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High Temperature Superconducting Current Leads for Micro-SMES Application*

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Presented at the Thirteenth International Conference on Magnet Technology, September 20-24, 1993, Victoria, B.C., Canada

*Work partially supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38, and Superconductivity, Inc., Madison, WI, USA

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Abstract—SMES is being applied on a micro-scale (1-10 MJ stored energy) to improve electrical power quality. A major portion of the SMES refrigeration load is for cooling the conventional (copper, vapor-cooled) current leads that transfer energy between the magnet and the power-conditioning equipment. The lead refrigeration load can be reduced significantly by the use of high-temperature superconductors (HTSs). A HTS current lead suitable for micro-SMES application has been designed. The lower stage of the lead employs HTSs. A transition between the lower stage and the conventional upper-stage lead is heat-intercepted by a cryocooler. Details of the design are presented. Construction and operating experiences are discussed.

I. INTRODUCTION

Use of HTSs for current leads to deliver power to devices at liquid helium temperature, now near commercial realization, has the potential to reduce refrigeration requirements to values significantly below the theoretically best values achievable with conventional leads [1]. Such leads are particularly advantageous for micro-SMES devices [2].

As part of the U.S. Department of Energy's Superconductivity Technology Program, Argonne National Laboratory and Superconductivity, Inc., are developing HTS current leads suitable for application to SMES systems [3].

II. PERFORMANCE SPECIFICATION

A current-lead performance specification was developed for a near-term SMES system. The specification included (1) operating current, (2) operating voltage, (3) charge/discharge cycles, (4) background magnetic fields, (5) refrigeration conditions/requirements, (6) geometry, (7) structural loading, and (8) thermal cycling.

The installation geometry is as shown by Fig. 1. Major elements of the performance specification are given by Table I.

III. GENERAL ARRANGEMENT

The general arrangement of the current lead is shown in Fig. 2. The major subassemblies of the current lead are the (1) conventional upper stage, (2) transition, and (3) HTS lower stage.

Fig. 1. Current lead installation geometry.

TABLE I
Major Elements of HTS Current-Lead Performance Specification

Parameter	Design value
Current (A)	1500
Voltage (kV)	7.5
Heat leak per lead to 4 K (W/lead at current)	≤0.7
Structural loading (g)	±5
Thermal cycling (cycles)	
• 300 K → 4 K → 300 K	100
• 77 K → 4 K → 77 K	1000

IV. CONVENTIONAL UPPER STAGE

A. Configuration

The upper stage requirements are to (1) provide an efficient and reliable electrical connection between the ambient environment and the transition, (2) provide a low heat load to the transition, and (3) be compatible with the cryostat geometry. The specific upper stage design parameters are (1) 1500 A operating current, (2) warm and cold end temperatures of 300 and 60 K, respectively, (3) helium-vapor flow equivalent to 1.2 L/hr per lead. The upper stage was designed and constructed by a commercial vendor.

Fig. 2. Current lead general arrangement.

B. Thermal Performance

The thermal performance estimate for the upper stage assembly is given by Table II.

V. TRANSITION

The transition's functions are to (1) provide electrical and mechanical connections between the lower and upper stages, (2) provide flow paths for the helium-vapor cooling stream, (3) provide a heat-intercept connection to a cryocooler, (4) provide electrical isolation between the lead and the adjacent cryostat components, and (5) provide pressure-vessel continuity within the cryostat.

The transition consists of (1) a central copper disk, (2) an insulating tube, (3) an outer copper ring, (4) twelve copper cables connecting the ring and the cryocooler heat intercept, and (5) stainless steel tubular sections for welding to the cryostat's helium vessel lead-penetration tubes. The lower and upper stages are connected to the disk by screw-joint connections. The connections provide low electrical resistance, low thermal resistance, structural integrity, and long-term reliability.

The transition is configured to minimize the temperature difference between the disk and the cryocooler intercept; this is achieved through geometry, materials selection, and fabrication methods. The transition must also provide effective and

TABLE II
Thermal Performance Estimate of Upper Stage Assembly

Heat leak per lead	Heat leak to 60 K (W)
Component	
Conventional current lead	45.00
Helium vessel pressure tube	1.85
Voltage isolation tubes	0.09
Helium gas	0.13
Total	47.07

reliable electrical isolation, i.e., very low leakage current and 7.5 kV voltage standoff.

VI. HTS LOWER STAGE

A. Geometry

Based on the current-carrying characteristics of available, well-characterized HTS conductors and the geometrical requirements of the cryostat, the lower stage was designed to consist of six parallel current-carrying HTS conductor rods. The rods are connected to the transition at their warm ends and to the bus collector assembly at their cold ends. Each rod is contained in an epoxy fiberglass tube that channels the helium vapor coolant and provides structural support for the rod. A safety lead is located central to the HTS rod array.

The geometry offers flexibility that can readily accommodate conductors of different materials and/or geometries.

B. Conductor

YBCO with 15 vol.% silver was selected as the baseline HTS rod material. Conductor selection was based on near-term material availability, balanced electrical and mechanical properties, and existence of an extensive data base on this material's performance characterization.

C. Thermal Performance

The thermal performance estimate of the overall lower stage assembly is given by Table III.

D. Structural Performance

The objective of the structural design and performance analyses was to ensure the long-term effective and reliable performance of the lower stage assembly.

Lateral loads to the conductor rods are controlled by supporting each conductor rod with a composite tube shroud and then configuring the conductor rods, composite tubes, and safety lead as cantilever beams acting in parallel. Axial loads to the conductor rods are controlled by loading the conductor rods in compression at assembly and then by loading the lower stage assembly in compression at final assembly.

E. Magnetic Shielding

The conductor rods are in the presence of applied magnetic fields from the solenoid and the other five rods in the lower stage assembly. Magnetic shielding is employed to attenuate

TABLE III
Thermal Performance Estimate of Lower Stage Assembly

Heat leak per lead	Heat leak to 10 K (W)
Component	
HTS elements	0.70
Element shroud tubes	0.01
Safety lead	0.11
Voltage isolation tubes	0.01
Helium gas	0.04
Total	0.87

the field from the solenoid. The shield is a cylinder concentric to the conductor array and located in the cryostat's insulating vacuum space adjacent to the lower stage.

F. Safety Lead

A safety lead is incorporated in the lower stage assembly as an alternate current path in the event of HTS conductor malfunction. The safety lead consists of a stainless steel tube connected in parallel to the conductor elements.

G. Bus Connections

The lower ends of the six HTS elements are connected to a bus collector by six low temperature superconductor (LTS) composite elements. The two bus collectors are connected to the magnet coil's terminals by LTS buswork. The connections at the coil terminals incorporate vertical compliance in order to minimize loading of the lead due to relative vertical displacements associated with magnet cooldown/warmup and coil energization/deenergization.

H. Voltage Isolation

Voltage isolation of 7.5 kV along the length of the lead is provided by epoxy fiberglass composite tubing that surrounds the lead elements.

VII. COMPONENT PERFORMANCE EVALUATIONS

A component performance evaluation program is being conducted to confirm the performance predictions and/or qualifying the design features for construction.

Components and/or design features evaluated by the program include (1) HTS conductor characterization, (2) lower stage element and assembly structure, (3) demountable electrical connections, (4) transition heat transfer, (5) magnetic shield attenuation, and (6) voltage isolation.

A. HTS Conductor Characterization

The HTS conductors are characterized both electrically and mechanically. The characterization criteria are as given by Table IV. YBCO/Ag conductors from a commercial source and the Argonne National Laboratory and BSCCO conductors from a commercial source have been characterized. Characterization is ongoing and considers improved materials for planned followon work.

TABLE IV
HTS Conductor Characterization Criteria

BEXTERNAL @ $I_c = 250$ A @ 77 K
Twenty...300-77-300K...Thermal Cycles
• J_c
• Contact Resistance
Flexural Strength
Fracture Toughness
Axial Thermal Contraction...300-77 K
T_c
J_c vs. σ_{AXIAL}
AC Loss
Crystal Structure

B. Demountable Electrical Connections Electrical Performance

The electrical connections to the transition are demountable. The upper stage connection is a clamped surface-to-surface joint with an indium gasket. The lower stage are screw joints that incorporate male and female machine-thread components with indium tinning. The connections have been evaluated experimentally in liquid nitrogen [4]. Experimental variables included clamped joint and thread surface treatment and assembly methods. The clamped joint, screwed joint, and base material apparent resistivities are as shown by Figs. 3 and 4. The results of the evaluations confirm that low-resistance, demountable electrical connections can be made readily with clamped and screwed joint geometries.

Estimated ohmic heating at 77 K for two lead assemblies, i.e., two upper stage connections, operating at 1500 A is 0.19 W. Estimated ohmic heating at 77 K for two lower stage lead assemblies, i.e., 12 connections, operating at 1500 A is 0.31 W. Both heating rates are small compared to the capacity of the cryocooler employed for heat intercept and the heat conducted down through the conventional upper-stage leads.

C. Transition Thermal Performance

Performance evaluations of prototype transition assemblies are in progress [5]. Upper-stage current lead heat load is electrically simulated. The transition is instrumented to provide a temperature profile throughout the assembly and its connections. Evaluation parameters include heater power and

Fig. 3. Clamped joint apparent resistivity vs. assembly torque.

Fig. 4. Screw joint resistivity vs. assembly torque.

heat intercept temperature. The evaluations are made in a vacuum.

The results of the initial evaluations indicated good agreement between the measured and predicted performance, i.e., temperature gradient vs. heater power, for the metallic components and connections. However, the measured temperature gradient across the isolating composite tube was several times that predicted, i.e., 6 K at 45-W heater power. Inspection of the disassembled transition indicated nonuniform surface contact and the presence of oxide layers on the metallic surfaces. Both conditions increase the contact resistance and thus the temperature gradient.

Design modification to reduce the contact resistance have been made. Included are contact pressure increase, reduced metallic component roughness, metallic component surface plating, and the inclusion of deformable thermally conductive materials between the tube and the adjacent metallic surfaces. A modified transition has been fabricated, instrumented and is undergoing thermal performance testing.

VIII. CONSTRUCTION STATUS

The commercial conventional upper stage leads have been procured.

Two transition assemblies have been fabricated.

Twelve HTS elements have been fabricated and their individual electrical performance measured.

Bus connections and voltage isolation components have been fabricated.

The leads are being assembled.

IX. SYSTEM PERFORMANCE EVALUATIONS

A system performance evaluation program has been developed to evaluate the performance of current lead assemblies. This program consists of three separate phases: the zero-field test, operational system test, and life-cycle test.

The zero-field test program objectives include (1) evaluation of assembly procedures, including tooling and quality assurance; (2) evaluation of thermal performance, including heat leak, temperature distribution, steady-state and upset response, and shield cooler performance effects; (3) evaluation of electrical performance, including voltage drops, voltage isolation, upset conditions, safety lead, and lead-to-lead differences; (4) evaluation of flow characteristics, including pressure drop vs. mass flow rate, voltage drop vs. mass flow rate, voltage drop vs. inlet temperature, and lead-to-lead differences; and (5) evaluation of mechanical characteristics, including thermal contraction, HTS rod strain, upset conditions, and stiffness of upper and lower end connections. The leads will be installed in a liquid helium test cryostat and connected at their cold ends by a current jumper. The leads will be heat-intercepted with a shield cooler.

The objective of the system operational test overall program is to determine the performance of the HTS leads during all phases of system operation. The test plan objectives include (1) performance verification of the HTS leads during magnet charge and DC field operation, (2) performance evaluation of the leads during rapid magnet discharge, (3) performance evaluation of the leads during pulsed magnet opera-

tion, and (4) performance of repeated charge/discharge cycles to partially simulate this aspect of lifetime requirements. The leads will be installed in a cryostat and operated with a coil controlled by the system's power-conditioning equipment.

The objective of the life-cycle test overall program is to evaluate factors that affect long-term performance of the HTS leads. The test plan includes examination of (1) motion due to thermal cycles and coil charge/discharge, (2) loading due to handling and transportation, and (3) long-term effects due to prolonged system operation.

X. CONCLUSIONS

The detailed design of a HTS current lead assembly suitable for micro-SMES applications has been completed.

A component performance evaluation program is underway.

Lead assemblies are being constructed for system performance evaluations that include zero-field operation, SMES operation, and life-cycle simulations.

ACKNOWLEDGMENT

The authors gratefully acknowledge the engineering contributions of J. D. Gonczy, and T. H. Nicol; the technical expertise of M. Bordson A. S. Wantroba, and K. Ziemer; and the manuscript preparation skills of J. A. Stephens and the editorial contributions of C. A. Malefyt. Work at ANL was supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38. The work at Superconductivity, Inc., was conducted as a part of the corporation's internal systems development program.

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