Practical AC Loss and Thermal Considerations for HTS Power Transmission Cable Systems*

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Practical AC Loss and Thermal Considerations for HTS Power Transmission Cable Systems

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***Abstract*—The use of high-temperature superconducting materials for power-transmission cable applications is being realized in prototype situations. It is well known that ac loss decreases as the temperature of the conductor decreases. Also, thermal losses are higher at lower temperatures, owing to the increased temperature difference between ambient and cryogenic operating conditions. Both counterflow and parallel-flow cooling arrangements have been proposed in the literature and significantly affect temperature distribution along the cable. In this investigation, the counteracting ac loss and thermal losses are analyzed for both cooling configurations to determine the benefits and limits of each. The thermal-insulation performance levels of materials versus those of typical systems in operation are presented. Widespread application of long-length flexible cable systems, from the refrigeration point of view, will depend on an energy-efficient cryogenic system that is economical to manufacture and operate. While the counterflow arrangement will typically have a lower heat load, it has a length limit arising from the large pressure drop associated with the configuration.**

***Index Terms*—cryogenic, high-temperature superconductivity, power-transmission lines**

II. Introduction

HIGH-temperature superconductor (HTS) power-transmission lines are slowly being placed in industrial settings [1] in order to gain experience and quantify performance and reliability of HTS power transmission cable systems in realistic settings.

An in-depth analysis of the HTS power-transmission cable system is required for a particular installation. However, the tendencies for direct system optimization can be determined from a generic study such as this one. The examples examined in this study are intended to illustrate the existence of limitations to a system through the use of assumed typical operating conditions and component sizes. In some cases, the limits shown may be overcome by simple measures such as raising the system pressure or increasing component dimensions. In a practical HTS power-transmission cable application, other constraints, such as the use of existing cable ducts, may limit the options available.

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III. HTS Cable System Model Description

A. Hardware

HTS cables are being proposed for retrofitting existing underground cables. In common underground-cable installations, the three separate phases are installed in separate ducts [2]. It is assumed that there is a refrigeration unit supplying subcooled liquid nitrogen at one end of the cable. The HTS cable configuration, shown in Fig. 1, illustrates a single-cryostat counterflow cooling arrangement for the HTS cable. The HTS cable former and cryostat walls are typically taken to be flexible corrugated stainless steel tubing. The HTS cable in this study is a cold dielectric configuration and requires a superconducting shield layer separated from the main conductor by a dielectric material. The shield carries the same current as the main conductor.

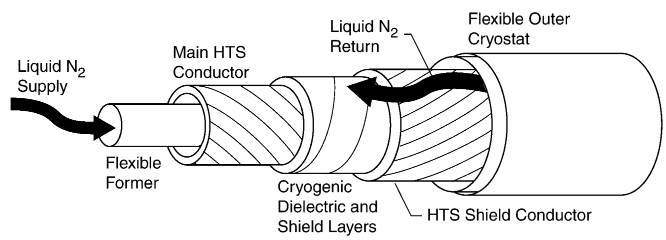

Fig. 1. Diagram of liquid nitrogen flow paths for a counterflow cooling arrangement.

In the counterflow cooling arrangement the liquid nitrogen flows through the HTS cable former, providing cooling to the terminations as well as the cable and returns in the annulus between the outside of the cable and the inner cryostat wall. In the parallel flow arrangement, liquid nitrogen flows in the same direction through the cable former and the annulus. The liquid nitrogen is returned through a separate vacuum-jacketed duct. The single cryostat for the return flow is the same size as the cable cryostat and returns the total cable cooling flow, or three times the flow per phase (i.e., 3000 g/s). The dimensions used in this study for these two cases are given in Table I.

It is assumed that two-phase flow of liquid nitrogen is not permitted in the HTS cable power transmission system. First, pressure drops for two-phase flow are higher than for those for single-phase flow. In addition, gas bubbles in the cold dielectric, which is wetted by the liquid nitrogen, could decrease the cable electrical insulation levels.

B. Theoretical Analysis

The ac-loss and thermal analysis of HTS power-transmission cable systems is accomplished by performing an

TABLE I
CRYOSTAT DIMENSIONS

Nominal dimension (mm)	Counterflow	Parallel flow
former diameter (mm)	38	38
cable diameter (mm)	65	65
cryostat inner diameter (mm)	75	75
cryostat outer diameter (mm)	125	125
return cryostat inner diameter (mm)	—	75
return cryostat outer diameter (mm)	—	125

energy balance of the cable system to determine the temperature distribution, T. For the HTS cable, the one-dimensional energy balance equation can be written as

$$\rho C_{HTS} \frac{\partial T_{HTS}}{\partial \tau} = \frac{\partial}{\partial z}\left(kA_{HTS} \frac{\partial T_{HTS}}{\partial z} \right) + P'_{AC} - \sum_i Q'_{conv,i} \quad , \quad (1)$$

where ρ is the density, C is the heat capacity, z is the coordinate direction along the cable axis, k is the thermal conductivity, and A is the cable cross-sectional area.

The HTS cable energy balance has convection heat-transfer terms, $Q'_{conv,i}$, that include convection to the liquid nitrogen flow in the former as well as in the annular region between the cable and the cryostat inner pipe. The product of the thermal conductivity and the cross-sectional area of the cable, kA_{HTS}, is constant for this work and is equal to 0.16 watt-meter per Kelvin. Additional energy-balance equations are needed for the liquid streams and are given by

$$\rho_{vi} c_{p,vi} \frac{\partial T_{vi}}{\partial \tau} = m \frac{\partial h_{vi}}{\partial z} + \sum_i Q'_{conv,i} \quad , \quad (2)$$

where i represents each liquid nitrogen stream (former flow, annulus flow, and return flow as applicable) and m is the mass flow per phase in the HTS cable.

The convection heat transfer to the inner flow is solely with the inside of the HTS cable former. The outer nitrogen flow exchanges heat convectively with the outside of the HTS cable and with the inside of the double-walled flexible cryostat.

The convective heat-transfer coefficients are calculated as follows:

$$N_{Nu} = \frac{C_h D_{hyd}}{k_{LN2}} = 0.023 N_{\text{Re}}{}^{0.8} N_{\text{Pr}}{}^{0.3} \quad , \quad (3)$$

where N_{Nu} is the Nusselt number, C_h is the heat transfer coefficient, k_{LN2} is the thermal conductivity of the liquid nitrogen, D_{hyd} is the hydraulic diameter of the flow path, N_{Re} is the Reynolds number, and N_{Pr} is the Prandtl number.

The equations are cast into a finite difference form and numerically integrated in time until a steady state is reached. After the determination of the temperature profiles, the pressure drop, dP, can be approximated by integrating the following equation over the flow path length:

$$dP + \rho V dV + f \frac{\rho V^2}{2} \frac{dz}{D_{hyd}} = 0 \quad , \quad (4)$$

where V is the liquid velocity and f is the friction factor.

In a rigorous treatment, the thermal-hydraulic solutions should be coupled, but it is assumed that compressibility effects and density variations are small for liquid nitrogen under the conditions considered in this work. Therefore, the temperature and pressure profile solutions were performed separately. The friction factor for cryogenic liquid flow in corrugated bellows has been suggested to be four times that for a smooth pipe [3]. In the cases presented here, the Reynolds numbers are in the range of 10^5 to 10^6, and a constant friction factor $f = 0.07$ was used. The pressure drop across the terminations is assumed to be small and is neglected.

IV. HTS CABLE THERMAL LOSSES

A. Cryostat

The HTS cable cryostat is taken to be a flexible double-wall construction with the dimensions listed in Table I. The sink temperature $T_\infty = 300$ K. Typical commercially available vacuum-insulated flexible cryostats have an effective or actual field-installation thermal conductivity, k_{eff}, of 0.0008 watt per meter per Kelvin. The local heat transfer per unit length can be calculated using (5) and depends on the local liquid nitrogen temperature, $T_{vi}(x)$, and the cryostat inner and outer tube diameters D_{ci} and D_{co}. The temperature difference driving this heat-transfer term is typically over 220 K for the outer cryostat.

$$Q'_{cstat,i} = \frac{2\pi k_{eff}(T_\infty - T_{v,i}(x))}{\ln(D_{co}/D_{ci})} \quad . \quad (5)$$

B. AC and Dielectric Losses

The critical current was scaled from earlier measurements on the 5-m system [4]. Using the measured linear fit in temperature, the critical current can be scaled with temperature using a reference value of 3000 A at 77 K by the following:

$$I_c(T) = 6188.2 - 41.405T \quad . \quad (6)$$

The ac loss, P'_{ac}, in watts per meter, is computed using the monoblock model [5],

$$P'_{ac} = \frac{\mu_0 f I_c^2}{2\pi h^2}\{(2 - Fh)Fh + 2(1 - Fh)\ln(1 - Fh)\} \quad , \quad (7)$$

where $F = I_p/I_c$ is the ratio between the peak current in the ac cycle and the critical current of the superconductor, f is the frequency, and $h = (D_o^2 - D_i^2)/D_o^2$. The terms D_i and D_o are the inner and outer diameters of the superconductor respectively. This study will show results for operating currents of 1500 A_{rms} and 2000 A_{rms}.

The dielectric loss depends on the design voltage of the cable. A nominal value of 0.05 W/m was assumed and is consistent with earlier work [6].

V. COMPARISON WITH 5-M EXPERIMENTS

The model has been compared with measurements on a 5-m HTS cable system reported in [7]. A comparison of the measured temperatures for operation as described in [7] is given in Fig. 2. In this case, the 5-m HTS cable was cooled

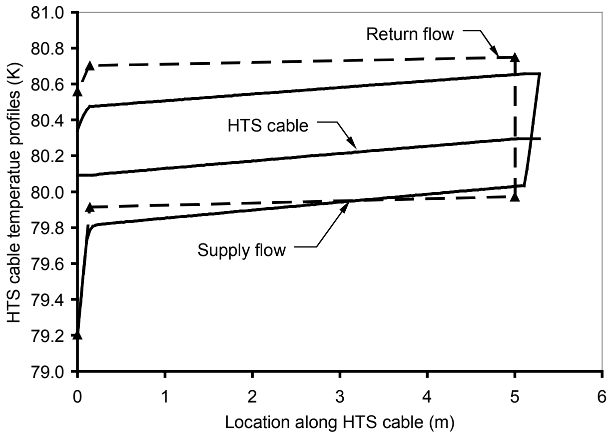

Fig. 2. Comparison of HTS cable thermal model with measurements from 5-m system. The solid lines represent the model calculations and the measured data are the symbols, connected with dashed lines for clarity.

with a flow of 210 g/s of liquid nitrogen supplied at a temperature and pressure of 79.2 K and 5.4 bar. The applied current to the cable was 1250 A_{rms}. The measurements qualitatively agree with the calculation. The discrepancies in temperatures are primarily due to the use of a simplified thermal model for the terminations, which for short cables is the dominant system heat load. The terminations in [7] had vacuum thermal and electrical insulation. Each termination contained two optimized current leads to carry in excess of the rated current of 1250 A_{rms}. The termination heat load in [7] is about 300 W for each end. This value is used in the rest of this study. While there is some variation in the termination heat load due to the level of operating current, the difference is considered to be small, particularly for long cables, and is neglected.

VI. Long-Length Cable Analysis

A. Baseline Conditions

For a HTS power transmission system, the termination heat loads are constant and independent of the length of the transmission cable system. The ac loss and thermal load through the cryostat depend on the length of the HTS transmission cable system, the cooling-flow configuration, and the supply temperature and flow rate.

For the results presented here, constant liquid-nitrogen conditions, a pressure of 10 bar, and a temperature of 67 K are used. GASPAK [8] was used to obtain the properties of liquid nitrogen. The pressure is well within the capabilities of commercially available flexible cryostats, and the temperature is typical for a subcooler refrigeration unit. The triple point of nitrogen is about 63.2 K, so lower temperatures, say 65 K, could be achieved with closed-cycle refrigeration systems. The use of lower temperatures or higher pressures will result in slight changes in the results shown in this work.

B. Critical Current, Temperatures, Pressure Drops and Refrigeration Loads

Critical-current and temperature profiles are shown for the two long-length cases at flows of 1000 g/s per phase and both cooling arrangements in Fig. 3 and Fig. 4. Temperature limits are clearly shown to exist in the counterflow flow case. In this case, the bottom temperature line is the former flow temperature, the center line is the HTS cable temperature, and the top line is the annular return-flow temperature. The pressure drop for the 500-m counterflow case, shown in Fig. 5, is 4.7 bar. Increasing the flow to reduce the cable

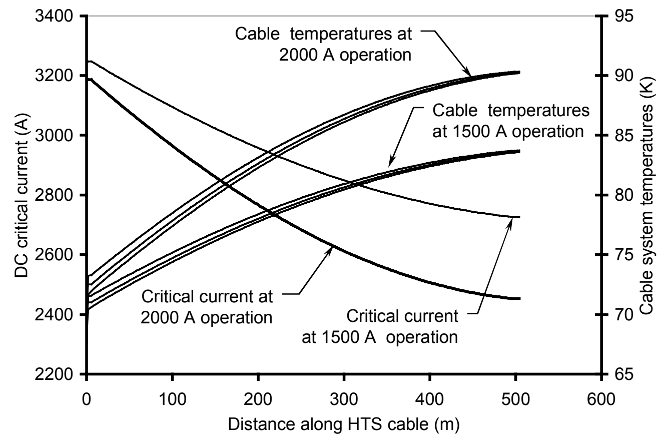

Fig. 3. Critical current and temperature distributions for a 500-m HTS cable transmission line in the counterflow cooling arrangement. The temperature rise produces a reduction in the critical current of the cable.

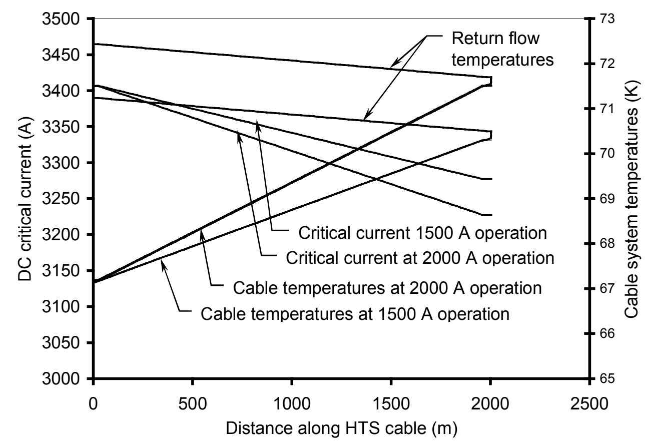

Fig. 4. Critical current and temperature profiles for a 2000-m HTS power-transmission cable in the parallel-cooling arrangement. The temperature rise is fairly low maintaining a high critical current in the HTS conductor.

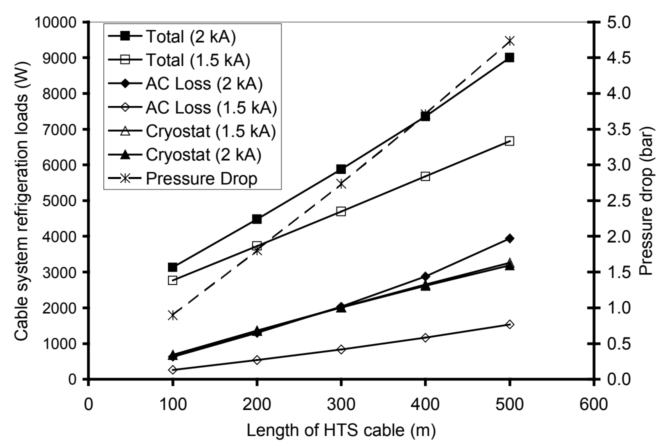

Fig. 5. Refrigeration loads (solid lines) and pressure drop (dashed line) loads for a counterflow cooled HTS power transmission system.

temperature would increase the pressure drop, which is already high, and would introduce the possibility of boiling in the cable. In both cooling arrangements the higher operating currents produced higher temperatures, reducing the HTS cable critical current and increasing ac loss.

The refrigeration loads at 67 K and 1000 g/s per phase are shown for both cooling arrangements as a function of length in Fig. 5 and Fig. 6. These results show that running the cable at the lower current results in a significant drop in the ac loss.

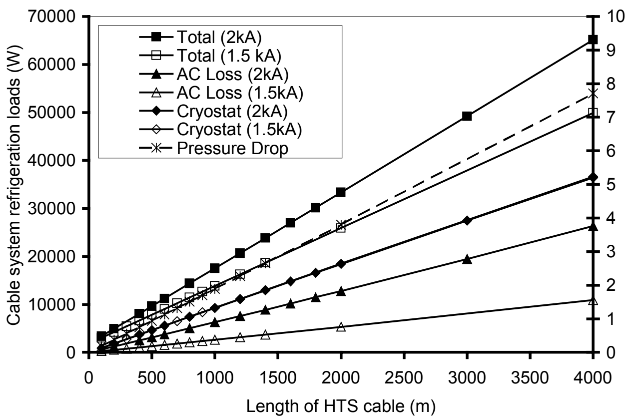

Fig. 6. Refrigeration loads (solid lines) and pressure drop (dashed line) for a parallel flow cooled HTS power transmission system.

C. *Factors that Limit Transmission Line Length*

Many crucial factors in a HTS power transmission cable system depend on the cooling flow rate. A 250-m counterflow case and a 1000-m parallel flow case were analyzed to determine the maximum cable temperatures and pressure drops at a current of 2000 A_{rms} at different flow rates. These results are presented in Fig. 7 and Fig. 8.

In both arrangements, higher temperatures are reached in the cable at lower flow rates. In the counterflow case, the system temperature, at which the liquid nitrogen is returned to the refrigerator, is lower than the cable maximum. The opposite is true for the parallel-flow cooling arrangement. For low flows, the counterflow-cooled cable maximum temperatures are high enough to significantly reduce the superconducting properties of the cable. Increasing the flow reduces the maximum temperature at the expense of higher pressure drop.

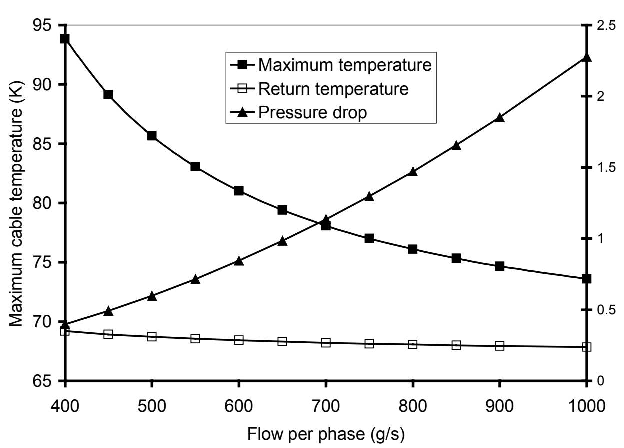

Fig. 7. Maximum cable temperatures and pressure drops for a 250-m counterflow-cooled HTS power transmission cable system.

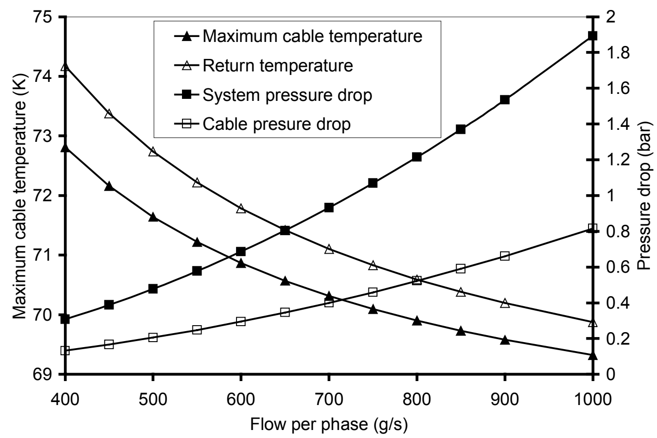

Fig. 8. Maximum temperature and pressure variations with flow for a 1000-m parallel-flow-cooled HTS power transmission cable system.

VII. Conclusions

Operational limits for long-length HTS cables depend on the cooling configuration, the cable ac loss, and thermal losses. AC and thermal losses vary with the temperature of the HTS cable and determine the flow required to keep all portions of the cable below a thermal limit. The required flows can exceed pressure-drop limits and can result in formation of vapor that can degrade the cable insulation level. Lower flows produce higher HTS cable temperatures, that reduce the cable critical current, producing higher ac losses. For a given length and flow rate, the temperatures and pressure drops are higher for the counterflow arrangement although the heat loads are lower.

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