A novel winding method for a no-insulation layer-wound REBCO coil to provide a short magnetic field delay and self-protect characteristics

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Abstract
The no-insulation (NI) technique is a very effective protection method for REBCO pancake coils. However, it is not suitable for a layer-wound coil, which is the optimum configuration for the persistent operation and generation of a homogeneous magnetic field, since an NI layer-wound coil suffers from an extremely long magnetic field delay. Such a delay is caused by large short circuits across the layers inside the winding. To combat this phenomenon, a simple winding method, denoted as ‘intra-layer no-insulation (LNI)’, is proposed in the present work. The method uses insulator sheets to prevent electrical contacts between the layers and copper sheets to increase electrical contacts between the turns in each layer: such a coil has the layer-wound geometry with the NI pancake-like internal circuit. An LNI REBCO coil shows a shorter field delay time constant by three orders of magnitude than an ordinary NI REBCO layer-wound coil, and also exhibits a self-protect behavior with more rapid thermal runaway propagation compared to a NI REBCO double-pancake coil.

Keywords: REBCO coil, thermal runaway, magnetic field delay, intra-layer no-insulation (LNI), self-protect

(Some figures may appear in colour only in the online journal)

1. Introduction

The no-insulation (NI) method [1] is effective for protecting high-temperature superconducting double-pancake coils from an irreversible quench, i.e. thermal runaway [1–3]. An NI pancake coil is self-protected, as the current flow changes from the ‘multi-turn-coil’ mode, i.e. current flow in the circumferential direction in individual turns, to ‘single-turn-coil’ mode, i.e. current flow dominated by the radial current [2]. During thermal runaway, this behavior drastically reduces the effective winding current density and Joule heating, and the coil is self-protected.

A major problem of an NI coil is a magnetic field delay during charging and discharging due to a radial current across contact resistances between turns, which are driven by the electric potential provided by the power supply [1]. To solve this problem a metallic cladding approach [4] and a partial insulation approach [5] have been proposed to shorten the time constant of the magnetic field delay. In addition, an
active control of the power supply current can eliminate the field delay [6]. Also, unbalanced electromagnetic forces [7, 8] and over-hoop stress [9] during thermal runaway are serious potential problems in NI double-pancake coils.

Considering the desire for persistent current operation and spatial homogeneity of the magnetic field, layer-winding is preferred over double-pancake winding for nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) magnets. However, an NI layer-wound REBCO coil shows a magnetic field delay which is orders of magnitude longer than that of an NI double-pancake REBCO coil [10, 11]. An NI layer-wound coil has large short circuits across the layers, which circuits are magnetically coupled with the main coil circuit, and they produce an extremely long magnetic field delay. Practically, this problem makes an NI layer-wound REBCO coil useless. This is an intrinsic phenomenon that results from the internal circuit structure of the coil and approaches that seek to increase the contact resistance will not sufficiently shorten the delay time constant.

In the present paper, we propose and demonstrate a new method to significantly shorten the magnetic field delay of an NI layer-wound REBCO coil by altering the circuit structure, while maintaining the layer-wound coil geometry. For a small test coil, we investigated the shortening effect on the field delay and the self-protect characteristics in a thermal runaway. We also discuss differences of coil characteristics between the proposed NI layer-wound coil and an NI double-pancake coil using coil experiments and circuit simulations.

2. Proposed method

Figures 1(a) and (a’) respectively show a cross-section and an equivalent circuit of an NI double-pancake coil [11–13]. Figures 1(b) and (b’) respectively show those of an ordinary NI layer-wound coil [11]. In the coils, each turn is regarded as an inductance magnetically coupled to the other turns. In the case of the NI layer-wound coil, a turn is shorted to turns in the adjacent layers through contact resistances. These short circuits across the layers behave as a secondary circuit strongly coupled to the primary coil circuit. During charging/discharging, induced current in the secondary circuit shields the magnetic field of the primary coil circuit and the current diffuses across the contact resistances. This process causes a very long magnetic field delay time constant.

In order to shorten the time constant, it is necessary to reduce the size of the secondary circuit. If we use insulator sheets to cut off all contact resistances between the layers and also use copper sheets to add electrical contacts between the turns in each layer (as shown in figure 1(c)), the large short circuit (secondary circuit) is converted into a number of small short circuits as shown in figure 1(c’). Since this circuit is similar to the equivalent circuit of the NI double-pancake coil
in the NI condition and so we call the present winding method an ‘intra-Layer No-Insulation (LNI)’ coil.

3. Experimental

In order to demonstrate the effectiveness of the LNI method, we fabricated a test coil (see figure 2(a)) with a bare REBCO coated-conductor manufactured by Fujikura Ltd, 4.05 mm in width and 0.13 mm in thickness. The coils were composed of a 75 μm thick Hastelloy substrate, a 2 μm thick REBCO layer and 20 μm thick electrically-plated copper. Physical parameters of the coil are described in column (A) in table 1, and are similar to those of the NI REBCO layer-wound coil showing a magnetic field delay time constant of 500 s used in our previous work [11]. Three bare REBCO conductors were soldered to bridge parts between the electrodes and the coil winding for increasing the current capacities. During winding, we inserted a set of a polyimide sheet, 12.5 μm in thickness, and a copper sheet, 7 μm in thickness, (see figure 2(b)) between the layers to realize the LNI configuration shown in figure 1(c). During winding, wrinkles were sometimes observed on the very thin copper sheets. Although we used copper and polyimide sheets in the present work, the use of copper sheets with coated insulation on one side is better from the standpoint of the winding process and winding packing factor.

Figure 3 shows a schematic circuit of the experiments. Three Hall sensors were installed at the upper end \( (B_{up}) \) at the center \( (B_{center}) \) and at the lower end \( (B_{low}) \) along the coil axis. Pairs of voltage taps were attached to all the layers to measure the layer voltages, \( V_{L1}-V_{L8} \) (from inner to outer layers). The supply current into the coil, \( I_{supply} \), was measured with a shunt resistor. Two Cernox temperature sensors were installed at a position 200 mm above the coil \( (T_1) \) and at the coil bottom.
(T_2) to estimate the coil temperature (T_{coil}) during experiments in helium gas.

We conducted current dump experiments and over-current experiments in liquid nitrogen and liquid/gas helium to obtain the magnetic field delay time constants and investigate the self-protect characteristics. The magnetic field intensities, the layer voltages, and the supply current were collected every 20 ms with a digital data recorder (NR-500, KEYENCE).

4. Results

4.1. Current dump experiment in liquid nitrogen (77 K)

We charged the LNI REBCO coil to 10 A with a current ramp rate of 0.167 A s^{-1} in liquid nitrogen (77 K). After the current hold, we shut down the power supply and measured the decay time constant of the magnetic field, i.e. the magnetic field delay time constant.

Figure 4(a) shows the supply current (I_{supply}, black-dashed line) and the central magnetic field (B_{center}, blue-solid line). The magnetic field decay after the current dump gave a magnetic field delay time constant, \( \tau_{lni} \), of 0.1 s as shown in figure 4(b). It is quite comparable to that of a similar shaped NI REBCO double-pancake coil described in column (B) of table 1, \( \tau_{dp} = 0.25 \) s [9], and is three orders of magnitude shorter than that of the conventional NI REBCO layer-wound coil, \( \tau_{lw} = 500 \) s [11].

4.2. Over-current experiment in liquid nitrogen (77 K)

An over-current experiment using the LNI REBCO coil was conducted to investigate its self-protect characteristics. Figure 5 shows the power supply current, \( I_{supply} \) (dashed line), the coil voltage, \( V_{coil} \) (open circles: sum of \( V_{L1--V_{L8}} \)), and the central magnetic field, \( B_{center} \) (solid line), during an over-current experiment. The supply current was ramped up to 150 A beyond the estimated coil critical current (112 A) and then held constant.

At \( t = 507.9 \) s (\( I_{supply} = 150.0 \) A: 134% of the coil \( I_c \), \( V_{coil} \) sharply increased due to a thermal runaway and it peaked...
at 1.8 V. Simultaneously, $B_{\text{center}}$ dropped from 232 mT to a steady state value of $\sim 26$ mT. This behavior shows the thermal runaway was automatically diminished due to current bypassing through contact resistances between the copper sheets and the turns. At $t = 539.0$ s, $I_{\text{supply}}$ was started to ramp down with a rate of $-0.33$ A s$^{-1}$ and the rate was changed to $-0.67$ A s$^{-1}$ at $t = 680.6$ s. During discharging the coil, $V_{\text{coil}}$ gradually decreased and reached 0 V, i.e. superconducting state, at $t = 789.1$ s ($I_{\text{supply}} = 27.4$ A: 24% of the coil $I_c$).

Figure 6(a) shows $I_{\text{supply}}$ and the layer voltages, $V_{L1}$-$V_{L8}$, versus time during the thermal runaway described in figure 5 (timescale of 507 s $< t < 516$ s). Figure 6(b) shows a lower voltage range plot of figure 6(a) (507.5 s $< t < 510$ s). Figure 6(c) shows $B_{\text{up}}$, $B_{\text{center}}$ and $B_{\text{low}}$ on the same timescale of figure 6(a). The magnetic fields were normalized by their initial values.

The thermal runaway was initiated in the 4th layer at $t = 507.9$ s (see $V_{L4}$ in figure 6(a)) although this layer did not have the lowest critical current among the layers. It is probable that cooling condition of the layer was worse since it was located inside the winding and was the first to suffer a thermal runaway. It propagated to both inner and outer layers and eventually reached $V_{L8}$ at $t = 513.2$ s. During the thermal runaway, negative voltage evolutions were observed in the other layers before their voltage take-offs as shown in figure 6(b). This indicates that each layer was strongly coupled to the other layers, and the propagation of the thermal runaway in the radial direction was accelerated by magnetic coupling as well as by thermal conduction. Similar voltage responses were also reported for an NI double-pancake coil [13, 14]. After the thermal runaway, each layer became steady state in the range of 0.1–0.4 V.

As shown in figure 6(c), at $t = 507.9$ s when $V_{L4}$ showed the take-off, $B_{\text{up}}$, $B_{\text{center}}$ and $B_{\text{low}}$ started to decrease along with the propagation of the thermal runaway. Characteristically, $B_{\text{up}}$, $B_{\text{center}}$ and $B_{\text{low}}$ decayed continuously and uniformly. After $V_{L4}$ became steady states at $t = 515.0$ s, $B_{\text{center}}$ saturated around 15% of its initial value. The average decaying rate of $B_{\text{center}}$ was 12%/s ($= (100\% - 15\%)/7.2$ s).

After the over-current experiment, the coil was charged again. The voltage–current curve agreed with that before the experiment. This result indicates that the coil was self-protected from the thermal runaway.

### 4.3. Current dump experiment in liquid helium (4.2 K)

So far, we have described experimental results at 77 K; the coil current is at most 150 A corresponding to a conductor current density of 285 A mm$^{-2}$. In the present and the following sections, we will show results of a current dump experiment and an over-current experiment under a higher current density operation in liquid/gas helium.

We charged the LNI REBCO coil to 98 A and shut down the power supply in liquid helium. The magnetic field delay time constant, $\tau_{\text{ini}}$, was 0.25 s which is longer than that obtained at 77 K, 0.1 s. The longer time constant is due to the lower resistivity of the copper sheets at 4.2 K. In addition, a current dump experiment from much larger currents of 970 A was conducted three times in liquid helium and gave almost the same time constant.
4.4. Temperature rise-induced over-current experiment in gas helium

After the current dump experiments in the previous section, $V_{L1}$ and $V_{L2}$ were not functioning anymore for an unknown reason. In the following experiments, we therefore measured the sum of $V_{L1}$ and $V_{L2}$ (hereafter represented by $V_{L1-L2}$) instead.

We charged the LNI REBCO coil to 385 A in liquid helium, and held constant. The liquid helium level decreased gradually by evaporation, exposing the whole coil to helium gas. This increased the coil temperature, $T_{\text{coil}}$, and decreased the coil critical current, leading an over-current thermal runaway.

Transient signals during the thermal runaway are described in figure 7. Figure 7(a) shows temperatures of $T_1$ (one-dot chain line) and $T_2$ (two-dot chain line). Figure 7(b) shows $I_{\text{supply}}$ (dashed line), $V_{\text{coil}}$ (open circle), and the coil terminal voltage including copper electrodes, $V_{\text{ter}}$ (open triangle). Figure 7(c) shows the layer voltages, $V_{L1-L2} (=V_{L1} + V_{L2})$ and $V_{L3-L8}$. Figure 7(d) shows $B_{\text{up}}$, $B_{\text{center}}$ and $B_{\text{low}}$ which are normalized by their initial values.

At $t = 2708.6$ s ($I_{\text{supply}} = 385$ A: corresponding conductor current density of 731 A mm$^{-2}$), a thermal runaway voltage appeared from in $V_{L1-L2}$ as shown in figure 7(c). This is because the inner layers were heated up by the inner electrode. Figure 7(a) indicates the temperature of the coil, $T_{\text{coil}}$, was between 56 K and 68 K. The negative peak and gradual reduction of $I_{\text{supply}}$ seen in figure 7(b) indicates that a part of the current was shunted to the room temperature dump resistor. After the initial take-off of $V_{L1-L2}$, the thermal runaway propagated to the outer layers and eventually reached $V_{L8}$ at $t = 2709$ s. At $t = 2708.6$ s when $V_{L1-L2}$ showed the...
take-off, the magnetic fields started to decay. Since the decay rate of the $B_{\text{center}}$ is much larger than that of $I_{\text{supply}}$, it is considered that the thermal runaway automatically diminished by current bypassing inside the coil winding. $B_{\text{up}}$, $B_{\text{center}}$ and $B_{\text{low}}$ decayed quite continuously and homogeneously, and decayed to 8% in 4.1 s. The average decay rate of $B_{\text{center}}$ was 22.4%/s ($=$ (100%–8%)/4.1 s), which is 1.9 times faster than that of the experiment in liquid nitrogen. As shown in figure 7(b), $V_{\text{ter}}$ still kept increasing after $t = 2712.7$ s, while $V_{\text{coil}}$ decreased. At $t = 2713.6$ s, $V_{\text{ter}}$ sharply increased and

Figure 7. Transient signals of the LNI REBCO coil during thermal runaways in a temperature rise-induced over-current operation in gas helium. (a) Temperature at a point 200 mm above the top of the coil, $T_1$, and that at the bottom of the coil, $T_2$. (c) Current supplied to the coil, $I_{\text{supply}}$, coil voltage, $V_{\text{coil}}$, and terminal voltage including electrodes, $V_{\text{ter}}$. (c) Layer voltages, $V_{L1-L2}$ ($=V_{L1} + V_{L2}$) and $V_{L3-L8}$, from innermost layer to outermost layer. (d) Normalized magnetic fields along the coil axis, at the upper coil end ($B_{\text{up}}$), at the center ($B_{\text{center}}$), and at the lower end ($B_{\text{low}}$).
the power supply was shut down due to the over-voltage protection. After the experiment, a bridge part between the innermost layer and the negative electrode was found to be burnt out as shown in figure 8, which was also observed in our previous paper employing an ordinary NI layer-wound coil [10].

We repaired the bridge part and charged the coil again in liquid nitrogen. The voltage–current curve agreed with the original curve. This shows the coil winding was self-protected from the thermal runaway under a corresponding conductor current density as high as $>700 \text{ A mm}^{-2}$.

Figure 8. Photograph of the burnout position on the bridge conductor between the innermost layer and the negative electrode.

Figure 9. Simulated coil scale dependence of field delay time constant. (a) NI double-pancake coil: $\tau$ versus $N_z$. (a') NI double-pancake coil: $\tau$ versus $N_r$. (b) Ordinary NI layer-wound coil: $\tau$ versus $N_z$. (b') Ordinary NI layer-wound coil: $\tau$ versus $N_r$. (c) LNI coil: $\tau$ versus $N_z$. (c') LNI coil: $\tau$ versus $N_r$.
5. Discussion

In this section, we will make numerical simulation on a magnetic field delay and additional coil experiments on self-protection behavior. Based on those results, we will discuss basic characteristics of the LNI REBCO coil by comparing it with the ordinary NI layer-wound REBCO coil and the NI double-pancake REBCO coil.

5.1. Effect of coil scale on the magnetic field delay

Effect of coil scale on the magnetic field delay time constants of NI double-pancake REBCO coils, ordinary NI layer-wound REBCO coils, and LNI REBCO coils were numerically simulated by using equivalent circuit models as shown in figures 1(a’)–(c’). A detailed explanation of the model can be seen in the previous paper [11].

In a LNI REBCO coil, a turn is connected to the axial adjacent turns through $R_{Cu}$ and $R_c$ as shown in figure 1(c’). Here, $R_{Cu}$ is the resistance of the copper sheet along the coil axis direction, and $R_c$ is the contact resistance between a turn and the copper sheet. $R_{Cu}$ was estimated as the measured resistivity of the copper sheet, $R_{Cu} = 3.56 \, \Omega \cdot m$ (at 77 K). $R_c$ was calculated by dividing the contact resistivity, $r_c$, by the contact area. In the present simulation, $r_c$ is the fitting parameter determined with a measured field delay time constant. Fitting to the time constant, as shown in figure 4(b), gave $r_c = 25 \, \Omega \cdot cm^2$. This value is much larger than the typical reported value of $70 \, \mu \Omega \cdot cm^2$ [15]. It is possible that wrinkles formed on the very thin copper sheet during winding process which produced bad contacts between conductors and the copper sheets. It is also possible that the equivalent circuit model in figure 1(c’) does not necessarily represent the real circuit structure in the LNI coil. For NI double-pancake REBCO coils and ordinary NI layer-wound REBCO coils, we adopted the contact resistivity used in the previous paper [11].

Figure 9 shows simulated scale dependences of field delay time constants. In this figure, $N_r$ and $N_z$ respectively show the number of turns along the r-axis and that along the z-axis (see the upper inset). The field delay time constants of NI double-pancake coils (a) and (a’), ordinary NI layer-wound coils (b) and (b’) and LNI coils (c) and (c’) are proportional to $\ln(N_rN_rN_z)$. It is possible that wrinkles formed on the very thin copper sheet during winding process which produced bad contacts between conductors and the copper sheets. It is also possible that the equivalent circuit model in figure 1(c’) does not necessarily represent the real circuit structure in the LNI coil. For NI double-pancake REBCO coils and ordinary NI layer-wound REBCO coils, we adopted the contact resistivity used in the previous paper [11].

Figure 10 shows transient signals of an NI double-pancake REBCO coil during thermal runaways in an overcurrent operation in 77 K. (a) Power supply current, $I_{supply}$, and double-pancake voltages, $V_{DP1}$–$V_{DP9}$, from upper to lower double-pancakes. (b) Expanded view of the dotted square space shown in (a) (543 s < $t$ < 545 s). (c) Normalized magnetic fields along the coil axis, at the upper coil end ($B_{up}$), at the center ($B_{center}$), and at the lower end ($B_{low}$). Figures 10(d)–(f) are data on the LNI REBCO coil reprinted from figures 6(a)–(c), respectively, with the same graph scales to those of figures 10(a)–(c).
innermost coil of a 1.3 GHz NMR magnet design [16]. The latter time constant is sufficiently short as to be practical.

5.2. Difference of thermal runaway behavior between the LNI REBCO coil and the NI double-pancake REBCO coil

For comparison, we conducted over-current experiments at 77 K for the NI double-pancake REBCO coil described in the column (B) of table 1. The power supply current was ramped up to 140 A. Figure 10(a) shows $I_{\text{supply}}$ and the voltages of each double-pancake coil, $V_{\text{DP1}}-V_{\text{DP9}}$ (from top to bottom of the coil) during thermal runaway. Figure 10(b) shows a lower voltage range plot of figure 10(a) ($543 \, \text{s} < t < 545 \, \text{s}$). Figure 10(c) shows $B_{\text{up}}, B_{\text{center}}$ and $B_{\text{low}}$ which are normalized by their initial values.

During current ramping, at $t = 541.4 \, \text{s}$ ($I_{\text{supply}} = 136.5 \, \text{A}$), $V_{\text{DP2}}$ rapidly increased due to a thermal runaway and peaked at 0.75 V. It propagated to the upper and lower double-pancakes and reached $V_{\text{DP9}}$ at $t = 576.2 \, \text{s}$. Along with the double-pancake voltage take-offs, negative inductive voltages were observed in other double-pancakes (see figure 10(b)) as reported in [14]. A spatially closer
double-pancake shows a larger inductive voltage since adjacent double-pancakes are more strongly coupled. During the thermal runaway, magnetic fields showed discontinuous and inhomogeneous decay as shown in figure 10(c). This kind of step-by-step thermal runaway behavior causes unbalances of the axial electromagnetic forces in the coil [7, 8]. $B_{center}$ eventually reduced to 6% of its initial value at $t = 579.9\text{s}$. The average decay rate of $B_{center}$ was 2.4%/s (=100%−6%)/38.5 s, which is much slower than that of the LNI REBCO coil shown in figure 6(c). At $t = 579.9\text{s}$, the power supply was shut down due to the over-voltage protection.

For clarity, transient signals of the LNI REBCO coil shown in figures 6(a)–(c) are respectively presented again in figures 10(d)–(f) with the same graph scales as those of the NI double-pancake REBCO coil (figures 10(a), (b) and 10)). As demonstrated earlier, in the case of an LNI REBCO coil, a thermal runaway continuously propagates along the coil radial direction and the magnetic field decays rapidly (see figures 10(d)–(f)). In contrast, in the case of an NI double-pancake REBCO coil, a thermal runaway discontinuously propagates along the coil axial direction with a longer time interval to finish the field decay. The mechanism of this notable difference can be explained as follows.

When a thermal runaway occurs in an NI double-pancake REBCO coil, a normal zone, or ‘current bypass zone’, fully propagates inside the pancake winding rapidly. This gives an instantaneous transition from multi-turn-pancake mode to single-turn-pancake mode in which the radial current dominates and the circumferential current density is very low (see the current vector distributions in a pancake presented in the middle-left part of figure 11) [2]. For a LNI REBCO coil, a similar phenomenon occurs inside each layer; i.e. a transition from ‘multi-turn-layer’ mode to ‘single-turn-layer’ mode where the axial current dominates (see the current vector distributions in a layer presented in the middle-right part of figure 11). Current from the upper positive electrode flows along the circumferential direction in the uppermost turn, spilling out along the axial direction to the lower turn. In most of the winding, substantially reduced circumferential current densities, $J_z$, behave as a single-turn-layer in combination with axial current densities, $J_a$. Note that ‘single-turn’ does not necessarily mean exactly ‘one-turn’ since it depends on the characteristic resistance of a coil. The overall current then concentrates into the lower negative electrode.

In a NI double-pancake-stacked coil, single-turn-pancake mode propagates along the axial direction from pancake to pancake. The propagation should be influenced both by thermal conduction and by electromagnetic coupling. For thermal conduction, spacers/gaps between pancakes interfere with the axial thermal propagation. In addition, for electromagnetic coupling, distant pancakes are weakly coupled each other (see table 2(b)) and this also slows the propagation over the coil, resulting in discontinuous and inhomogeneous field decay (see the lower-left part of figure 11). Note that the above-discussed behavior can be influenced by conditions such as the operating temperature [17], current densities and coil scales, considering the fact that a larger NI multi-width double-pancake REBCO coil tested in liquid helium showed a more rapid propagation of thermal runaway over the multi-stacked winding [14].

| Table 2. Magnetic coupling coefficient matrix. (a) Layer-wound REBCO coil (16 turns × 8 layers). (b) Double-pancake REBCO coil (16 turns × 9 double-pancakes). |
|---|---|---|---|---|---|---|---|---|
| (a) Layer-wound | 1st layer | 2nd layer | 3rd layer | 4th layer | 5th layer | 6th layer | 7th layer | 8th layer |
| 1st layer | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.95 | 0.94 | 0.93 |
| 2nd layer | 0.99 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.95 | 0.94 |
| 3rd layer | 0.98 | 0.99 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.95 |
| 4th layer | 0.97 | 0.98 | 0.99 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 |
| 5th layer | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 | 0.99 | 0.98 | 0.97 |
| 6th layer | 0.95 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 | 0.99 | 0.98 |
| 7th layer | 0.94 | 0.95 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 | 0.99 |
| 8th layer | 0.93 | 0.94 | 0.95 | 0.96 | 0.97 | 0.98 | 0.99 | 1.00 |
| Scale | 1 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0 |
In a LNI coil with multi-layers, the single-turn-layer mode propagates from layer to layer. In the coil, wide thermal contact area between layers provides a good thermal conduction along the radial direction. Furthermore, each layer is strongly coupled (see table (2(a)) and this also accelerates the propagation of the single-turn-layer mode over the winding (see the lower-right part of figure 11). To clarify the more detailed propagation mechanism, a multi-physics numerical simulation study such as those in [17, 18] is required.

Based on the experimental and simulated results on the NI double-pancake REBCO coil and LNI REBCO coil, differences between their conceptual characteristics are summarized in figure 11 from the viewpoints of the magnetic field delay time and the self-protect behavior during thermal runaway. The LNI method provide a short field delay time constant as well as self-protect characteristics, which enables the use in a practical magnet. Considering the self-protect behavior, the LNI method is preferred from the standpoint of suppression of the unbalance of electromagnetic forces along the coil axis, which may mechanically damage the coil [7, 8]. Moreover, such a fast propagation throughout the entire winding may provide quicker dissipation of the stored energy in a larger coil compared to a NI double-pancake coil.

5.3. Potential problems of the LNI REBCO coil
A major drawback of the LNI method is a reduction in packing factor of the winding due to inserted materials between the layers. This reduces the overall current density and mechanical rigidity of the winding. In the present work, we simply demonstrated the effectiveness of the LNI method with coil experiments in self-fields. More experiments need to be carried out in external magnetic fields, in which situation coils are under strong electromagnetic forces [19–21]. We will conduct such experiments in the near future.

6. Conclusions

We have proposed a new method to significantly shorten the field delay time of an NI layer-wound REBCO coil. An LNI REBCO coil showed a magnetic field delay time constant of 0.1 s, which is three orders of magnitude shorter than that of an similar shaped NI layer-wound REBCO coil, 500 s. The LNI REBCO coil also showed a self-protect behavior in an over-current operation even under a high current density >700 A mm⁻², which is one of the major technical benefits of the NI technique. In the LNI coil, a thermal runaway continuously propagates from layer to layer, which is a preferable characteristic from the viewpoint of suppression of the unbalance of electromagnetic forces.

The LNI method is promising for the use in a REBCO inner coils in NMR/MRI magnets operated in persistent current mode since layer-winding gives a smaller number of joints and a homogeneous magnetic field.

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References

[1] Hahn S, Park D K, Bascunan J and Iwasa Y 2011 HTS pancake coils without turn-to-turn insulation IEEE Trans. Appl. Supercond. 21 1592–5
[2] Yanagisawa Y, Sato K, Yanagisawa K, Nakagome H, Jin X, Takahashi M and Maeda H 2014 Basic mechanism of self-healing from thermal runaway for uninsulated REBCO pancake coils Physica C 499 40–4
[3] Yoon S, Kim J, Cheon K, Lee H and Hahn S 2016 26 T 35 mm all-GdBa₂Cu₃O₇₋ multi-width No-insulation superconducting magnet Supercond. Sci. Technol. 29 04LT04
[4] Kim J, Yoon S, Cheon K, Shin K H, Hahn S, Kim D L, Lee S, Lee H and Moon S 2016 Effect of resistive metal cladding of HTS tape on the characteristic of No-insulation coil IEEE Trans. Appl. Supercond. 26 4601906
[5] Choi Y H, Hahn S, Song J B, Yang D G and Lee H 2011 Partial insulation of GdBCO single pancake coils for protection-free HTS power applications Supercond. Sci. Technol. 24 125013
[6] Kim S, Hahn S, Kim K and Labaralestier D 2017 Method for generating linear current-field characteristics and eliminating charging delay in no-insulation superconducting magnets Supercond. Sci. Technol. 30 035020
[7] Terao Y, Ozaki O, Kawashima S, Saito K, Hase T, Kitaguchi H, Sato K, Urayama S and Fukuyama H 2014 Analysis of an abnormal event in a 3-T MRI magnet wound with Bi-2223 tape conductors IEEE Trans. Appl. Supercond. 26 4401105
[8] Painter T et al 2017 Design, construction and operation of a 13T 52mm no insulation REBCO insert for a 20T all-superconducting user magnet Int. Conf. of Magnet Technology 25Or31-03
[9] Noguchi S, Park D, Hahn S and Iwasa Y 2018 Thermal and mechanical stability of no-insulation REBCO magnets for ultra high magnetic field generation 96th CSSJ Conf. 3B-a02 (written in Japanese)
[10] Yanagisawa K, Iuchi S, Xu Y, Li J, Saito A, Nakagome H, Takao T, Matsumoto S, Hamada M and Yanagisawa Y 2016 A long charging delay for a No-insulation REBCO layer-wound coil and its influence on operation with outer LTS coils IEEE Trans. Appl. Supercond. 26 4602304
[11] Suetomi Y, Yanagisawa K, Nakagome H, Hamada M, Maeda H and Yanagisawa Y 2016 Mechanism of notable difference in the field delay times of no-insulation layer-wound and pancake-wound REBCO coils Supercond. Sci. Technol. 29 105002
[12] Hahn S, Kim Y, Park D K, Kim K, Voccio J P, Bascuña J and Iwasa Y 2013 No-insulation multi-width winding technique for high temperature superconducting magnet Appl. Phys. Lett. 103 173511
[13] Markiewicz W D, Jaroszynski J J and Abraimov D V 2016 Quench analysis of pancake wound REBCO coils with low resistance between turns Supercond. Sci. Technol. 29 25001

[14] Song J-B, Hahn S, Lécrevisse T, Voccio J, Bascuñán J and Iwasa Y 2015 Over-current quench test and self-protecting behavior of a 7 T/78 mm multi-width no-insulation REBCO magnet at 4.2 K Supercond. Sci. Technol. 28 114001

[15] Wang X, Hahn S, Kim Y, Bascuñán J, Voccio J, Lee H and Iwasa Y 2013 Turn-to-turn contact characteristics for an equivalent circuit model of no-insulation REBCO pancake coil Supercond. Sci. Technol. 26 035012

[16] Yanagisawa Y et al 2018 Development plan for a persistent 1.3GHz NMR magnet in a new MIRAI project on joint technology for HTS wires/cables in Japan Korea Inst. Appl. Supercond. Cryog. (KIASC) 20 15–22 Special issue

[17] Miyao R, Igarashi H, Ishiyama A and Noguchi S 2018 Thermal and electromagnetic simulation of multistacked no-insulation REBCO pancake coils on normal-state transition by PEEC method IEEE Trans. Appl. Supercond. 28 4601405

[18] Ikeda A, Oki T, Wang T, Ishiyama A and Monma K 2016 Transient behaviors of no-insulation REBCO pancake coil during local normal-state transition IEEE Trans. Appl. Supercond. 26 26–9

[19] Kajita K et al 2016 Degradation of a REBCO coil due to cleavage and peeling originating from an electromagnetic force IEEE Trans. Appl. Supercond. 26 4301106

[20] Kajita K, Takao T, Maeda H and Yanagisawa Y 2017 Degradation of a REBCO conductor due to an axial tensile stress under edgewise bending: a major stress mode of deterioration in a high field REBCO coil’s performance Supercond. Sci. Technol. 30 074002

[21] Yanagisawa Y et al 2016 27.6 T Generation Using Bi-2223/REBCO Superconducting Coils, IEEE/CSC & ESAS Superconductivity News Forum (global edition) http://snf.ieee/csc.org/sites/ieeecsc.org/files/edSTH42-HP112_Yanagisawa%2CY_27.6%20T_generation-final_071816.pdf