Partial-Insulation Winding Technique for NbTi Coils

Youngjae Kim, Seungyong Hahn, Jiayin Ling, Kwang Lok Kim, Jungbin Song

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Francis Bitter Magnet Laboratory,
Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

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Partial-Insulation Winding Technique for NbTi Coils

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Abstract—In 2010, we reported, for the first time, the no-insulation (NI) winding technique for high-temperature superconducting (HTS) pancake coils. Based on our test results of small NbTi NI coils, reported in 2011, the key benefits, i.e., enhanced mechanical integrity, compactness, and thermal stability, of the NI winding technique, appear intact for low-temperature superconducting (LTS) windings. However, the intrinsic charging delay observed in NI coils, caused by the lack of insulation, is more pronounced in LTS coils of a bare round wire than in HTS pancakes of thin, wide tape. Thus, to significantly reduce the charging delay in LTS coils of a bare round wire, we proposed a partial-insulation (PI) winding technique, a variation of the NI technique. In the PI winding of a bare round wire, a thin insulation sheet is introduced every few layers—note that in the PI winding, there are no turn-to-turn insulations. This paper reports results, experimental and analytical, of the PI winding technique in which bare-round-wire NI and PI coils were prepared to quantify the effects of PI winding technique. Three LTS coils of the identical dimension and magnet constant were wound with 0.4 mm diameter NbTi mono-filament wire and tested in a bath of liquid helium at 4.2 K, respectively, with three winding techniques: insulated (INS); NI; and PI. We analyzed the experimental results by applying an equivalent circuit model that had earlier been successfully applied to another set of experimental results. A graph model of resistance matrix was applied to estimate characteristic resistance of both NI and PI coils.

Index Terms—characteristic resistance, NbTi, no-insulation, partial-insulation.

I. INTRODUCTION

This paper reports our feasibility study on no-insulation (NI) and partial-insulation (PI) winding techniques applied to NbTi low-temperature superconducting (LTS) coils. In 2010, we reported, for the first time, the NI winding technique for high-temperature superconducting (HTS) pancake coils [1]. The key idea of the NI technique is to use bare wire to permit a single turn in an winding to divert its current away from a local quench spot to its adjacent turns for enhanced stability. The key benefits, i.e., enhanced mechanical integrity, thermal stability, and compactness of the NI winding technique, have been proven in our test results of a small NbTi NI coil [2]. Specifically, the NI winding technique improves the low thermal stability of LTS magnets (typical an enthalpy density margin of < 10 mJ/cm³ [3]) to a level high enough to virtually eliminate premature quenches.

However, a charging delay intrinsic to NI coils, caused by lack of turn-to-turn insulation, may become a major disadvantage of the NI technique for a magnet that requires a “fast” charging time. We have also reported that the charging delay of an HTS NI pancake coil is related to its equivalent characteristic resistance ($R_c$) that is proportional to its contact resistance and number of turns [4]. Unlike HTS pancake coils, it is more complex to estimate the charging delay and $R_c$ of an LTS NI coil because the LTS coil is usually wound with layer winding, a conventional way with round or rectangular cross section wire. The layer winding of bare-round wire in an LTS NI coil will electrically connect all the single turns in the winding to their adjacent turns. This network of contacts will form a “contact resistance matrix” that contains multiple delta resistance connections. This network of an NI winding will have several parallel connections, i.e., increased number of turns or layers may not be related to its charging delay and $R_c$ directly.

To significantly mitigate the charging delay in LTS NI coils, we have proposed a partial-insulation (PI) winding technique, a variation of the NI technique. In the PI winding of a bare round wire, a thin insulation sheet is introduced every few layers to divide one large NI winding into several small NI winding sections. To demonstrate the effectiveness of the PI technique on shortening the charging delay of LTS magnets, three NbTi test coils were wound, respectively, with insulated (INS), NI, and PI winding technique and tested. This paper presents charging test results of three NbTi test coils to compare their charging delays in terms of time constant ($\tau_c$) and $R_c$ in a lumped equivalent circuit model [1], [2]. Furthermore, a graph model to estimate $R_c$ from its equivalent contact resistance matrix of NI and PI windings in a given contact resistivity ($R_{cd}$) is also introduced to compare with our test results. Although there was a discrepancy of charging delay between measured value and estimated value, both test results and the analytical model suggest that the PI technique is effective in reducing charging delay of bare-round-wire LTS coils. Through experimental results and analytical results, it is concluded that the PI winding technique is applicable even to a superconducting magnet that requires a fast charging time.

II. EXPERIMENTAL RESULTS

A. Configuration of NbTi Test Coils

Three NbTi test solenoid coils of the identical 101.6 mm inner diameter were wound, respectively, with different turn-

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Y. Kim, S. Hahn, J. Ling, K. L. Kim, J. Song, J. Voccio, J. Bascuñán, and Y. Iwasa are with Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA (phone: +1-617-253-8293; fax: +1-617-253-5405; e-mail: syhahn@mit.edu).
to-turn insulation methods, INS, NI, and PI techniques. Table I contains key parameters of the three test coils. A monofilament NbTi round wire of 0.4 mm diameter was chosen as a magnet conductor for the test coils. The three test coils had identical number of turns and number of layers which were intended to obtain the same magnet properties, inductance and magnet constant. For the INS test coil, the identical NbTi wire except with a 0.02 mm thick insulation layer around its perimeter was used and this insulation layer made slight differences in coil dimensions, outer diameter, and height. These differences, though less than 3%, made the inductance, center field, and estimated $I_d$ of the INS test coil slightly different from those of the other test coils.

Fig. 1 shows sectional diagrams of turns in the two test coils having NI winding (left) and PI winding (right). Pairs of numbers in round brackets are coordination of single winding turn in order of turn and layer. The PI winding diagram also contains a insulation layer.

<p>| TABLE I: Key Parameters of NbTi Test Coils |</p>
<table>
<thead>
<tr>
<th>Items</th>
<th>INS</th>
<th>NI</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductor (Vendor)</strong></td>
<td>T48B-G (Supercon Inc.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Filament scheme / Shape</strong></td>
<td>Monofilament / Round</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cu-to-NbTi ratio</strong></td>
<td>3:1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Insulation</strong></td>
<td>Insulated</td>
<td>Not insulated</td>
<td></td>
</tr>
<tr>
<td><strong>Diameter [mm]</strong></td>
<td>0.44</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td><strong>Coil (winding scheme)</strong></td>
<td>Solenoid (orthocyclic layer winding)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>i.d.:o.d. [mm]</td>
<td>101.6;105.9</td>
<td>101.6;105.9</td>
<td>101.6;105.9</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>12.32</td>
<td>11.2</td>
<td>11.2</td>
</tr>
<tr>
<td><strong>Number of turns</strong></td>
<td>165</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td><strong>Turns per layer</strong></td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td><strong>Number of layers</strong></td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>PI layer sectioning</strong></td>
<td>-</td>
<td>-</td>
<td>3/3</td>
</tr>
<tr>
<td><strong>Inductance [mH]</strong></td>
<td>5.07</td>
<td>5.22</td>
<td>5.22</td>
</tr>
<tr>
<td><strong>Magnet constant [mT/A]</strong></td>
<td>1.98</td>
<td>1.99</td>
<td>1.99</td>
</tr>
<tr>
<td><strong>Coil $I_d$ (estimated at self field, 4.2 K) [A]</strong></td>
<td>137</td>
<td>135</td>
<td>135</td>
</tr>
<tr>
<td><strong>Characteristic resistance, $R_c$ [µΩ]</strong></td>
<td>N/A ($\infty$)</td>
<td>28.9</td>
<td>126.9</td>
</tr>
<tr>
<td><strong>Time constant, $\tau_c$ [s]</strong></td>
<td>0</td>
<td>180.6</td>
<td>41.1</td>
</tr>
<tr>
<td><strong>Winding type</strong></td>
<td>dry</td>
<td>dry</td>
<td>dry</td>
</tr>
</tbody>
</table>

Symbols in those two specific turns also stand for the current terminals, + (input) and − (output) of the winding. Each contact resistance between two adjacent turns in an orthocyclic layer winding results in a resistance matrix of multiple delta resistance connections. For the INS test coil each contact resistance is obviously infinite. As shown in the right diagram of Fig. 1, the PI test coil has one 50 µm thick layer of adhesive tape insulator between the 3rd and 4th layers. With this insulation layer, the NI winding is now divided into two 3-layer NI winding sections. The contact resistance between the 3rd and 4th layers is now infinite, except at one point in the bottom, where the 3rd layer transitions to the 4th layer.

B. Charging Test of NbTi Test Coils

Charge and discharge test was performed on the three NbTi test coils to obtain charging delay and $R_c$ of each coil. The charging current was 30 A and its ramping rate was 0.0475 A/s. Fig. 2 presents the magnetic field traces of the charging test of INS, NI, and PI test coils. Except with the INS test coil trace (black line with square symbol in Fig. 2), the current was maintained at 30 A for 10 minutes to observe saturation of magnetic field and then discharged. The highest measured field of INS, NI, and PI test coils were 58.7 mT, 59.9 mT, and 60.3 mT, respectively. The NI and PI test coils produced slightly higher center field than that of INS test coil. Compared with the INS coil result in time domain, it is observed that magnetic field of NI test coil (red line with circles) and PI test coil (blue line with triangles) are lagging significantly. It took 489 s and 363 s for NI and PI test coil, respectively, to produce a magnetic field of 30 mT (gray dashed line in Fig. 2), whereas the INS test coil took only 323 s. Fig. 3 shows the voltage and current traces measured during these charging sequences for the INS, NI, and PI test coils. The INS coil voltage trace (black line with squares) shows a typical voltage response of an LTS coil that can be modeled as a pure inductor, i.e., $voltage = coil inductance \times current \ rate$. In the NI and PI test coils, current traces each shows a delayed voltage response corresponding to a parallel inductor/resistor circuit.
III. ANALYTICAL RESULTS

Analysis on the test results was performed in two steps: 1) calculation of $R_c$ for each of the LTS NI and PI test coils based on an equivalent circuit model and 2) estimation of $R_c$ from its winding configuration (number of turns per layer × number of layer) between adjacent turns based on graph modeling of a contact resistance matrix.

A. Equivalent Circuit Model Analysis

Fig. 4 shows a circuit diagram of the charging test setup. Equivalent circuit model of LTS coil, inside of blue dashed line, is also depicted with three electrical parameters, inductance ($L_{\text{LTS}}$), characteristic resistance ($R_c$), and azimuthal resistance ($R_\alpha$).

Equation (1) and (2) can be used to find best match of $R_c$ with given coil inductance ($L_{\text{LTS}}$) and measured magnet constant ($\alpha$), power supply current ($I_{PS}$), and magnetic field ($B_z$). It should be noted that $R_\alpha$ is neglected based on relationship between the maximum charging current, 30 A, of a test and estimated $L_{\text{LTS}} \sim 135$ A [2]. Best matching $R_c$ values of the NI and PI test coils resulting from (1) and (2) are 28.9 $\mu$Ω and 126.9 $\mu$Ω (Table I), respectively. Their time constants, given by $L_{\text{LTS}}/R_c$, are also included in Table I. Fig. 5 presents measured and estimated voltage and magnetic field of the PI test coil with the best matching $R_c$. With a given $R_c$ of 126.9 $\mu$Ω, calculated voltage and magnetic field traces agree well with its measured results. Through test results and equivalent circuit analysis, it is confirmed that the PI technique, because it increases $R_c$, is effective in reducing the charging delay of an LTS NI coil without significant change in the coil parameters.

$$L_{\text{LTS}} \frac{dl_z(t)}{dt} = (I_{PS}(t) - I_\alpha(t))R_c$$  \hspace{1cm} (1)

$$B_z(t) = c\alpha_\theta(t)$$  \hspace{1cm} (2)

B. Contact Resistance Matrix Analysis

Compared with NI HTS pancake coils, it is complicated to calculate $R_c$ of LTS NI and PI coils from a given $R_\alpha$ and vice versa. Although all the contact resistance in Fig. 1 are identical, the contact resistance matrix should be analyzed to obtain a lumped resistance, a major component of $R_c$, between first turn and last turn.
The contact resistance matrices of an LTS NI and PI layer windings can be modeled by a graph model of Kirchhoff’s law [5]. Fig. 6 shows a graph model for our NI test coil (28 turns per layer and 6 layers in total) to construct an incidence matrix, \( A \), and stiffness matrix, \( A'CA \), which represent all connections of nodes (single turn of NbTi wire) and edges (contact resistance between adjacent turns.) All the nodes and edges are numbered separately in ascending order from top-left to bottom-right. Node numbers and edge numbers are assigned in gray circles and yellow boxes, respectively as shown in Fig. 6, and our NI winding graph model will contain 165 nodes and 429 edges to make our \( A \) matrix to be 429 (edges) \( \times \) 165 (nodes) matrix. \( C \) matrix also should be obtained to consider conductance of each edge. The \( C \) matrix, 429 \( \times \) 429 matrix in this case is a diagonal matrix with entries \( c_i > 0 \), where \( c_i \) is the conductance in \( i \)-th edge. The \( c_i \) can be equated as (3), where \( r_i \) and \( R_{ce} \) are, respectively, radius of \( i \)-th contact point and average line contact resistivity between two turns [\( \mu \Omega \cdot \text{cm} \)]. With \( A \) and \( C \) constructed from the graph model and NI winding dimension, a system matrix equation can be constructed as (4), where \( w, u, b, \) and \( f \) are vectors of closed loop flow, nodal voltage, input voltage source, and input current source, respectively. To simplify those vectors, our graph model has only a 1-A current source that connects the first and end turns, which makes \( b = 0 \) and \( f \) to contain only two non-zero entries at 1st and 139-th elements. With the system matrix equation simplified, we may obtain (5) from (4) by eliminating \( w \). Calculation of (5) can give us \( u \), vector of voltage at entire nodes, of our graph model with 1-A input current applied to first and end turns. The lumped resistance between the first and end turns, analytical \( R_c \) of contact resistance matrix, can be obtained by calculation of voltage difference of those two turns from the vector \( u \).

\[
c_i = 2\pi r_i / R_{ce}
\]

\[
\begin{bmatrix}
C^{-1} \\
A' \\
0
\end{bmatrix}
\begin{bmatrix}
w \\
u
\end{bmatrix}
= 
\begin{bmatrix}
b \\
f
\end{bmatrix}
\]

\[
u = -(A'CA)^{-1}f
\]

Table II contains calculated lumped \( R_c \) [\( \Omega \)] of an m-turn \( \times \) n-layer LTS NI coil whose \( r_i \) is modeled from the LTS test coils and \( R_{ce} \) is assumed to be 1 [\( \Omega \cdot \text{cm} \)]. Five numbers (7,14,21,28,35) and eight numbers (from 1 to 8) were chosen for \( m \) and \( n \), respectively, and used to calculate \( R_c \) from (3) and (5). Referring Table II, it is possible to discuss rules of lumped \( R_c \) creation in an m-turn \( \times \) n-layer NI LTS coil as follows: 1) if \( n \) is even, \( R_c \) will be lower than when \( n \) is odd in general and \( R_c \) cannot be increased effectively by increasing \( m \), turns per layer and 2) if \( n \) is odd, \( R_c \) can be increased with more turns per layer but also tends to decrease with increment of \( n \), number of layers.

To estimate factor of \( R_c \) increment from NI test coil to PI test coil, two specific numbers in Table II, 0.046 [\( \Omega \)] at 28-turn \( \times \) 6-layer for NI winding and 0.23 [\( \Omega \)] at 28-turn \( \times \) 3-layer for PI winding can be used. Effective \( R_c \) of PI test coil will be 0.46 [\( \Omega \)] (2 \( \times \) 0.23 [\( \Omega \)]) because the PI test coil may be modeled as series connection of two 28-turn \( \times \) 3-layer NI windings. On the other hand, the NI winding configuration is estimated to produce only 0.046 [\( \Omega \)], which makes a charging delay 10 times that of the PI test coil. In the test results, however, the NI test coil had a charging delay 4.4 times longer than PI test coil. This discrepancy may be caused by: 1) imperfect layer-winding unlike that illustrated in Fig. 1; 2) short circuit between stainless steel bobbin and the NI/PI test coil windings; 3) imperfect partial insulation; 4) nonuniform line contact resistivity within the winding; and 5) disagreement of graph model and real test coils. These possible causes will be further studied to refine our matrix models, which in turn enable us to minimize the number of PI winding sections while keeping a charging delay to an acceptable level. Meanwhile, it is still possible to conclude that PI winding technique is effective to improve charging delay of NI winding technique with negligible change of magnet properties.

**Table II**

<table>
<thead>
<tr>
<th>Turns per layer</th>
<th>Number of Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>0.187</td>
</tr>
<tr>
<td>14</td>
<td>0.406</td>
</tr>
<tr>
<td>21</td>
<td>0.624</td>
</tr>
<tr>
<td>28</td>
<td>0.843</td>
</tr>
<tr>
<td>35</td>
<td>1.061</td>
</tr>
</tbody>
</table>

IV. **CONCLUSION**

Three LTS test coils, INS, NI, and PI test coils, operated in a bath of liquid helium at 4.2 K, have shown that it is possible to significantly shorten a charging delay time, one chief detrimental characteristic of the NI coil that may render the NI technique unsuitable to magnets that require a “fast” charging time. The INS coil may be modeled as a pure inductor, while the NI or PI coil as a parallel inductor/resistor circuit. The key to delay is an effective contact resistance representing the turn-to-turn contact resistances that exist throughout a PI or NI winding. In this study, experimental and analytical, the PI coil had a charging delay time 1/4.4th that of the NI counterpart: division of the NI test coil into two NI winding sections with a layer of insulation in middle of the NI winding, i.e., creation of the PI test coil, resulted in this dramatic effect. An analysis based on contact resistance matrices and graph models was applied to simulate the experimental results. Although agreement between analysis and experiment is obviously not perfect, even at this stage of development, we may conclude that the PI winding technique is a promising practical solution that enables an essentially NI NbTi-based LTS magnet to take full advantage of the NI winding technique, while still meet charging time requirements.
REFERENCES


