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A REBCO Persistent-Current Switch, Immersed in Solid Nitrogen, Operating at Temperatures near 10 K

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Abstract

We present design and test results for a thermally-activated persistent-current switch (PCS) applied to a double pancake (DP) coil (151 mm ID, 172 mm OD), wound, using the no-insulation (NI) technique, from a 120-m long, 76- μm thick, 6-mm wide REBCO tape. For the experiments reported in this paper, the NI DP assembly was immersed in a volume of solid nitrogen (SN₂), cooled to a base temperature of 10 K by conduction to a two-stage cryocooler, and energized at up to 630 A. The DP assembly operated in quasi-persistent mode, with the conductor tails soldered together to form a close-out joint with resistance below 6 n Ω . The measurements confirm PCS activation at heating powers below our 1-W design target, and a field decay time constant in excess of 900 h (i.e 0.1% h⁻¹ field decay rate), limited by the finite resistance of the close-out joint.

Index Terms

Conduction cooling; no-insulation; persistent current switch; REBCO double-pancake; solid nitrogen

I. Introduction

Persistent current switches (PCS) [1], [2] are used in two broad categories of superconducting magnets. One category includes persistent-mode NMR and MRI magnets, where a PCS is needed to achieve field decay rates on order of 10 ppb h⁻¹ [3], [4]. The other is typified by magnetically levitated magnets, e.g., for transportation [5], [6] or magnetospheric plasma studies [7]–[9], where the PCS permits the magnets to operate in

quasi-persistent mode for several hours without connection to a power supply (and in some instances without external cryogenic cooling), and field decay rates below fractional percent per hour are acceptable. We have been developing PCS using REBCO conductors as a base technology suitable for either application [10], [11].

Several examples of high-temperature superconductor (HTS) based PCS have been reported [5]–[14]. For instance, the bifilar-wound PCS, based on Bi-2223 tape, developed for the mini-RT experiment required 50-W heating power to open [7], while the PCS subsequently developed for the Ring Trap experiment, RT-1, using thick film REBCO deposited on sapphire substrate required 20-W heating power [8]. These heating powers are representative of most HTS PCS reported in the literature. Although these high heat loads can be tolerated during charging of an HTS magnet cooled by forced flow of helium gas at 20 K, it is generally desirable to reduce dissipation in the superconducting system to the extent possible. This is especially true for magnet systems cooled by recondensing helium bath, where the thermal budget is necessarily limited.

The objectives of our present research were summarized in [10]. In brief, we set two requirements for a PCS that could be integrated with a no-insulation (NI) double-pancake (DP) coil wound from REBCO tape: 1) 1 W heating power to open at liquid helium temperatures; and 2) open-state resistance on the order of 1 m Ω .

Operation of our PCS coil in solid nitrogen (SN2) near 10 K was motivated in part by the continuing helium shortage [15]. Coincidentally, this activity contributes to another current MIT project – to investigate the feasibility of a significantly higher-field Floating Coil for a successor to the Levitated Dipole Experiment [16] using NI coil technology.

II. PCS Coil Configuration

A. Coil Configuration

Fig. 1 shows the general arrangement of our PCS coil, which was assembled using a spare NI DP remaining after fabrication of Coil 2 of our 800-MHz REBCO insert for a 1.3-GHz spectrometer magnet [17]. Nominal conductor and coil characteristics are summarized in [17].

One conductor turn was removed from the end of each pancake to form the PCS and close-out splice, leaving the NI DP with a total turn count of 243 turns and computed inductance of 17.7 mH. The PCS is housed in a G-10 tube with 35-mm OD, 120-mm length and 1.5-mm thick walls, and arranged to shunt the current in the NI DP coil when closed. This PCS is a modified version of the design we presented in [11]. The reverse bend in the left conductor lead as it wraps around the guide in Fig. 1 brings the REBCO sides of the conductors together to form the close-out splice, in which 150-mm lengths of the conductor tails were soldered together using 60/40 Pb/Sn solder.

Because nitrogen contracts by 8.4% upon solidification and another 9.4% during cooling to 10 K [18], we added cooling fins and cooling links to the coil to enhance conduction to the cryogen bath, encourage SN2 to solidify near the coil first, and bridge gaps that could form

during cooling to 10 K. However, due to design oversight, extended cooling surfaces were not applied to the present version of our PCS.

B. Persistent Current Switch

Fig. 2 shows the PCS configuration of this study. Three 350- Ω strain gauges, each 6 mm $\times$ 12 mm, were epoxy bonded to the substrate side of the REBCO tape. Heater 1 (H1) was 25.4 mm to the left of center, Heater 2 (H2) was centered along the length of the PCS, and Heater 3 (H3) was 25.4 mm to the right of center. The PCS was also instrumented with two thermocouples (TC) to monitor the conductor temperature, TC1 located at the center of the PCS and TC2 located 38.1 mm to the right of center. Both thermocouples were referenced to the surrounding cryogen bath to permit differential temperature measurement. As with our previous prototypes, the space between the instrumented conductor section and surrounding G-10 tube was filled with Loctite Tite Foam[®] expanding polyurethane foam [19].

III. Conduction-Cooled Probe

Fig. 3 shows a to-scale, partial section view of our conduction-cooled test stand. Cooling was provided by a two-stage, Sumitomo RDK-408D cryocooler [20]. To minimize SN2 volume, the PCS coil was suspended in a 16-liter cryogen reservoir placed within a straight bucket cryostat with 315-mm ID and 1080-mm depth. Void space below this reservoir was filled by a stack of ten, closed-cell foam spacers, 310 mm in diameter by 45 mm thick.

The PCS coil was suspended from the 2nd stage of the cryocooler through a pair of 63 mm $\times$ 3 mm OFHC copper straps. Thermal radiation from the upper cryostat wall and cover plate was intercepted by a copper radiation shield attached to the 1st stage of the cryocooler. The multi-layer insulation blankets that surrounded the radiation shield are not shown in Fig. 3. We sought to minimize thermal radiation from the lower cryostat wall by continually filling the cryostat's nitrogen jacket with LN2.

Each resistive lead was formed from a pair of 3.2-mm diameter, 150-mm long copper wires. The lower end of each pair was soldered into a 19-mm wide, 13-mm thick, 150-mm long copper current bus, firmly clamped to, but electrically insulated from, the top plate of the radiation shield by a 25- μ m thick sheet of Kapton MT[®] film [21], coated on each side with Apiezon N thermal conductive grease [22]. Each HTS lead was formed from a pair of 12-mm wide REBCO tapes, with 0.25-mm thick by 20.5-mm wide OFHC copper strip soldered to each side. The coil's center field was measured with a cryogenic Hall probe. To monitor thermal performance, we strategically placed five Cernox[®] sensors [23] (Cx1-Cx5) on the test rig as indicated in Fig. 3; note that Cx5 is attached to a phenolic-linen centering disk inside the NI-DP coil.

IV. Experimental Results

A. Cool-Down

At the start of a test campaign, the inner reservoir was filled with approximately 16 liters of LN2, to within $\sim$ 1 cm of the top, after which the fill and vent tubes were removed and their access ports sealed. The inner volume of the cryostat was slowly evacuated to approximately

17 kPa (65 K), at which point the cryocooler was switched on and the cryostat was valved-off before the nitrogen began solidifying at 63 K.

Initial cooling of the coil to 77 K occurred rapidly due to the LN₂ transfer. Settling of the test probe temperatures to roughly 38 K at the cryocooler 1st stage (Cx1), 41~42K at the base of the resistive leads (Cx2 and Cx3), 9 K at the 2nd stage (Cx4), and 10 K at the coil (Cx5) occurred within one day from the start of cooldown. Although the coil space was not always actively evacuated, its vacuum continued to fall due to the decreasing vapor pressure of SN₂ with temperature.

B. Coil Energization

Fig. 4 shows signals recorded when taking the PCS coil out of persistent-mode operation at 150 A and placing it into persistent-mode operation at 300 A. Fig. 4 shows measured traces of (a) power supply (PS) current and coil voltage vs. time; (b) PS current and central magnetic induction vs. time; and (c) PS current, PCS heater power and PCS temperatures vs. time. Note that the PCS conductor voltage (including the close-out splice) and coil voltage must remain identical at all times.

The current up-ramp rate for the test shown in Fig. 4 was 0.25 A s^{-1} . During the initial current up-ramp to 150 A with the PCS closed, the coil voltage in Fig. 4a remained zero as expected, and the Hall probe reading remained essentially constant at 0.285 T. At the start of each day, we temporarily switched off current to the Hall probe to confirm the absence of drift in the Keithley 2182 nanovolt meter [24] that we used to monitor long term trending of the Hall probe signal.

An approximately 2-min hold time was needed at 150 A to open the PCS, by application of 0.75-W power (Fig. 4c) to the heaters mounted on the PCS conductor. The slight jump in coil voltage (Fig. 4a) during switch opening shows that the PS current was slightly above the coil's initial persistent current. The thermocouple readings in Fig. 4c show a fairly steep temperature gradient along the PCS conductor, from a center (TC1) temperature of ~100 K to a TC2 temperature of ~55 K. That is, only a small region near the center of the PCS is above REBCO's transition temperature of ~95 K. Despite the short normal zone length, we are concerned that repeated activation of the PCS heater to above the normal melting point of SN₂ (77 K) will eventually lead to migration of SN₂ away from the PCS. The introduction of feedback heater control in our next design iteration, like that developed for [25], should provide repeatable PCS temperature profiles over time even if the PCS heat transfer characteristics were to change.

The variations in coil voltage and central magnetic induction vs. time during the up-ramp from 150 A to 300 A with the switch open is largely similar to that observed during the charging of any NI coil. The 4.2 mV asymptotic voltage observed near the end of the up-ramp (Fig. 4a) is consistent with the computed coil inductance times the current ramp rate, while the measured, asymptotic magnetic induction of 0.567 T at 300 A is within 1% of its expected value.

The charging delay time constant [26] of 131 s, deduced from voltage settling at 300 A, indicates a parallel combination of the turn-turn coil resistance, R_m , and open-state PCS resistance, R_{pcs} , of roughly 0.12 m Ω . A circuit schematic for this arrangement is shown in Fig. 2 of [10]. By comparison, the charging delay time constant for the DP near 10 K with the PCS conductor removed was 63 s, indicating a coil R_m of 0.28 m Ω , leading to a computed open-state PCS resistance, R_{pcs} , of 0.21 m Ω , significantly below the >2 m Ω achieved with 0.25 W heater input during prototype testing at 77 K [11]. The smaller 10 K resistance is due to much steeper temperature gradient along the PCS during 10 K operation.

C. Persistent Current Decay

Fig. 5 shows normalized central magnetic induction vs. time data at semi-persistent currents of 50 A, 150 A, 300 A and 480 A, and a coil temperature (Cx5) of 10 K. We computed normalized magnetic induction by dividing the instantaneous magnetic induction by the magnetic induction present when the PS current reached zero at the end of the corresponding current down-ramp. The data overlap to high degree. Exponential fitting of the data yields a decay time constant of 3.3×10^6 s, or a field decay rate of 0.1 % hr⁻¹. This decay rate is consistent with a close-out splice resistance, R_s , of about 5.5 n Ω , which could be directly measured, although not to such high accuracy, only during down-ramp from high current with PCS closed and the splice voltage amplified using a Keithley 155 microvolt meter.

D. Thermal Performance

Fig. 6 shows peak temperatures vs. PS current, observed at the cryocooler 1st stage (Cx1) and current leads (Cx2 and Cx3). The dashed and dotted lines show results from third order fits of the data and are intended simply to guide the eye. Lead temperatures increase from initial values of 41~42 K at zero current to peak values of 81 K at 630 A, while 1st stage temperature increase from ~39 K to 65 K. The results show that heat loads from the resistive leads can easily be accommodated at currents below ~450 A, their optimized design current [27]. Above 450 A lead temperatures never fully stabilize, but continue to climb through the charging sequences, which could be kept reasonably short by use of fast current ramp rates. By comparison, the temperatures at the 2nd stage (Cx4) and coil (Cx5) remained within ~1 K of their base temperatures throughout all charging sequences.

E. PCS Protection

An attempt to place the coil into persistent mode operation at 630 A failed due to an unanticipated quench of the closed PCS during the current down-ramp. Fig. 7 shows the PCS voltage vs. PCS current during this event. We computed the PCS current by subtracting the instantaneous PS current from the PS current present when the PCS was closed. During the initial down-ramp from 630 A the transition to the normal state began at a PCS current of roughly 530 A. The PCS, formed from the same conductor and operated at significantly lower field than that in the DP, should have remained superconducting through the downramp: we suspect that the conductor could have been partially damaged during PCS fabrication, or even during operation, and that this damage lead to the quench. Subsequent attempts to place the PCS coil into persistent-mode operation at 500 A showed even further degradation, with normal-state transition beginning at roughly 50 A. Examination of the PCS conductor after test showed evidence of buckling near the center of the PCS. We

believe that this buckling was caused by rapid thermal expansion of the PCS conductor during quenching, as a significant portion of the DP's 7-kJ stored magnetic energy of was deposited into this short conductor length.

Although a NI DP is generally self-protecting in event of quench [28], the same cannot be said of the PCS conductor. The results in Fig. 7 underscore the importance of protecting the PCS with parallel protection resistor as reported in [6], [8]. To incorporate a low-resistance protection resistor in parallel with our PCS we will need a significantly higher open-state PCS resistance than we designed to, which may require us to significantly revise our basic design approach.

V. Conclusion

We developed a thermally-activated PCS for a conduction-cooled NI DP coil, wound from REBCO tape, immersed in a volume of SN2 cooled to near 10 K, and operated at currents up to 630 A. We could open the PCS at 10 K with heater power less than our maximum design target of 1 W. Our PCS coil demonstrated a field decay rate of 0.1 % h⁻¹ at operating currents up to 480 A. We are re-evaluating our basic design approach, following the unprotected quench and subsequent damage to our PCS conductor near an operating current of 530 A.

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Fig. 1.
PCS coil configuration.

Fig. 2.
PCS configuration.

Fig. 3.
To-scale, partial section view of conduction-cooled test stand.

Fig. 4.

Signals recorded during the transition from persistent mode operation at 150 A to persistent mode operation at 300 A. a) PS current and coil voltage vs. time, b) PS current and central magnetic induction vs. time, and c) PS current, PCS heater power, and PCS temperatures vs. time.

Fig. 5.
Normalized central magnetic induction vs. time at persistent currents of 50 A, 150 A, 300 A and 480 A.

Fig. 6.
Peak temperatures vs. PS current during the charging sequences.

Fig. 7.

PCS voltage vs. PCS current traces showing unexpected transition to the normal state during initial down-ramp from 630 A, with degradation observed during subsequent down-ramp from 500 A. The PCS current was computed by subtracting the instantaneous PS current from the peak value present at the start of the current downramp.