Effect of Winding Tension on Electrical Behaviors of a No-Insulation ReBCO Pancake Coil

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Abstract—This paper presents a study on the effects of winding tension on the characteristic resistance of a no-insulation (NI) coil. Two ReBCO NI test pancake coils, having the same winding i.d. (60 mm), o.d. (67.6 mm) and number of turns (60), were sequentially prepared in a way that the first test coil was wound with a winding tension of 12-N, tested, and then rewound with a new winding tension of 20-N for the same tests. In each test, the test coil was energized at a target current, the power supply was "suddenly" disconnected, and then the temporal decay of the coil center field was measured, from which the time constant of the test coil and the consequent characteristic resistance were obtained. To check the reproducibility of experimental data, each test was repeated 4 times and each time the test coil was unwound and rewound with a given winding tension. The experimental results were analyzed with equivalent circuit analyses. Correlation between the winding tension and the characteristic resistance was discussed in detail.

Index Terms— Characteristic resistance, no-insulation coil, ReBCO, winding tension.

I. INTRODUCTION

RECENTLY, the no turn-to-turn insulation (NI) winding technique for high temperature superconductor (HTS) pancake coil was introduced [1]-[4]. Although the electrical insulation has been regarded indispensable in magnets [5]-[7], the NI winding technique enables the coil highly compact and self-protecting due to the "automatic bypass" of current through the turn-to-turn contacts in a quench [8]-[14].

For the NI technique to be practically applied to actual DC HTS magnets, the electrical responses of an NI HTS coil, such as charging delay, need to be characterized [15]-[19]. Our previous research reported that a charging delay could be estimated using an equivalent circuit model that consists of two major circuit elements in parallel: 1) coil inductance, $L_i$; and 2) characteristic resistance, $R_c$ [1]-[4], [20]-[22]. Also, we reported that $R_c$ of an NI coil was essentially proportional to the sum of all the turn-to-turn contact resistances of the coil [1]-[2], [21]-[23].

This paper presents the results of a follow-up research on the effects of winding tension on $R_c$. Two NI test pancake coils, both having 60-mm i.d., 67.6-mm o.d., and 60 turns, were sequentially prepared in a way that the first coil of 12-N winding tension was rewound for the second coil of 20-N winding tension after the completion of the first coil tests in a bath of liquid nitrogen at 77 K. The "sudden discharge" tests were performed to measure the charging time constant of the test coil at a given winding tension and the consequent $R_c$. To check the reproducibility of experiments, each test at a winding tension was repeated 4 times and each time the test coil was unwound and rewound. The experimental results were analyzed with the equivalent circuit analyses. The paper also presents detailed discussion on the effects of winding tension on $R_c$.

II. EXPERIMENTAL DETAILS

A. Construction of NI Test Coil

Table I lists the specifications of NI test coil wound with ReBCO conductor (manufactured by SuperPower Inc.) without any insulating material. The test coil has 60 turns with winding inner diameter and outer diameter of 60.0 and 67.6 mm, respectively. The construction was conducted by the following sequence: 1) NI coil was fabricated and completely tested in a liquid nitrogen bath, 2) the coil was rewound with a same winding tension after the completion of the first coil tests in a bath of liquid nitrogen at 77 K. The "sudden discharge" tests were performed to measure the charging time constant of the test coil at a given winding tension and the consequent $R_c$. To check the reproducibility of experiments, each test at a winding tension was repeated 4 times and each time the test coil was unwound and rewound. The experimental results were analyzed with the equivalent circuit analyses. The paper also presents detailed discussion on the effects of winding tension on $R_c$.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Specifications of the ReBCO CC Tape and NI Test Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Specifications</td>
</tr>
<tr>
<td><strong>Conductor</strong></td>
<td></td>
</tr>
<tr>
<td>Overall width; Thickness</td>
<td>[mm] 4.0; 0.063</td>
</tr>
<tr>
<td>Copper stabilizer thickness</td>
<td>[μm] 10 (5 for both sides)</td>
</tr>
<tr>
<td>Conductor $I_c$ @ 77K, self-field</td>
<td>[A] 80</td>
</tr>
<tr>
<td><strong>Coil</strong></td>
<td></td>
</tr>
<tr>
<td>i.d.; o.d.; height</td>
<td>[mm] 60.0; 67.6; 4.0</td>
</tr>
<tr>
<td>Turns; Layers</td>
<td>60; 1</td>
</tr>
<tr>
<td>Inductance</td>
<td>[μH] 432</td>
</tr>
<tr>
<td>Magnet constant (Center $B_c$ at 1 A)</td>
<td>[mT] 1.18</td>
</tr>
<tr>
<td>Peak field in the coil at 1 A</td>
<td>[mT] 5.27</td>
</tr>
</tbody>
</table>
Coil $I_c$ at 77 K, self-field

Fig. 1. A photograph of the NI test coil.

winding tension and tested, 3) the second process was repeated 4 times to examine the repeatability of the experiments. This wind-unwind-rewind-test sequence was conducted with the winding tensions maintained at 12 and 20-N. During the fabrication process of the NI test coil, the face of the conductor was wiped several times with acetone in order to make the same surface preparation. The axial field ($B_z$) of the coil was measured using a Hall sensor with a sensitivity of 97.9 mV/T at 77 K fixed at the center of the bobbin and continuously recorded with a data acquisition system. Fig. 1 shows a photograph of the NI test coil.

**B. Equivalent Circuit Model for NI Coil**

Fig. 2 shows the electrical circuit diagram of experimental setup comprised of a DC power supply, the NI test coil in a cryogenic condition (shaded box), and a shunt resistor. In the circuit model of NI test coil, there are three components: $L_{coil}$ (self-inductance of NI coil); $R_0$ (azimuthal resistance including matrix resistance and index loss); $R_c$ (characteristic resistance). The equivalent circuit model can be established by the following equation which contains $R_c$, current from power supply ($I_p$) and current to azimuthal direction of the coil ($I_L$):

$$ (I_p - I_L)R_c = L_{coil} \frac{dI_L}{dt} + R_0 I_L $$

To facilitate the calculations, $R_0$ was assumed to be zero in this study, because the tests were conducted below the critical current and temperature.

III. RESULTS AND DISCUSSION

**A. Preliminary Test**

To investigate a reliability of experiments, $B_z$ of NI test coil was measured 3 times in series while ramping rates were maintained at 2 and 10 A/s with the other test condition unchanged. Fig. 3 shows the normalized $B_z$ of NI test coil with the winding tension of 12-N, ramping rates of 2 and 10 A/s. The NI test coil was energized at 30 A, and held for about 20 s before the power supply was shut down manually. The inset graph in Fig. 3 was an enlarged view of sudden discharging, where the normalized $B_z$ traces at each test show no discrepancy.

As shown in Fig. 3, the NI coil experienced longer charging delay when the charging rate was increased [22]. From the experimental results, the decay time constant ($\tau$) of 1st, 2nd, and 3rd test could be obtained, and $R_c$ of corresponding test was calculated from the following equation:

$$ R_c = \frac{L_{coil}}{\tau} $$
Table II presents the obtained \( \tau \) and \( R_c \) of 1st, 2nd, and 3rd test at the ramping rate of 2 and 10 A/s. The average values of \( \tau \) and \( R_c \) at 2 A/s ramping rate were 486.7 (1.7) ms and 887.7 (3.4) \( \mu \Omega \), and those at 10 A/s ramping rate were 484 (1.4) ms and 892.3 (2.4) \( \mu \Omega \), respectively, where the parentheses indicate standard deviations. The \( \tau \) and \( R_c \) at each test was almost identical to average values which demonstrated that the measurement error was not observed. The difference between \( R_c \) value at ramping rate of 2 and 10 A/s was caused by the AC loss at \( R_0 \) of equivalent circuit model.

### Table II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1st( [\text{ms}] )</th>
<th>2nd( [\text{ms}] )</th>
<th>3rd( [\text{ms}] )</th>
<th>Average( [\text{ms}] )</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau )</td>
<td>485</td>
<td>489</td>
<td>486</td>
<td>486.7</td>
<td>1.7</td>
</tr>
<tr>
<td>( R_c ) [( \mu \Omega )]</td>
<td>891</td>
<td>883</td>
<td>889</td>
<td>887.7</td>
<td>3.4</td>
</tr>
</tbody>
</table>

### B. Sudden Discharge Test

In order to verify the effect of winding tension on electrical characteristics of the NI coil, the sudden discharge test was performed and its \( B_z \) was measured simultaneously. The test coil was charged to 30 A with a ramping rate of 10 A/s and the power supply was turned off manually after the operating current was stabilized. Fig 4 (a) shows the results of sudden discharge test of NI coil with the winding tension of 12-N, and the \( \tau \) was determined as 535, 666, 538, and 667 ms, respectively. As shown in this figure, the overall normalized \( B_z \) profiles were agreed well. Fig 4 (b) presents the results of sudden discharge test with winding tension of 20-N. The \( \tau \) of each tests were 3118, 3600, 3107, and 3353 ms, respectively. Also, the overall normalized \( B_z \) plots of NI coil with winding tension of 20-N showed similar tendency.

The calculated \( R_c \) using (2) and \( \tau \) obtained from Fig 4 were summarized in Table III and Fig. 5. The average value of \( \tau \) at the winding tension of 20-N was about 5 times higher than that at the 12-N, which leads to the average value of \( R_c \) was calculated as 783.8 \( \mu \Omega \) at 12-N winding tension and 160.2 \( \mu \Omega \) at 20-N winding tension. These results implied that the \( \tau \) and \( R_c \) was highly affected by winding tension of the NI coil. Also, we proved that the maintaining winding tension of the coil, during the fabrication, considered as an important factor, which can decide the electrical property of the NI coil. More importantly, \( R_c \) of the NI coil can be predicted from the fixed tension during the winding process because obtained \( R_c \) showed marked difference between the winding tension of 12 and 20-N.

### C. Numerical Analysis by Equivalent Circuit Model

The NI test coil was suddenly discharged after the charging at 30 A with ramping rates of 2, 6, and 10 A/s, respectively. Fig. 6 presents the experimental (filled symbols) and simulation

### Table III

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1st( [\text{ms}] )</th>
<th>2nd( [\text{ms}] )</th>
<th>3rd( [\text{ms}] )</th>
<th>4th( [\text{ms}] )</th>
<th>Avg.( [\text{ms}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau )</td>
<td>535</td>
<td>666</td>
<td>538</td>
<td>667</td>
<td>601.5</td>
</tr>
<tr>
<td>( R_c ) [( \mu \Omega )]</td>
<td>807</td>
<td>649</td>
<td>803</td>
<td>648</td>
<td>726.8</td>
</tr>
</tbody>
</table>

Fig. 5. Characteristic resistance (\( R_c \)) and decay time constant (\( \tau \)) as a function of winding tension of NI test coil.

Fig. 4. Normalized \( B_z \) vs. time functions from the sudden discharge tests of NI coil with winding tension of 12-N (a), and 20-N (b). The insets are enlarged view at the moment of sudden discharging. Note that the wind-unwind-rewind sequence was conducted in this test.
which was able to match between the normalized results, respectively. The simulation results were obtained, where the charging time constant and the consequent characteristic resistance were obtained, the first coil was rewound to form the second coil with a new winding tension of 20-N for the same tests. The experimental results showed that the overall $\tau$ at the winding tension of 20-N was about 5 times higher than that of 12-N. Equivalent circuit analyses have been used to simulate the temporal behavior of the center field in the NI coil; the calculation results agreed reasonably well with the experimental results. The results obtained to date, experimental and analytic, demonstrate the significant impact of the winding tension on the characteristic resistance of the NI coil, which implies the importance of precise estimation of the "average" turn-to-turn contact resistance to understand the time-varying responses of an NI magnet.

Fig. 6. Normalized $B_z$ vs. time functions from the charging/sudden discharging tests of NI coil with winding tension of 12-N (a), and 20-N (b). The filled and unfilled symbols represented the experimental and simulation results, respectively.

(mutually exclusive) results of normalized $B_z$. The simulation was conducted using the equivalent circuit model and (1). The specific $R_c$ value was obtained from the numerical analysis, which was able to match between the normalized $B_z$ traces of experiments results, and those of simulated ones. $R_c$ values, which were defined by $I_c$ at each ramping rate of the test coil, were summarized in Table IV. As shown in Fig. 6 and Table IV, the difference between each result was less than 3 %, which indicated that the simulation results showed good agreement with measured ones.

IV. CONCLUSION

In order to investigate the characteristic resistance ($R_c$) of no-insulation (NI) coil with respect to the winding tension, a 60-turn NI test coil was constructed and tested repetitively 4 times with a constant winding tension of 12-N. Each time, the test NI coil was unwound and rewound with the same winding tension. After the sudden discharge tests of the coil were completed, where the charging time constant and the consequent characteristic resistance were obtained, the first coil was rewound to form the second coil with a new winding tension of 20-N for the same tests. The experimental results showed that the overall $\tau$ at the winding tension of 20-N was about 5 times higher than that of 12-N. Equivalent circuit analyses have been used to simulate the temporal behavior of the center field in the NI coil; the calculation results agreed reasonably well with the experimental results. The results obtained to date, experimental and analytic, demonstrate the significant impact of the winding tension on the characteristic resistance of the NI coil, which implies the importance of precise estimation of the "average" turn-to-turn contact resistance to understand the time-varying responses of an NI magnet.

### REFERENCES


