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HIGH TEMPERATURE SUPERCONDUCTING CURRENT LEADS FOR FUSION MAGNET SYSTEMS*

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Submitted to *14th Symposium on Fusion Engineering*, San Diego,
September 30 - October 3, 1991.

*Work at Argonne National Laboratory was supported by the U.S. Department of Energy, Conservation and Renewable Energy, as part of a program to develop electric power technology, through the Argonne Superconductivity Pilot Center, under Contract W-31-109-Eng-38.

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14th Symposium on Fusion Engineering
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Abstract

Superconducting magnets for fusion applications typically have very high operating currents. These currents are transmitted from the room temperature power supplies to the low temperature superconducting coils by way of helium-vapor-cooled current leads. Because of the high current magnitude and the resistive characteristics associated with the normal metallic lead conductors, a substantial amount of power is dissipated in the lead. To maintain a stable operation, a high rate of helium vapor flow, generated by the boil-off of liquid helium, is required to cool the lead conductors. This helium boil-off substantially increases both the installation capacity and the operating cost of the helium refrigerator/liquefier. The boil-off of liquid helium can be significantly reduced by employing ceramic high temperature superconductors, such as Y-Ba-Cu-O, in the low temperature part of the lead conductor structure. This concept utilizes the superconducting, as well as the low thermal conductivity properties of the superconductor materials in eliminating power dissipation in part of the current lead and in inhibiting heat conduction into the liquid helium pool, resulting in reduced helium boil-off. This design concept has been conclusively demonstrated by a 2-kA current lead test model using Y-Ba-Cu-O(123) material which, although not optimized in design, has significantly reduced the rate of helium boil-off in comparison to optimized conventional leads.

There appear to be no major technological barriers for scaling up this design to higher current levels for applications in fusion magnet systems or in fusion related testing activities.

The theoretical basis of the current lead concept, as well as the important design and technology issues are addressed. The potential cost saving derived from employing these leads in fusion magnets is also discussed. In addition, a design concept for a 10-kA lead is presented.

Introduction

Superconducting magnets proposed for magnetic fusion systems typically require current flows on the order of tens of kiloamperes. These currents are required to be transmitted from the room temperature power supplies to the superconducting magnets via cryogenic current leads. Because of the resistive heating in the lead conductors and the thermal conducting path it provides, each current lead is a major source of heat leak into the cryogenic environment. The cooling requirement for current leads constitute a significant if not a dominant portion of the installation capacity requirement, as well as the electrical power consumption of the cryogenic refrigeration/liquefaction plants.

Conventional high capacity current leads typically employ a vapor-cooled design to reduce the heat leak. In this design the cryogen vapors, generated by the current lead heat leak at the cryogen pool or produced elsewhere in the cryogenic systems, are used to cool the entire current lead conductor. Metallic conductor such as phosphorus deoxidized copper is used as the lead conductor for its entire length, covering a temperature range from around 300K to 4.2K for superconducting devices operating at liquid helium temperature. The optimum designs of the conventional leads produce a heat leak of about 1.16 W for each kA of current carried. This corresponds to a specific helium boil-off rate of 56.8 mg/kA · s. To liquefy this rate of helium boil-off, the power required for the refrigerator/liquefier is approximately 2 kW/kA. For a multiple of current leads, each carrying tens of kA in fusion magnet systems, the refrigeration/liquefier power required could reach hundreds of kilowatts.

It has been conclusively demonstrated by a 2 kA test model¹ that the heat leak associated with a current lead can be reduced significantly by employing one of the newly discovered ceramic high temperature superconductor such as $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Y-Ba-Cu-O). The combined effects of superconductivity and very low thermal conductivity of these ceramic superconductors not only reduce the overall power dissipation in the current lead, but also inhibit heat conduction into the cryogen pool, resulting in very low heat leak. There appear to be no major technological barriers for scaling up this design concept to the current level of tens of kiloamperes for applications in fusion magnet systems. It is to be noted that, unlike magnet applications the current lead application of high temperature superconductors does not require very high critical current density nor long conductor length. In addition, the leads are generally not located in high external magnetic field environments. A critical current density of 100 to 1000 A/cm^2 at 77K in an applied field of 0.01 to 0.1 T, and a conductor length of 5 to 50 cm are sufficient for most practical current lead applications.

Applications of High Temperature Superconductors in Cryogenic Current Leads

The theoretical basis of cryogenic current lead design has been studied extensively in the literature and has been treated in Wilson's monograph.² Detailed analysis generally requires a numerical modelling which takes into account the temperature variations of thermal, electrical and transport properties of the lead conductor as well as the heat transfer between the conductor and the cooling helium vapor. As a general guideline, the design of current leads is considered optimum when the temperature gradient at the warm end of the lead approaches zero, and the exit helium vapor temperature stabilizes at near room temperature. Under this condition, there is no external heat conduction into the lead and the cooling power of the helium vapors is utilized in its entirety. Application of high temperature superconductors to current lead design does not change this fundamental guideline. However, the characteristics of superconductivity at temperatures of up to around 100K and having a thermal conductivity of more than two to three orders of magnitude lower than copper at 4.2K provide these conductors a significant advantage for their use in current leads. Various analytical studies³⁻⁷ have shown that the potential of applying high temperature superconductors to current leads can produce savings in the cooling power requirement of from 30% to 85%.

Application of high temperature superconductors to helium vapor-cooled current lead design can be illustrated in a simplified schematic in Figure 1. In this design approach, the lead conductor consists of two sections - a high temperature superconductor section for temperatures from 4.2K to an intermediate temperature below the critical temperature of the superconductor, and a copper section for temperatures from the intermediate temperature to room temperature. The lengths and cross-sectional areas of each conductor section are determined through detailed numerical analysis in order to produce an optimum design for the operating current and the desired cryogenic system arrangement.

The combination of superconductivity and low thermal conductivity means that the cooling requirement in the superconductor section is minimal and that the required cooling vapor flow rate in the lead is essentially determined by the cooling requirement in the copper section. These characteristics provide several options for current lead operation, as shown in Figure 2.

Figure 2(a) shows a conventional self-cooled application for a high temperature superconducting current lead in which the cooling vapor flow ($\dot{m}$) is entirely produced by the vaporization of liquid helium as a result of heat leak (Q). The warm (300K) helium vapor exhaust needs to be refrigerated to 4.2K and then liquefied. A second operation scheme, Figure 2(b) has the helium vapors (at a temperature higher than 4.2K) introduced at an intermediate location ($\dot{m}_2$) in addition to those generated at the cold end ($\dot{m}_1$). The length and the cross-sectional area of the high temperature superconducting section are selected such that only a very small flow rate ($\dot{m}_1$) is produced by the heat leak while the major portion of the cooling flow requirement in the copper section is met by $\dot{m}_2$. $\dot{m}_2$ at an intermediate temperature can be obtained from an external source such as a refrigerator.⁷ Extracting the major portion of the refrigerator output as a vapor at temperature well above saturation substantially reduces the required capacity of the refrigerator/liquefier system. As shown in Ref. 7, this scheme can produce a factor of seven reduction in the refrigerator input power requirement. Figure 2(c) shows the extreme case of this operation scheme by setting $\dot{m}_1=0$, i.e., conduction cooling only in the high temperature superconductor section. In this case the cryogen for cooling the copper section can either be helium vapor or nitrogen vapor.

In an earlier work,¹ the authors designed, fabricated and tested a 2-kA High Temperature Superconducting Current Lead test model employing Y-Ba-Cu-O/15% Ag as the superconductor material (Figure 3). This lead is approximately 63.5 cm long and has outside diameters of 3.18 cm in the copper section and 7.62 cm in the superconductor section. The lead was tested in a helium dewar in the self-cooled operation mode for currents from zero to 2000 A. The maximum current densities were 250 A/cm² in the superconductor section and 2000 A/cm² in the copper section. Heat leak performance for currents of 1000 to 2000 A, expressed in terms of specific helium boil-off rate, and the exit helium vapor temperatures are shown in Figure 4. The boil-off rate of optimum conventional current leads is also shown for comparison. It is obvious from these test results that the optimum operating current, i.e., the current at which the exit helium vapor reaches 300K, of this superconducting current lead is around 1800 A. At this current, the reduction in specific helium boil-off rate is 39.2% as compared to the optimum conventional lead. These results confirm the benefit of high temperature superconductors in current lead applications.

Important design and technology issues related to the application of high temperature superconductors in cryogenic current leads can be addressed in two categories: those related to the overall lead and those pertaining only to the superconductor. The former include items similar to the conventional leads such as (1) lead reliability; (2) lead performance under steady state, cool-down and warm-up, and current ramping conditions; (3) zero-flow stability of the lead; and (4) environmental effects. For the latter, the items include (1) critical current density of the superconductor with respect to temperature and external magnetic field; (2) stability and quench protection of the superconductor bars; (3) physical, electrical and mechanical properties of the superconductor; (4) effects of thermal cycling on the superconductor and its joints with normal metals; and (5) environmental effects. These important design and technology issues are being evaluated by Westinghouse as part of an ongoing program in developing high temperature superconducting current leads.

Design Concept of a 10 kA Current Lead

To illustrate the application of high temperature superconductors in current lead design for fusion magnets, a 10 kA lead design concept is given in Figure 5. Higher current capacity can be obtained by straight-forward scaling up of this design or by using a modular approach.

The 10-kA current lead design concept is generally an adaptation of the 2-kA lead test model design. Design refinements for cost reduction and to account for the expected improvement in critical current density of superconductors were incorporated. The lead has a cylindrical copper section, made of copper rod with internal flow passages as shown in Section A-A of Figure 5, and a superconductor section consisting of an assembly of rectangular high temperature superconductor bars within a cylindrical G-10 housing. Helium vapor flow is introduced at the cold end of the lead and, if desired, at the upper portion of the superconductor section to cool the lead conductors. The outside diameters of the lead are 8 cm in the copper section and 10 cm in the superconductor section, and the overall length of the lead is 80 cm.

As shown in Section B-B in Figure 5, there are 22 rectangular superconductor bars, each 0.6 cm x 1.5 cm in cross-section. For a 10-kA operating current, this corresponds to an operating current density of 505 A/cm^2 and a maximum self-magnetic field of approximately 580 G in the superconductors. A current density of such magnitude is feasible for high temperature superconductors, especially if the maximum operating temperature of the superconductor is kept at a somewhat lower temperature (e.g., 50 to 60K).

Cost Saving Potential of High Temperature Superconducting Current Leads

Cost saving by use of a high temperature superconducting current leads in magnet systems can be realized in two areas: saving from reduced refrigerator installation capacity, and saving from reduced electrical power consumption in operation. These savings will be partially offset by the expected higher cost of the current leads.

A simple formula was recently given by Green et al,⁸ for estimating the cost of helium refrigerator systems as:

$$C_1 = 1.51 \times 10^6 P^{0.7},$$

where C_1 is the cost of the refrigerator system in 1991 dollars, and P is the refrigeration load at 4.5K in unit of kW. This formula can be used to calculate the cost associated with the cooling of current leads by noting that a helium boil-off rate of 1 g/s is equivalent to approximately 100 W of refrigeration load at 4.5K. In general, the refrigeration need of current leads constitutes only one part of the overall cryogenic system refrigeration capacity. Because of the non-linear dependence of cost with respect to the refrigeration load, the cost saving of using high temperature superconducting current leads can not be readily calculated without consideration of the total system refrigeration load. For illustration purposes however, we assume that only the refrigeration load associated with the current leads is present in the system. Under this condition, a pair of 40 kA leads for ITER magnets will require 454.4 W of 4.5K refrigeration power when optimum conventional leads (56.8 mg/kA · s specific helium boil-off rate) are used. The refrigerator system for cooling these leads will cost \$868.8K. Using an easily achievable performance of 40% reduction in specific helium boil-off rate, a pair of 40 kA high temperature superconducting current leads will require only 272.4 W of refrigeration power, and the refrigerator system will cost \$607K. The net saving in refrigerator system cost is therefore:

$$\Delta C_1 = \$262K$$

for a pair of 40 kA leads.

In terms of cost related to the power consumption of current leads, we can use the following simple formula:

$$C_2 = 8760 \frac{P \cdot T \cdot R}{\eta}$$

where C_2 is the yearly electrical energy cost, P is as defined earlier, F is the ideal power requirement per unit of refrigeration load at 4.5K, η is the Carnot efficiency and R is the electric rate in \$/kW hour. Using $F = 70$ W/W, $\eta = 0.2$ and $R = \$0.075/\text{kW hr.}$, a pair of 40 kA leads of conventional design will cost \$104.5K per year in electrical power to operate. For the high temperature superconducting current leads, the cost is \$62.7K. The saving in yearly electrical power cost is

$$\Delta C_2 = \$41.8\text{K/year}$$

for one pair of 40 kA leads.

It is obvious from the above simple calculations that the predicted savings of using high temperature superconducting current leads is significant based on the already achieved performance. With design improvements and judicious use of the cooling configuration as discussed earlier, even higher saving levels can be achieved.

Conclusion

Ceramic high temperature superconductors have been employed in vapor-cooled cryogenic current leads and have produced a performance level significantly superior to optimum conventional designs. This performance level can produce significant savings in both the refrigerator system cost and the operating cost, especially for systems having very high current ratings such as in fusion magnets. There is room for further improvement in performance.

There appear to be no major technical barriers to developing high temperature superconducting current leads in the tens of kA rating range. A program should and can be initiated in the near future to develop leads for fusion magnet systems applications.

Acknowledgment

The authors are grateful to the Westinghouse Electric Corporation and Argonne National Laboratory for permission to publish this paper. The work at Westinghouse was supported by an internally funded program. Work at ANL was supported by the U.S. Department of Energy, Conservation and Renewable Energy, as part of a program to develop electric power technology, through the Argonne Superconductivity Pilot Center, under Contract W-31-109-Eng-38.

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Figure 1. Simplified design sketch of current leads using high temperature superconductors.

Figure 2. Operating schemes of high temperature superconducting current leads.

Figure 3. W/ANL 2-kA high temperature superconducting current lead.

Figure 4. Specific He boil-off rate and exit vapor temperature of the W/ANL 2-kA high temperature superconducting current lead.

Figure 5. Design concept of a 10-kA high temperature superconducting current lead.

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Fig. 1 -Simplified design sketch of current leads using high temperature superconductors

Fig. 2 -Operating schemes of high temperature superconducting current leads

Figure 3

Curve 783782-A

Fig. 4 — Specific He boiloff rate and exit He vapor temperature of the Cu / ANL 2-kA high temperature superconducting current lead

Figure 5

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