High resolution locating of normal transitions in a high temperature superconducting coil by capacitor type voltage terminals

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Abstract. It is important to locate positions of normal transitions in a high temperature superconducting coil for identifying its design and fabrication weakness. The authors have proposed capacitor type voltage terminals as a contactless method to measure voltages of the coil windings through insulation of the windings. This method was useful for locating the positions of the normal transitions. Higher resolution of the location is achieved by attaching many terminals to the coil. Then shorter electro-conductive sheets of capacitor type voltage terminals are needed. However, the shorter sheets make the measured voltage signals small and the signals are supposed to be incorrectly measured. In this paper, the authors propose a method to achieve high resolution locating by long electro-conductive sheets of capacitor type voltage terminals. Numerical values of the measured voltage by the terminals depend on the positions of the normal transitions and therefore analysis of the values can achieve high resolution locating without increasing the number of the terminals. Through experimental results for a Bi2223 HTS coil, it was confirmed that the proposed method could achieve the high resolution locating.

1. Introduction
Locating normal transitions in high temperature superconducting (HTS) coils is important to discuss thermal stability of the coils. The authors have presented capacitor type voltage terminals as a contactless method to measure voltages of the coil windings [1-3]. References [2,3] show that the method is useful for locating the positions of the normal transitions. It is needed in order to make resolution of the location much higher that many voltage terminals are mounted on the windings, and then distance between adjacent two terminals are shortened. However, it makes the measurement system complex and makes measured voltage values small and then it is supposed to cause incorrect measurement. In this paper, the authors propose a method to achieve high resolution locating by using less voltage terminals based on the capacitor terminal method. Numerical values of the measured voltage by the terminals depend on the positions of the normal transitions and therefore analysis of the values can achieve high resolution locating without increasing the number of the terminals. Experimental results for a Bi2223 HTS coil showed that the proposed method could achieve the high resolution locating.
2. Principle of location method

Figure 1 shows an outline of the contactless voltage measurement method [1]. A pair of electrically conductive sheets is attached on the surface of an HTS coil and is connected with an outside capacitor. Then a capacitor is formed at each sheet and a voltage of the coil winding is measured as a voltage of the outside capacitor based on voltage dividing by the three capacitors. \( C_1 \) and \( C_2 \) are capacitances at the two sheets, and \( C_3 \) and \( v_c \) are respectively a capacitance and a voltage of the outside capacitor.

Figure 2 shows two states at a certain time after occurrence of the normal transitions as a 1D model on distribution of the normal zones in the HTS wire. When the normal zone occurs at (A) in Figure 2 which is between two sheets, relationship between the voltage of the HTS wire \( v_z \) and the voltage of the outside capacitor \( v_c \) is shown as follows [2].

\[
v_z = \frac{C_1 C_2 + C_1 C_3 + C_2 C_3}{C_1 C_2} v_c = \alpha v_c,
\]

where

\[
\alpha = \frac{C_1 C_2 + C_1 C_3 + C_2 C_3}{C_1 C_2}.
\]

Whereas the normal zone occurs at (B) in Figure 2 which is under the sheet, a following equation is obtained [2].

\[
\alpha v_c = v_z - \left\{ \frac{L - l - l_s}{L} r(l) + \frac{1}{L} \int_0^l r(x) \, dx \right\} i.
\]

Here, \( l_s \) is the length between the left end of the electro-conductive sheet (point “a”) and the left end of the normal zone, \( l \) is the length of the normal zone, \( L - l - l_s \) is the length between the right end of the normal zone and the right end of the sheet, \( L \) is the length of the sheet, \( r(x) \) is the resistance of the
normal zone at $x$ ($x = 0$ at the left end of the normal zone) and $i$ is a transport current through the HTS wire.

From the equations (1) and (3), the closer the position of the normal transition is the area between two sheets, the smaller the second term of the equation (3) becomes, and then the ratio of $\alpha v_c/v_Z$ increases. In case of (A), $\alpha v_c/v_Z$ becomes 100 % and in case of (B) $\alpha v_c/v_Z$ becomes smaller than 100 % with dependence of the position of the normal transition. Therefore locating normal transitions can be achieved by measuring the ratio of $\alpha v_c/v_Z$. Based on this method, high resolution locating can be achieved by less electro-conductive sheets of capacitor type voltage terminals. Moreover less sheets can actualize long sheets to make measured voltages larger for more correct measurement.

3. Experiments for a Bi2223 HTS coil

3.1. Experimental setup

Experiments on the locating of the normal transitions were carried out for a Bi2223 HTS coil. Figure 3 and Table 1 show an outline of a test Bi2223 HTS coil and its specifications, respectively. AC current of 60 Hz and 150 Apeak was supplied to the HTS coil which was cooled in liquid nitrogen. The normal transitions were caused by four heaters mounted on the positions I to IV of the 2nd turn of the HTS coil shown in Figure 4. Voltage terminals except the capacitor terminal were soldered to the windings to confirm the positions of the normal transitions and measured voltages by the terminals were $v_1$ to $v_{11}$. Distances between adjacent two terminals were 30 mm except 60 mm for $v_6$. Table 2 shows specifications of the capacitors.

The other capacitor terminal was attached on the 7th turn of the HTS coil. A voltage of the 2nd turn $v_{c1}$ had an inductive voltage and therefore it was cancelled by subtracting a voltage of the 7th turn $v_{c2}$ from $v_{c1}$ as follows.

$$v_{cd} = v_{c1} - k_c v_{c2}.$$  \hspace{1cm} (4)

$k_c$ was a ratio of an inductive voltage in $v_{c1}$ to that in $v_{c2}$ in superconducting state. $v_{cd}$ had some electromagnetic noise and therefore it was transformed into an active power and filtered shown as following equations to locate the positions of the normal transitions more precisely.

$$P_c = v_{cd} i,$$  \hspace{1cm} (5)

$$P'_c = \frac{P_c}{1 + sT}.$$  \hspace{1cm} (6)
Figure 3. Outline of a test Bi2223 HTS coil.

Table 1. Specifications of HTS coil

| Specification                  | Value |
|--------------------------------|-------|
| Inner diameter (mm)            | 140   |
| Outer diameter (mm)            | 150   |
| Height (mm)                    | 95    |
| Number of turns                | 7.5   |
| $I_c$ (at 77 K, self-field) (A)| 189   |

Figure 4. Attached voltages terminals and heaters.

Table 2. Specifications of capacitors

| Description                                      | Value |
|--------------------------------------------------|-------|
| Outside capacitors : $C_{s1}$ and $C_{s2}$ (nF) | 100   |
| Electro-conductive sheet capacitors              |       |
| : $C_1$ (nF)                                    | 0.231 |
| : $C_2$ (nF)                                    | 0.279 |
| : $C_3$ (nF)                                    | 0.276 |
| : $C_4$ (nF)                                    | 0.267 |
| Length of the sheets (mm)                        | 150   |
| Width of the sheets (mm)                         | 4.2   |
| Distance between adjacent two sheets (mm)        | 60    |

Equation (6) is expressed by Laplace transform and $T$ is a time constant of the filter. As well as the inductive voltage in $v_c$, that in $v_z$ is removed resulting in $v_{zd}$. As the results, the ratio of $\alpha v_{cd}/v_{zd}$ was shown as a following equation.
\[
\frac{\alpha v_{Cd}}{v_{zd}} = \frac{\alpha v_{Cd i}}{v_{zd i}} = \frac{\alpha P_c}{v_{zd i}} = \frac{\alpha P'_c}{(v_{zd i})^*}.
\]  
(7)

\( (v_{zd i})^* \) means filtered \( v_{zd i} \).

3.2. Experimental results

Figures 5-8 show experimental results for the occurrence of the normal transitions at I-IV, respectively. (a) and (b) in each figure were shown by root mean square values. (a) in each figure shows the voltages of the areas with the normal zones. It was found that the each normal transition occurred at the position of the each heater and the normal zone propagated into its adjacent areas. (b) in each figure shows \( v_{zd} \) and (c) shows active power signals \( P'_c \).

By using the \( v_{zd} \)s and the \( P'_c \)s, the each ratio of \( \alpha v_{Cd}/v_{zd} \) was calculated for the normal zone size of 30 mm in each case. For example, in case of II, following calculations were carried out.

- Experimental value of equation (7)
  - Normal zone size became 30 mm at 15.5 s when \( v_4 \) and \( v_6 \) started to increase as shown in Figure 6 (a).
  - Based on the equation (7), experimental value of \( \alpha v_{Cd}/v_{zd} \) was calculated from the \( v_{zd} \) and \( P'_c \) which were values at 15.5 s in Figures 6 (b) and (c), respectively. \( i = 120/\sqrt{2} \).
  - The experimental value was normalized by \( \alpha v_{Cd}/v_{zd} \) measured in case of I in order to suppress measurement errors.

- Theoretical value of equation (3)
  - Equation (3) was transformed into following one.

\[
\frac{\alpha v_{Cd}}{v_{zd}} = 1 - \frac{1}{v_{zd}} \left\{ \frac{L - l - l_s}{L} r(l) - \frac{1}{L} \int_0^l r(x) dx \right\} i.
\]  
(8)

- \( r(x) \) was assumed to have a liner resistivity for \( x \) and then the equation (8) could be derived as

\[
\frac{\alpha v_{Cd}}{v_{zd}} = \frac{l + 2l_s}{2L}.
\]  
(9)

- In case of II, the theoretical value was obtained for \( l = 30 \) mm and \( l_s = 120 \) mm.

Table 3 shows the calculation results. Experimental results were in good agreement with the theoretical values. The results show that the proposed method can locate the position of the normal zone for the normal zone size of 30 mm. However, it was found from other experimental results that it was hard to locate the position of shorter normal zone than 30 mm. In case of IV, the value of \( \alpha v_{Cd}/v_{zd} \) becomes very small value according to equation (9) for \( l_s = 0 \). Therefore \( P'_c \) became a low S/N ratio.

![Figure 5](image_url)

(a) Voltages of the areas where the normal transition occurred (\( v_5, v_6, v_7 \))

\( v_{zd} \) and \( P'_c \) at I.

\textbf{Figure 5.} Experimental results for the normal transition at I.
Figure 6. Experimental results for the normal transition at II.

(a) Voltages of the areas with the normal zones ($v_4$, $v_5$, $v_6$)

Figure 7. Experimental results for the normal transition at III.

(a) Voltages of the areas with the normal zones ($v_2$, $v_3$, $v_4$)

Figure 8. Experimental results for the normal transition at IV.

(a) Voltages of the areas with the normal zones ($v_1$, $v_2$)
signal for the shorter normal zone in case of IV and it was hard to be measured correctly. The authors will study on locating for the shorter normal zone especially for case IV hereafter.

In these experiments, many voltage terminals were soldered on the superconducting wire for verifying the principle of the proposed method, however, only two soldered terminals on the both ends of the HTS coil are needed for $v_Z$ in actual use. Then the inductive voltage in $v_Z$ is removed by a cancel coil [4].

4. Conclusions
In this paper, the authors proposed a method to achieve high resolution locating of the normal transitions in the HTS coil by less and long electro-conductive sheets of capacitor type voltage terminals. The proposed method achieves the location by calculating a ratio of a voltage of a capacitor voltage terminal to a voltage of the HTS coil wire. Experimental results for a Bi2223 HTS coil showed the proposed method could locate the position of the normal zone of 30 mm. The authors will study on higher resolution method.

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References
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