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A (RE)BCO Pancake Winding With Metal-as-Insulation

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Abstract

In this paper, we report preliminary experimental results on protection study of two REBCO pancake coils based on the metal-as-insulation (MI) winding technique, a variant of the no-insulation (NI) winding technique, in which a metallic tape is cowound. Against the more-proven NI technique, our results demonstrate that the MI technique, too, is quite viable for HTS pancake coils with the following features: 1) nearly self-protecting; 2) significantly smaller charging-delay time constant; and 3) better control of coil parameters. It also permits stable operation at 97% of a quench current. We present 77-K results of NI and MI pancakes: first, comparing the advantages and drawbacks of the two winding techniques and, second, dealing with stability and quench parameters. Finally, using a simple circuit model, we quantitatively show that metallic tape thickness has little detrimental effect on the self-protecting feature of the MI pancakes.

Index Terms

High-temperature superconductors; HTS coils; HTS quench protection; metallic insulation

I. Introduction

NEW high field magnets of high-temperature superconductors (HTS) are under development worldwide. HTS materials like the Second Generation (2G) coated conductors, REBCO (RE: rare earth) tape, particularly has made a remarkable progress in the past 10 years and accordingly been applied to high-field magnets [1]–[3]. Its attractive parameters—upper critical magnetic field (H_{c2}), current density, operating temperature, and high stability against most disturbances occurring within a winding—justify a great interest in its use for high-field magnets. Nevertheless their protection against local quench remains a key issue.

The no-insulation (NI) winding technique [4] makes HTS coils self-protecting. Recent work on a stack of NI (and multi-width [5]) double-pancake (DP) coils of REBCO tape has shown that a quench in one pancake quickly spreads to the other DP coils [6]. This behavior is due

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mostly to heating by the radial current flowing through the contact resistance, R_c , as given in the NI coil circuit model [7] and the magnetic coupling between DP coils. The NI coil has two drawbacks: a large charging-delay time constant (τ); and somewhat uncertain value of R_c . According to the circuit model, $\tau = L/R_c$, but R_c is highly affected by the conductor surface conditions and coil winding tension. Recent measurement on tens of almost identical NI double pancake (DP) coils gives a factor of 2 between the lowest and highest τ 's [8]. Among different ways to reduce τ (like partial insulation with Kapton [9]), we present results of the Metal-as-Insulation technique (MI), in which a resistive metallic tape is co-wound to increase R_c large enough thereby to reduce τ by an order of magnitude and yet still preserve the self-protecting feature of the NI technique. With a metallic tape, because we create a complete and reproducible resistive barrier between turns, R_c variation should be minimized. The metallic tape also contributes to the coil strength. This technique has already been used for HTS high-field magnets but not as a part of a magnet's protection [10]–[14].

Although normal-zone propagation (NZP) plays a minor role in protection of the HTS coil [15], an MI coil, compared with an insulated coil, will have better thermal contact and radial thermal conduction, both of which promote turn-to-turn quench propagation. Also the presence of additional metallic material like stainless steel (SS) in the winding is expected to improve the stability and to help lower the hot spot temperature.

This preliminary study, performed with both NI and MI test pancakes in a liquid nitrogen (LN2) environment at 77 K, focuses on: 1) quench behavior comparison of the NI and MI pancakes at current near and above their critical currents (I_c); 2) stability and quench parameters of a highly instrumented MI pancake coil, HI-MI, against a hot spot induced by a local heat input; and (3) a quantitative effect on the protection of the metallic tape thickness.

II. Samples Fabrication and Parameters

We wound all pancakes using 2G HTS tape SCS6050-AP from SuperPower Inc. The tape contains around $\sim 1\text{-}\mu\text{m}$ thick REBCO layer on a $50\text{-}\mu\text{m}$ thick Hastelloy substrate. Other materials are Ag overlayer ($\sim 2\text{-}\mu\text{m}$) each side, buffer stack ($\sim 0.2\text{-}\mu\text{m}$), and copper stabilizer ($10\text{-}\mu\text{m}$) each side. The total tape thickness is $\sim 75\text{ }\mu\text{m}$. In each MI pancake, a $76\text{-}\mu\text{m}$ thick-for real applications, likely too thick-stainless steel 304 (SS304) tape was co-wound. Three pancakes have been wound: an NI, an MI, and an HI-MI. NI and MI coils include only global voltage surveillance. The HI-MI coil includes many voltage taps and a heater in order to study in more detail the quench behavior. Main coils parameters are presented in Table I. Each coil was wound with a 50-N tension corresponding to a 100-MPa tensile stress on the conductor. Pictures of the coil samples are in Fig. 1.

III. Experimental Results

A. Experimental Set-Up

The electrical test circuit applicable to each coil is presented in Fig. 2. An Oxford IPS 120–10 (120 A/10 V) power supply was used for test under 110 A and up to 4 parallel-connected Hewlett Packard 6260B DC PS (100 A/10 V) for higher current tests. The coil current I_{coil} was measured with a high precision 200-A/0–1 V shunt. We used a Toshiba THS118 Hall

sensor to measure the center magnetic field (B_z). No dump resistance was connected across the coil; the PS was protected by a freewheeling diode (FWD; R_{FWD}). For HI-MI tests, the Oxford PS effectively protected the coil: when its voltage reached ~ 10 V, the PS current quickly dropped, protecting the coil. Each HP PS had no such built-in protection feature; its current dropped because the PS switched to a voltage-limiting mode.

Data were recorded with an NI DAQ system comprising one NI-cDAQ-9178 USB Chassis with one NI 9220 and four NI 9269 modules. Data were recorded with Labview program at the frequency range 10–1 kHz depending on test needs.

Each pancake was tested in a bath of liquid nitrogen (LN2) at 77 K in self-field (SF).

B. NI and MI Pancakes

Here, we compare responses of the NI and MI pancakes (see Table I) sudden discharge and overcurrent.

1) Critical Current and Overcurrent Tests: Critical current given in Table I are measured with a $1 \mu\text{V}/\text{cm}$ E-field criterion.

The overcurrent test results are presented in Fig. 3: measured B_z , coil voltage (U_{NI} , U_{MI}), and calculated B_z vs. normalized current (I_{coil}/I_c) traces.

While both coils behaved stably above I_c , the NI coil was stable up to $2.2 \cdot I_c$ (192 A, maximum current in our test), obviously because of the bypassing current. On the other hand the MI coil tolerated a small over I_c current (about 7%) and then fully quenched at 101–104 A. This is because, unlike in the NI coil, in the MI coil almost no current bypassed up to the quench and the center field reached the expected value.

2) Behavior With Current Variation: One main advantage of MI coil is a low bypassing current that results in a lower charging time. The time constant τ of each coil is determined from a 3τ criterion, i.e., the time delay between when B_z reaches 95% of its final value and when the I_{coil} reached its the final value. Also from the field values we estimate that $\sim 3.3\%$ of the I_{coil} bypassed the NI coil at 1 A/s, while only $\sim 0.05\%$ in the MI coil at 2 A/s.

In all our tests the MI τ is 1 to 2 orders of magnitude smaller than its NI counterpart. Fig. 4 presents the results of a sudden discharge of both coils. As soon as the PS is shut down, depending on voltage, its current can pass through the low-resistance FWD. For the NI coil, the voltage is too low (because R_c is much less than the FWD resistance) for FWD to carry significant current. In this case current mainly flows through R_c , causing the center field to decrease. On the other hand in the MI coil, its field follows the PS current, i.e., little current bypasses the coil, demonstrating that its R_c is much larger than the FWD resistance.

C. HI-MI Coil Stability and Quench Behavior

A heater of SS304, 4-mm wide and $12.6 \mu\text{m}$ thick, was embedded between the turns 150 and 151. Its length was varied from 10 mm until 50 mm, at which point the HI-MI coil could be

quenched. We planted 30 voltages taps, each 12.6- μm thick and 1–2-mm wide SS304 strip, to follow the voltage behavior of the coil-Table II lists information on the voltage taps. The heater position was chosen to provide enough conductor length along its each side to study the longitudinal normal-zone propagation (NZP). Unfortunately 4 voltages taps near the heater were broken during the wiring process, limiting our measurement to the radial NZP.

1) I_c , I_q and Thermal Runaway Near I_q : For the HI-MI coil we also first measured its I_c with an E-field criterion of 1 $\mu\text{V}/\text{cm}$. Next, we examined its quench responses under various conditions.

We determined the I_c of the weakest parts and whole coil through a classical I_c test. Results show that innermost part of the coil (Radm8), the highest magnetic field region, is limiting the coil current with an $I_{c,\text{Radm8}}$ of 54.5 A, followed by Radm7 with an $I_{c,\text{Radm7}}$ of 64.4 A. The PS voltage reached maximum at 67 A, while no other parts quenched. The whole coil critical current $I_{c,\text{coil}}$ is 58.8 A. Also we estimate the heated turn's I_c ($I_{c,\text{ht}}$) at around 75 A.

Next we measured I_q quench current, in a constant-current thermal runaway experiment with a 0.5-A increment in the I_{coil} range of 58–60 A. No thermal runaway occurred for I_{coil} up to 59 A with a 600-s heating duration. At 59.5 A the coil slowly and locally warmed up, quenching after ~ 70 s (Fig. 5): voltages, coil current, and central magnetic field vs. time. The inset shows a zoomed-in view of the voltage, current, and field time functions near the quench. I_q is estimated between 59–59.5 A, is $\sim 9\%$ higher than $I_{c,\text{Radm8}}$.

The HI-MI's τ is estimated to be in the range of 29–35 ms, similar to MI coil, for a current rate of 2 A/s up to 50 A with the same criterion as that used for NI and MI coils.

2) Induced Quench Near I_q : More than 35 quenches were induced with a local energy input E_h . The heating period (t_{heat}) is between 670 ms and 720 ms. The example given in Fig. 6 is a test comprising five heat deposition pulses with increasing t_{heat} , and thus E_h , till quench. We waited ~ 10 s between pulses to cool the test coil to 77 K. We estimated that $I_{c,\text{ht}}$ is ~ 75 A i.e., a current margin near I_q of $\sim 0.8 \cdot I_{c,\text{ht}}$. I_{coil} was fixed at 58 A ($0.99 \cdot I_{c,\text{coil}}$) to prevent the innermost part thermal from runaway and lower E_h . Even at this current E_h was higher than 38 J to induce the quench.

Fig. 6(a) presents measured traces from the first 4 heat pulses, with E_h between 37.24 J–38.20 J, each resulting full recovery, where the coils voltage reached 200 mV. The bypass effect, which protects the hot spot, can be seen through B_z drop for a heated turn E-field $> 60 \mu\text{V}/\text{cm}$. This self-protecting behavior is similar to that for NI coils [16].

The coil was quenched with the 5th pulse (E_h of 38.68 J in 714 ms). We estimate dissipation in LN2 bath to be between 2 J and 6 J, which seems to have critically depended on convective cooling. Value depends on the contact area with LN2 bath. Fig. 6(c) presents E-field time functions for selected coil during the quench. The sudden drop at ~ 171.4 s is because of the power supply 10-V limit. Oxford PS then reduces quickly the current to help the coil to recover. At a coil voltage of 10 V the resistive area reached Radm6. Before the current decreased, all coil's parts, except those three innermost, had an E-field > 2 mV/cm.

From the quench sequence we estimate that radial NZP velocity is in the range of 1.2 to 2.2 mm/s (7 to 15 turns/s). The 10-V limit was reached in 3.5 s after heating.

IV. SS Tape Thickness: Protection Analysis

In this part, using a simple circuit model (Fig. 7), we analyze the effect of SS thickness on protection. The analysis includes only the resistances of the copper layers, SS tape, and Hastelloy substrate and no inter layer/tape contact resistances. Equations (1) and (2) give the resistances, respectively of, the “insulating” materials (SS and Hastelloy), i , and the copper layers, cu , along their current paths. ρ and δ are the respective electrical resistivity and current path length, indicated by subscripts i , and w is the tape width. Thus, $R_{i,p}$, e.g., is path i resistance. Transition length $l_{tr,(1/2)}$, at which half of the current bypasses through i is given by equation (3)

$$R_{i,p} = \frac{\rho_i \cdot \delta_i}{l_{tr} \cdot w} \quad (1)$$

$$R_{cu, //} = \frac{\rho_{cu} \cdot l_{tr}}{\delta_{cu} \cdot w} \quad (2)$$

$$l_{tr, \frac{1}{2}} = \sqrt{\frac{\rho_{ss,p}}{\rho_{cu, //}} * \delta_{cu} * (\delta_{ss} + \delta_{hast})} \quad (3)$$

With a copper RRR of 50, $\rho_{ss,p}/\rho_{cu, //}$ in (3) gives ~ 230 at 77 K and ~ 1500 at 4.2 K. With appropriate dimensions inserted in (3) (δ_{hast} , δ_{ss} , δ_{cu} , respectively, 50, 76 and 10 μm), we obtain a $l_{tr,(1/2)}$ of 0.5 mm at 77 K and 1.4 mm at 4.2 K. Those $l_{tr,(1/2)}$ values are near or lower than an estimated REBCO-layer/Copper current transfer length (CTL) of ~ 0.8 mm [17]. Because $l_{tr,(1/2)}$ varies as $\sqrt{(\delta_{ss} + \delta_{hast})}$, a half thick SS tape (38 μm) reduces $l_{tr,(1/2)}$ only by 16%. However, for l_{tr} in the range of CTL or even less, SS tape has no detrimental effect on protection.

V. Discussion and Conclusion

Our preliminary results from two MI pancake coils have confirmed that they respond much quicker than and nearly self-protect as their NI counterparts. They too have an ample stable overcurrent regime beyond their nominal I_{op} . Our MI coils remained intact after over 30 quenches at 77 K. Although for self-protection these small test coils relied partly on the voltage limitation of their power supplies. For “real-size” pancake coils, a quench-induced rapid increase in the internal resistance built-in within the winding, a characteristic of both NI and MI coils, is the key to their self-protecting feature.

Using a simple electrical circuit model, we have derived an equation relating the transition length at which half of the current bypasses through the metallic insulator to the parameters of 3 key conductive elements in the MI pancake: SS tape (here, the metallic insulator), Hastelloy substrate, and copper layers. In this respect, SS tape thickness is a readily

adjustable design variable. Thus, for example, reduction in its thickness from 75 μm to even 1 μm reduces $I_{tr,(1/2)}$ by only $\sim 100 \mu\text{m}$ (at 77 K), hardly an improvement in the MI protection feature, because $I_{tr,(1/2)}$ is already near or shorter than CTL, at which the current will be driven to bypass. Clearly, the thinner the thickness, the greater will be the overall current density, provided the winding does not require extra reinforcement, an added benefit of the MI technique.

Further investigation, experimental and analytical, is needed to make the MI winding technique a viable design option for HTS pancake coils. Protection of the MI pancakes for high energy HTS magnet is another challenging study assignment.

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Fig. 1.
Picture of (a) NI coil, (b) MI coil, and (c) HI-MI coil.

Fig. 2.
Schematic of the test circuit.

Fig. 3.

Overcurrent tests on NI and MI. MI coil maximum voltage is limited at 500 mV for better view of NI coil voltage. Real MI voltage reaches 10 V. Current is normalized to the I_c value in Table I.

Fig. 4.

Normalized current and magnetic field to values at 10 A during a sudden discharge (turn off the power supply). The inset shows a zoom-in view on the first 0.6 s of the discharge.

Fig. 5.

HI-MI thermal runaway during step at 59.5 A ($1.09 \cdot I_{c,\text{radm8}}$) after a ramping at 20 A/s. The inset shows a zoom-in view during the step showing the stable current and magnetic induction with a slow Radm8 voltage increase.

Fig. 6.

HI-MI coil quench test at $I_{\text{coil}} = 58$ A. (a) Coil voltage and magnetic induction versus time during the first 4 pulses following by a recovery. (b) Coil part E-fields versus time during the fourth pulse following by a recovery. (c) Coil part E-fields versus time during the fifth pulse following by a quench.

Fig. 7.

Not-to-scale drawing of quenched part and next turn. Purple lines represent the REBCO layers, and black lines represent the electrical circuit. Green and orange arrows represent the longitudinal current going through the copper or the REBCO layer and the transversal current going through the SS and Hastelloy tapes, respectively. Red oval represents the quenched REBCO layer part with a length l_{tr} .

TABLE I

(NI/MI/HI-MI) Coils Calculated (*) and Measured Parameters

Parameters	Unit	Value
ID	mm	36/36.4/50.5
OD	mm	51/66.2/115
# Turns	-	100.5/100.5/206.5
Self-Inductance, L_{coil} *	mH	0.573/0.592/3.798
Conductor length	m	13.7/16.1/53.1
Field Constant, α_m *	mT/A	2.88/2.46/3.46
Charging delay time constant, τ	s	2.3–2.1/0.044–0.05/0.029–0.035
Contact resistance R_c **	M Ω	0.21–0.25/11.8–13.5/110–130
Surface resistance R_{ct}	$\mu\Omega \cdot \text{cm}^2$	19.2/1100–1300/8500–9800
I_c (1 $\mu\text{V}/\text{cm}$)	A	88/97/59
I_q	A	>192/101–104/59.5***–65.5****

***. R_c Calculated from τ considering a constant inductance L .

***. Thermal runaway with constant current

****. E-field of 100 $\mu\text{V}/\text{cm}$ during current ramping at 100 A/min

TABLE II

HI-MI Voltages for Radial Quench Study

Voltage name (*)	Position (N_i/N_f) (**)	Turns number	Conductor length [cm]
Radm8	1/40	40	709
Radm7	40/80	40	863
Radm6	80/110	30	748
Radm5	110/130	20	547
Radm4	130/135	5	143
Radm3	135/140	5	145
Radm2	140/145	5	147
Radm1	145/149	4	120
Heated Turn	149/150	1	30
RadP1	150/160	10	307
RadP2	160/190	30	978
RadP3	190/206.5	16.5	575
Coil	0/206.5	206.5	5312

*. For simplification “Rad” might be removed on charts.

. Positions are from the coil innermost turn. **i is for initial and **f** is for final