperature.

[Graphs showing power consumption vs. cable temperature]

**Figure 2.** Power consumption of CRS to compensate for all thermal load.

**Figure 3.** Power consumption of CRS depending on the type of thermal load.

It is useful to show the negative impact of low temperatures on the energy efficiency of the HTS CL. Compare the operational characteristics of two cables with cooling temperatures $T_{in}=65$ K, $T_{out}=75$ K and $T_{in}=83$, $T_{out}=93$ K, respectively (see table 1).

| Table 1. Parameters of HTS cable. |
|-----------------------------------|
| Cable temperature, K | Number of tapes | Cable diameter, mm | Hydraulic losses, kPa | $COP_{car}$ | $\Sigma q$, W | $W$, kW |
|-----------------------|-----------------|--------------------|-----------------------|-------------|-------------|--------|
| 65-75                 | 19              | 64                 | 321                   | 0.276       | 6283        | 91     |
| 83-93                 | 51              | 86                 | 211                   | 0.38        | 6205        | 65     |

Due to an increase in the cooling temperature of the cable, the critical current of the HTS tapes has decreased, so the number of the tapes has almost doubled, and the outer diameter of the cable has become 25% larger. But, despite the increase in the cable size, the intensity of thermal load has scarcely changed. At the same time, due to an increase in the temperature level of cooling, the power...
consumption of the CRS has decreased by 28%. Taking into consideration the duration of the HTS cable operational campaign, such energy savings significantly increase the investment prospects of such projects.

5. Conclusions
The decrease in power consumed by the CRS is related to the fact that the COP of cryogenic refrigerators increases with an increase in temperature. The HTS tapes have not been mass-produced so far. Generally the tapes are produced on preliminary request. As the introduction of HTS technologies in urban power grids grows and the production of the HTS tapes increases, a significant reduction in prices can be expected. When performing a full economic assessment of HTS projects, it is necessary to take into account the purchase costs for the CRS and HTS conductor. The increased temperature of the coolant increases the dimensions and cost of the cable, but reduces the dimensions and cost of the CRS, as well as power consumption for cooling. If these two factors are taken into account, the optimum cooling temperature of the cable is in the range of 65-75 K at present, since the cost of the HTS conductor is very high.

The choice of the temperature range of 65-75 K is based on the assumption that the coolant flows out of the cryostat in the CRS at atmospheric pressure. Under such conditions, a maximum temperature of 75 K guarantees a single-phase state of the coolant. However, the single-phase state of the coolant along the length of the cable can be ensured at higher temperatures by increasing the pressure in the cable path. When choosing a temperature of 83–93K, the overpressure in a closed-loop system of the CRS should be at least 0.6 MPa, which will require an increase in the wall thickness of the cryostat.

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