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Locating of normal transitions in a Bi2223 high temperature superconducting coil by using capacitor type voltage terminals and the active power method

N Nanato, K Okura, H Kumagai, H Aoyama

Graduate School of Natural Science and Technology, Okayama University,
3-1-1, Tsushima Naka, Kita-ku, Okayama, 700-8530, Japan

nanato@okayama-u.ac.jp

Abstract. It is important to locate positions of normal transitions in a high temperature superconducting (HTS) coil for identifying its design and fabrication weakness. In this paper, the authors propose a locating method by using capacitor type voltage terminals and the active power method. The former is a method to measure voltage in a HTS coil without electric contact and the latter is a method to detect the normal transitions by measuring active power dissipated in the coil. Combination of the two methods can achieve precise location of the normal transitions. The authors show usefulness of the method through experimental results for a Bi2223 HTS coil.

1. Introduction

AC HTS power applications have been developed in recent years such as motors and transformers [1]. For identifying their safety design and fabrication weakness, it is important to understand behaviors of HTS coils after occurrence of superconducting to normal transitions. Locating the normal transitions is very useful to understand the behaviors. Generally, many voltage taps are placed directly on the coil for the purpose to locate the normal transitions. However the placement of the taps may cause serious problems such as high voltage sparks because insulations of the coil has to be removed to solder the taps on the coil. The authors have presented capacitor type voltage terminals as a method to measure voltages in the coil without electric contact [2]. Reference [3] shows that this method is useful for locating the positions of the normal transitions. In this paper, the authors propose a more precise location method using the capacitor type voltage terminals and the active power method [4]. The latter method can recognize polarity of the measured voltage by the former method and the polarity contributes to make the location method more precise. Also, temperature in the normal areas has to be kept under allowable temperature of the coil windings to avoid their deterioration due to excessive heating in the occurrence of the normal transitions. The active power method is originally a quench detection / protection method for a superconducting coil [4] and therefore the proposed method can safely locate the positions of the normal transitions. As experimental results for a Bi2223 HTS coil, it was found that the proposed method enabled to locate the positions of the normal transitions without exceeding the allowable temperature more precisely than the conventional method.

2. Principle of location method

As shown in Figure 1, a pair of electrically conductive sheets is attached on the surface of an HTS coil

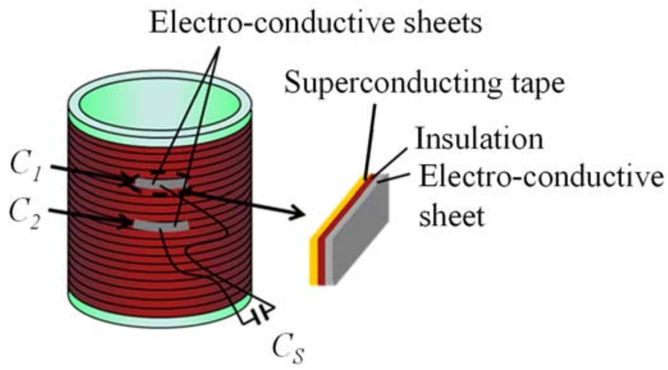

Figure 1. Capacitor type voltage terminals.

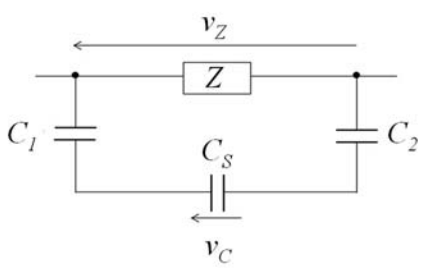

Figure 2. An equivalent circuit.

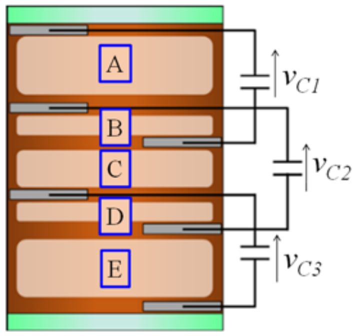

Figure 3. An outline of an HTS coil with three voltage terminals.

and is connected with an external capacitor. Then insulation exists between an HTS wire and the each sheet as shown in right hand side of Figure 1 and therefore a capacitor is formed at the each sheet. Its equivalent circuit is shown as Figure 2. Z and v_z are respectively an impedance and a voltage between the two sheets, C_1 and C_2 are capacitances at the two sheets, and C_s and v_c are respectively a capacitance and a voltage of the external capacitor. Then following equation is derived.

$$v_z = \frac{C_1C_2 + C_1C_s + C_2C_s}{C_1C_2} v_c = \alpha v_c. \qquad (1)$$

The equation shows a voltage v_z in the HTS coil can be measured without electric contact by measuring v_c. Also, the electro-conductive sheets are adhesive aluminum tapes. Each sheet has thickness of 0.05 mm and its adhesive agent is also electrically conductive. The external capacitor was connected to the electro-conductive sheet by soldering.

Figure 3 shows an outline of an HTS coil which three pairs of electrically conductive sheets are attached on. Then, principle of the location method is explained as follows. v_{c1}, v_{c2} and v_{c3} are shown as following equations.

$$\alpha_1 v_{c1} = L_1 \frac{di}{dt}, \qquad (2)$$

$$\alpha_2 v_{c2} = L_2 \frac{di}{dt}, \qquad (3)$$

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$$\alpha_3 v_{c3} = L_3 \frac{di}{dt}, \tag{4}$$

where i is a transport current through the coil and L_1, L_2 and L_3 are self-inductances between the two sheets for measuring v_{c1}, v_{c2} and v_{c3}, respectively. In actual measurement, all the sheets are attached so that all of α_1, α_2 and α_3 are the same α. In order to detect the normal transitions, the inductive voltages have to be canceled. Following equations achieve the cancellation.

$$v_{12} = \alpha(v_{c1} - k_{12} v_{c2}), \tag{5}$$
$$v_{23} = \alpha(v_{c2} - k_{23} v_{c3}), \tag{6}$$
$$v_{31} = \alpha(v_{c3} - k_{31} v_{c1}), \tag{7}$$

where

$$k_{12} = \frac{L_1}{L_2}, \tag{8}$$
$$k_{23} = \frac{L_2}{L_3}, \tag{9}$$
$$k_{31} = \frac{L_3}{L_1}. \tag{10}$$

In actual measurement, all the sheets are attached so that all of k_{12}, k_{23} and k_{31} are set to 1. This means $L_1 = L_2 = L_3$. Then $v_{12} = v_{23} = v_{31} = 0$ in a superconducting state. On the other hand, for example, when a normal transition occurs in area "A" shown in Figure 3, only v_{c1} has a resistive voltage and then following equations are derived.

$$v_{12} = \alpha(v_{c1} - k_{12} v_{c2}) = \alpha(ri + L_1 \frac{di}{dt} - k_{12} L_2 \frac{di}{dt}) = \alpha ri, \tag{11}$$
$$v_{23} = \alpha(v_{c2} - k_{23} v_{c3}) = \alpha(L_2 \frac{di}{dt} - k_{23} L_3 \frac{di}{dt}) = 0, \tag{12}$$
$$v_{31} = \alpha(v_{c3} - k_{31} v_{c1}) = \alpha \left\{ L_3 \frac{di}{dt} - k_{31} \left(ri + L_1 \frac{di}{dt} \right) \right\} = -\alpha ri, \tag{13}$$

where r is a resistance of the normal area. v_{12} is a resistive voltage with same polarity as the current i and v_{31} has a reversed polarity to the polarity of v_{12}. The polarity can be recognized by transforming the voltages into active powers shown as following equations.

$$P_{12} = \alpha(v_{c1} - k_{12} v_{c2}) i = \alpha ri^2 \rightarrow \text{Averaging} \rightarrow P'_{12} = \alpha r I^2 > 0, \tag{14}$$
$$P_{23} = \alpha(v_{c2} - k_{23} v_{c3}) i = 0 \rightarrow \text{Averaging} \rightarrow P'_{23} = 0, \tag{15}$$
$$P_{31} = \alpha(v_{c3} - k_{31} v_{c1}) i = -\alpha ri^2 \rightarrow \text{Averaging} \rightarrow P'_{31} = -\alpha r I^2 < 0, \tag{16}$$

where I is a root mean square value of i. According to the above results, when a normal transition occurs in area "A" shown in Figure. 3, $P'_{12} > 0$, $P'_{23} = 0$ and $P'_{31} < 0$.
When a normal transition occurs at "B", v_{c1} and v_{c2} have same resistive voltage and v_{c3} has no resistive one. Then

$$P_{12} = \alpha(v_{c1} - k_{12} v_{c2}) i = \alpha(ri^2 - ri^2) = 0 \rightarrow \text{Averaging} \rightarrow P'_{12} = 0, \tag{17}$$
$$P_{23} = \alpha(v_{c2} - k_{23} v_{c3}) i = \alpha ri^2 \rightarrow \text{Averaging} \rightarrow P'_{23} = \alpha r I^2 > 0, \tag{18}$$

$$P_{31} = \alpha(v_{c3} - k_{31}v_{c1})i = -\alpha r i^2 \;\rightarrow \text{Averaging} \rightarrow P'_{31} = -\alpha r I^2 < 0. \qquad (19)$$

Table 1. Logic of locating the positions of the normal transitions.

The place of the occurrence of normal transitions	A	B	C	D	E
P'_{12}	+	0	–	–	0
P'_{23}	0	+	+	0	–
P'_{31}	–	–	0	+	–

All cases of the normal transitions are summarized in Table 1.
The areas of the normal transitions can be located by the logic. Higher resolution of the location method can be achieved by increasing the number of pairs of electrically conductive sheets.

3. Locating test for a Bi2223 HTS coil

3.1 Experimental setup
Figure 4 shows a photograph of a test Bi2223 HTS coil. Table 2 shows specifications of the HTS coil, which is a solenoidal coil wound with $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi2223) tape on Glass Fiber Reinforced Plastic bobbin. Table 3 shows specifications of capacitors. Three voltage terminals were attached on the HTS coil so that v_{c1} was a voltage across the 1st to 4th turn, v_{c2} was 3rd to 7th turn and v_{c3} was 6th to 9th turn. Figure.5 shows an experimental circuit. AC current of 60 Hz and 110 A_{peak} was supplied to the HTS coil which was cooled in liquid nitrogen. The normal transitions were caused by heaters mounted on five areas A – E of the HTS coil shown in Figure 3. Each heater has height of 4.2mm and width of 12mm. The thyristor switch is turned off to protect the HTS coil from excessive heating in the normal zone when any of positive active powers such as equations (14) and (18) become larger than a specified positive threshold or any of negative ones such as equations (16) and (19) become smaller than a specified negative one. The specified threshold is decided by coupling of 1D heat equation and electric circuit equation [5].

3.2 Experimental results
Figure 6 shows experimental results for the occurrence of the normal transition at “A”. Figures 6 (a), (b) and (c) show the active power signals. P'_{12} increased from about 13 s (positive), P'_{23} was almost constant (zero) and P'_{31} decreased from about 13 s (negative). These results agreed well with the logic shown in Table 1.

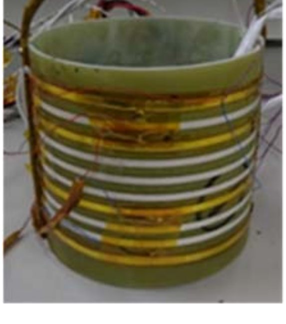


Figure 4. A photograph of the HTS coil.

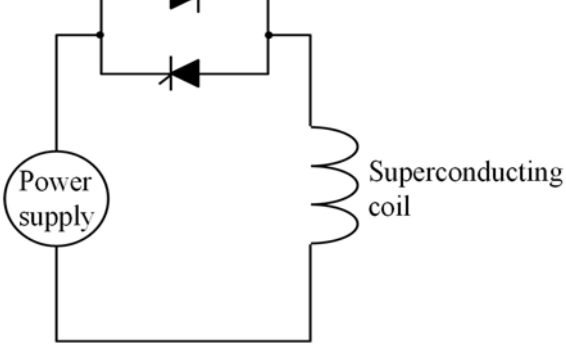


Figure 5. An experimental circuit.

Table 2. Specifications of an HTS coil.

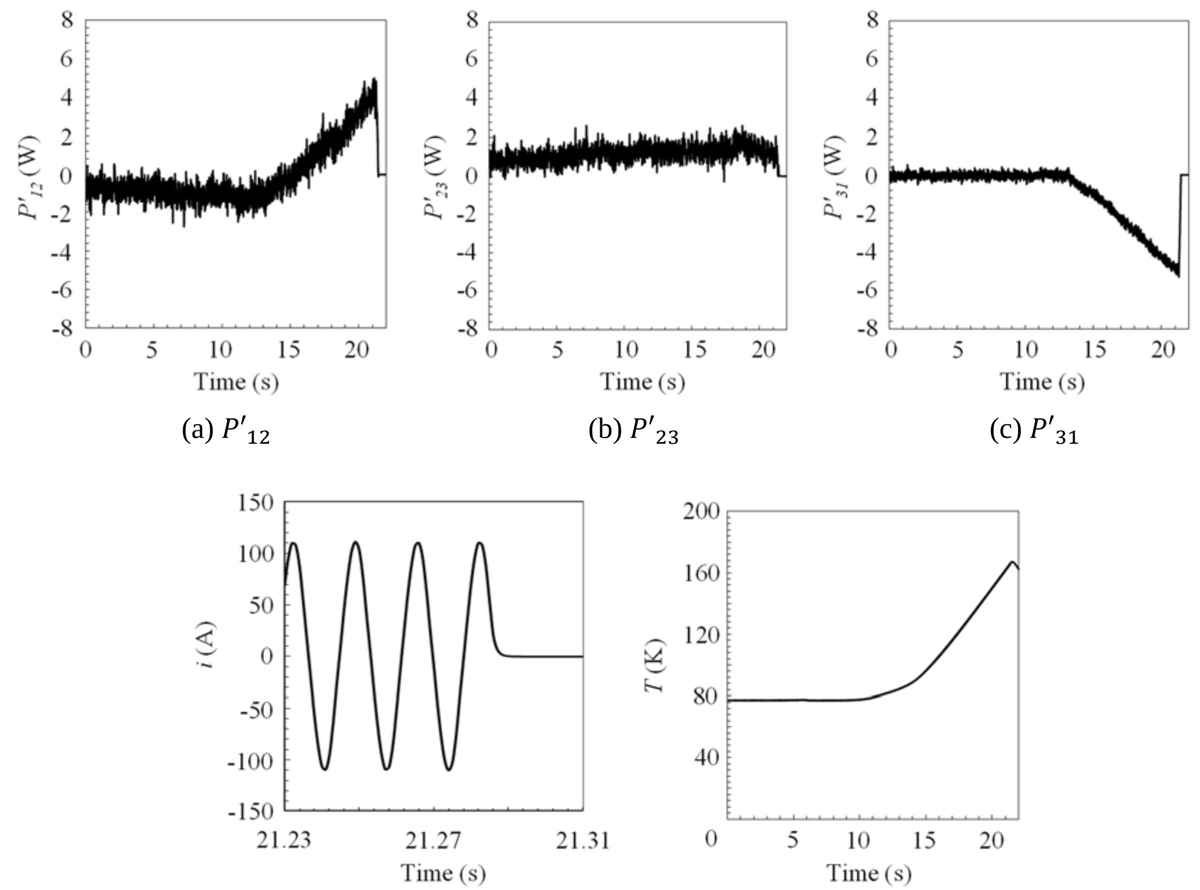
Inner diameter (mm)	147
Outer diameter (mm)	150
Height (mm)	105
Number of turns	9.5
Inductance (μH)	11.9
I_C (at 77 K, self-field)(A)	193.5

Table 3. Specifications of capacitors.

External capacitors : C_{s1}, C_{s2}, C_{s3} (nF)		100
Electro-conductive sheet capacitors	: C_1 (nF)	0.275
	: C_2 (nF)	0.270
	: C_3 (nF)	0.282
	: C_4 (nF)	0.275
	: C_5 (nF)	0.267
	: C_6 (nF)	0.272

Figure 6 (d) shows the current through the circuit. The current was shut off at 21.29 s because the active power P'_{12} reached a specified threshold of "5 W". Figure 6 (e) shows temperature of the normal zone. The temperature increased after the normal transition and then it decreased after the shutdown of the current. Its maximum value is 167 K which is allowable temperature for the test coil [6].

Figure 7 shows experimental results for the occurrence of the normal transition at "B". Figures 7 (a), (b) and (c) show the active power signals. P'_{12} was almost constant (zero), P'_{23} increased from about 10 s (positive) and P'_{31} decreased from about 10 s (negative). These results also agreed well with the logic shown in Table 1. Figure 7 (d) shows the current through the circuit and Figure 7 (e) shows temperature of the normal zone. As well as Figure 6 (e), maximum temperature 134 K of the normal zone was under the allowable temperature.



(a) P'_{12} (b) P'_{23} (c) P'_{31}

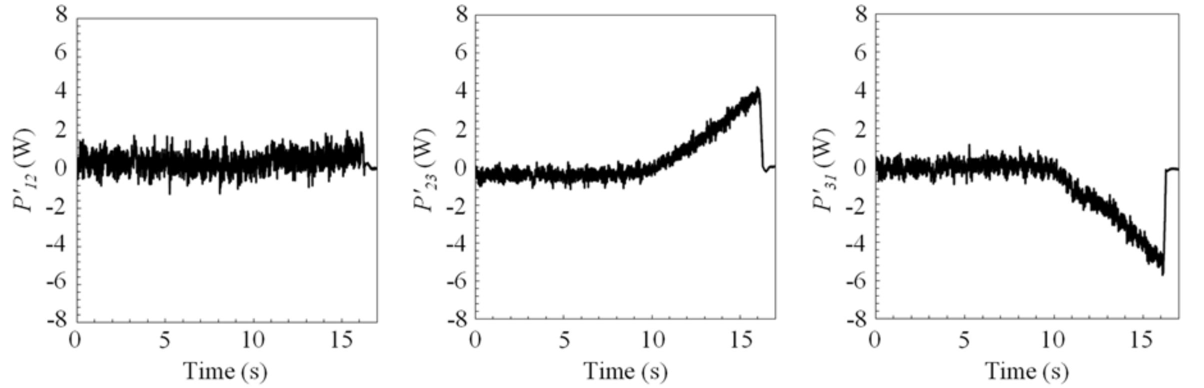
(d) Current (enlarged view) (e) Temperature

Figure 6. Experimental results for the normal transition at "A".

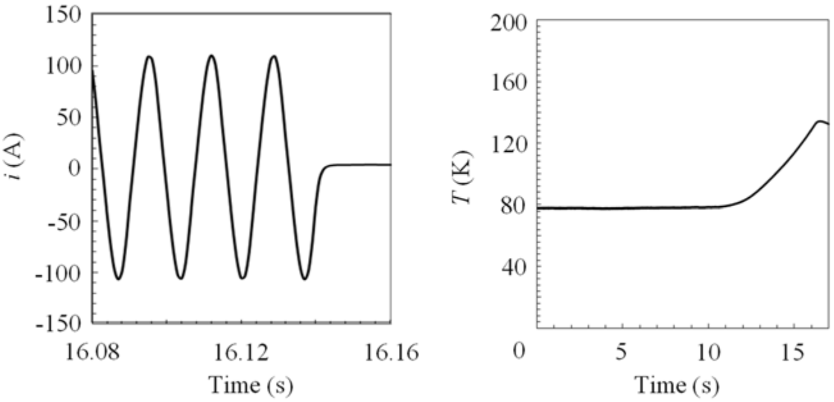
From the test results, it was verified that the proposed method could locate the positions of the normal transitions so as to suppress the temperature of the normal zone under the allowable temperature.

4. Conclusions

In this paper, the authors proposed a method to locate normal transitions in HTS coils by using capacitor type voltage terminals and the active power method. The proposed method can locate the positions of the normal transitions without electric contact so as to suppress the temperature of the normal zone under the allowable temperature. The experimental results showed validity of the method for a Bi2223 HTS coil. Hereafter the authors will study higher resolution of the method.



(a) P'_{12} (b) P'_{23} (c) P'_{31}



(d) Current (enlarged view) (e) Temperature

Figure 7. Experimental results for the normal transition at "B".

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