Numerical Electromagnetic Simulation of Effective Partial-Insulation NbTi Superconducting Coil

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Abstract

The no-insulation winding technique is a promising way of enhancing the thermal stability of NbTi superconducting coils. However, it takes a long time to charge a no-insulation superconducting coil, because the time constant is relatively large. Hence, a partial-insulation winding technique was also proposed to reduce the time constant with a high thermal stability. However, the time constant of the previously proposed partial-insulation NbTi superconducting coil could not drastically be improved, and the cause was investigated using a partial-element equivalent circuit model. Therefore, in this paper, we propose a new partial-insulation structure, and the effectiveness is verified using a partial element equivalent circuit model. The results show that a relatively small time constant is achieved when charging and discharging the proposed partial-insulation NbTi superconducting coil.

Keywords: No-Insulation technique; partial-Insulation technique; superconducting magnet; PEEC simulation; thermal stability; time constant

1. Introduction

In recent years, the no-insulation (NI) technique of superconducting coil winding has been considered an effective technique. It was reported that an NI NbTi superconducting coil could improve the dynamic thermal stability compared with a conventional superconducting coil wound with an insulated wire [1]. The transport current of an NI NbTi coil can bypass and flow into the adjacent wires to prevent the coil from quenching. However, it was also reported that one problem of an NI NbTi superconducting coil was the large charging time constant; that is, it takes a long time to reach a maximum magnetic field in a charging process, as the transport current can directly flow the adjacent wires during charging. To solve this problem, a partial-insulation (PI) winding technique was proposed in [2]. The PI winding technique could decrease the bypassing current by turn-to-turn partial insulation. However, the previously proposed PI structure could not drastically improve the time constant.

Based on the background, in this paper, we propose a more effective PI structure of a NbTi superconducting coil to decrease the time constant and confirm its validity based on a partial-element equivalent circuit (PEEC) simulation [3], [4]. Moreover, by comparing the simulation results of a PI with an NI coil, the effectiveness of the proposed PI structure is established.

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2. Simulation Approach

2.1. Simulation model

Table 1 and Fig. 1(a) respectively show the major parameters and schematic view of an NI coil wound with a bare NbTi wire as a simulation model. The specifications of the NI NbTi coil are referred to [2], where the electromagnetic behavior in simulation has been already reported. The wire consists of NbTi filaments and copper stabilizer without insulation. The schematic cross-sectional view is shown in Fig. 1(b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of NbTi wire [mm]</td>
<td>0.4</td>
</tr>
<tr>
<td>Coil inner diameter (r_1) [mm]</td>
<td>101.6</td>
</tr>
<tr>
<td>Coil outer diameter (r_2) [mm]</td>
<td>105.9</td>
</tr>
<tr>
<td>Coil length (h) [mm]</td>
<td>11.2</td>
</tr>
<tr>
<td>Number of layers</td>
<td>6</td>
</tr>
<tr>
<td>Number of total turns</td>
<td>165</td>
</tr>
<tr>
<td>Calculated inductance (L_{est}) [mH]</td>
<td>5.11</td>
</tr>
</tbody>
</table>

Fig. 1. (a) The schematic view of NI coil and (b) NI NbTi wire winding.

2.2. Simulation method

A simulation in this paper is carried out by the PEEC method [3], [4]. In the PEEC method, the PI/NI winding is azimuthally divided into many wire elements, and they are represented as an equivalent circuit composed by the self and mutual inductances and the resistance of the copper stabilizer. The contact between the adjacent wires in the PI/NI coil is represented by a contact resistance [1]. Fig. 2 shows the schematic view of the PEEC model including the divided PI/NI wire elements and the contact resistances in the PI/NI coil. The inductive voltage \(V_{li}\) of the \(i\)th element and the contact resistance \(R_{ct}\) of \(j\)th element are given by:

\[
V_{li} = \sum_{k=1}^{n} M_{ik} \frac{dI_k}{dt} \quad \text{and} \quad V_{ct} = R_{ct} I_{ct}
\]

where \(V_{li}\), \(M_{ik}\), \(I_k\), \(V_{ct}\), and \(I_{ct}\) are the inductance voltage, the self/mutual inductance, the number of partial elements, the current of the inductance, the voltage across contact resistance, and the current across contact resistance, respectively. Using (1), Kirchhoff’s equations are derived, as follows:

\[
\sum_{i} V_{li} + \sum_{m} V_{om} = 0 \quad \text{and} \quad \sum_{p} I_{lp} + \sum_{q} I_{cq} = 0.
\]

In the PEEC method, (2) is solved using the backward difference method. In this paper, the contact resistance \(R_{cq}\) is given by \(R_{cq} = \rho_{ct} / l_{cq}\), where \(l_{cq}\) is the length of contact surface. The contact resistivity \(\rho_{ct}\) is assumed to be 0.013 \(\Omega\)m, that is given in [3].

Fig. 2. The schematic view of partial element equivalent circuit (PEEC) model of PI/NI coil.

(a) Solenoid coil with inductance per one layer, and (b) contact resistance.
3. Proposed PI Coil

3.1. Review of NI coil

The drawback of an NI coil is a large time constant, whereas the advantage is high thermal stability [1]. A simple electrical circuit, as shown in Fig. 3, was used for simulating the electrical behavior in [1]. The time constant \( \tau \) is represented by \( \frac{L_{\text{coil}}}{R_{\text{ct}}} \). The low constant resistance of an NI coil produces the large time constant.

As the PEEC simulation result of a charging test up to 32 A (64 mT), Fig. 4(a) shows the bypass current distribution on the cross section of an NI coil at 800 s with a ramping rate of 0.05 A/s [3]. As shown in Fig. 4(a), a large amount of bypass current to the next layer is observed in the top and bottom of the NI coil. The large bypass current results in the small contact resistance and causes the large time constant.

3.2. Proposed effective PI coil

The high bypass current increases the time constant of NI coil for charging and discharging. To reduce the time constant, a partial insulation technique has been proposed in [2] and [5]. The previously proposed PI structure has insulation along the entire length of a given layer internal to the winding. However, the resulting time constant was not drastically improved.

Based on this background, we are proposing a new PI structure. It has insulations of approximately one-fourth length (3 mm) on the top every odd layer and also on the bottom of every even layer, as shown in Fig. 5. The insulation is placed on the large-current bypath in the case of NI coil, as shown in Fig. 4(a). The effective protection of the current path increases the contact resistance and the time constant. The high thermal stability is maintained on this winding without insulation.

4. Comparison between PI and NI coil

The effectiveness of the proposed PI coil is verified by comparing the simulation results of a sudden discharge test of a PI and an NI coil, from 30 to 0 A. Fig. 6 shows the center magnetic field, where the time constant of the PI and NI coil are approximately 19 and 47 s, respectively. The proposed effective PI technique reduces to ~40% of the time constant.
Next, the center magnetic field of the charging test of these coils is shown in Fig. 7, where the current increases up to 32 A with a ramping rate of 0.05 A/s. It takes approximately 800 s and 1300 s to reach the maximum center magnetic field in the cases of the PI and NI coil, respectively. The charging time of the proposed PI coil decreases approximately 38%, compared with the NI coil.

Fig. 8 shows the bypass current and azimuthal transport current distribution in the cross section of the proposed PI coil at 800 s. The effective partial insulation at the top and bottom of the coil prevents the bypass current from flowing to the adjacent turns during charging, as shown in Fig. 8(a). As shown in Fig. 4(b), the azimuthal current in the case of the NI coil is not uniform because of the large bypass current. On the other hand, the partial insulation prevents the bypass current and results in the uniform azimuthal current, shown in Fig. 8(b).

The proposed effective PI technique is useful in decreasing the time constant. In the near future, we will confirm the validity of the effective PI technique in experiments.

![Fig. 7. Central magnetic field of proposed PI coil and NI coil when charging.](image)

![Fig. 8. Bypass and azimuthal transport current distribution of cross section of NI coil at 800 s during charging up to 32 A with 0.05 A/s, simulated by PEEC method.](image)

5. Conclusion

The NI NbTi superconducting coil and the previously proposed PI NbTi superconducting coil have a problem in that it takes a long time to reach a peak magnetic field in a charging process. This long time constant is caused by the small contact resistance, although these coils have high thermal stability. To solve the problem, we propose a new PI structure for a NbTi superconducting coil, that has partial insulation for cutting the large-bypass-current pass. We verify that the proposed PI coil can effectively decrease the time constant, compared with the NI coil, by the partial-element equivalent circuit simulation. The charging time of the proposed PI coil is shortened by approximately 38%.

In the future, we will investigate the features of the proposed PI coil by experiment. Moreover, the detailed thermal and electromagnetic behavior needs to be investigated by the PEEC method coupling with a thermal simulation.

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References


