

Identification of Normal Transition in a Bundle HTS Cable Used for an HTS Transformer^{*)}

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We have been developing an AC power source with a high-temperature superconducting (HTS) transformer that is small and can supply a large AC current. The HTS transformer needs a detection system of normal transition for high reliability. We have proposed the active power method as the detection system. The system enabled early detection of the normal transition in a secondary coil of the transformer, which was wound with a bundle of some HTS tapes. However, we could not identify the normally transitioned HTS tape in bundle conductors using the conventional method. Therefore, in this paper, we propose a method to identify the normally transitioned HTS tape in the bundle conductor by improving the active power method. The improved method is based on measuring the active power in each HTS tape in the bundle conductor. Experiment results show that the proposed method works successfully for early and accurate identification under outputting a secondary maximum current of 1 kA_{peak} at 1 kHz.

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1. Introduction

An experimental power source with a large current capacity is needed for measuring the electromagnetic characteristics of a short sample superconductor used in a superconducting coil such as a helical coil [1]. Conventional sources are very large and heavy and therefore miniaturizing the sources is paramount for convenient use. We have been studying a power source with a high-temperature superconducting (HTS) transformer that is small and light and can supply a large current [2–4]. The supply has an HTS transformer of which the secondary coil is wound with a bundle of HTS tapes, which are insulated from each other, for securing large current capacity. In addition, we have reported the active power method as the detection system of the normal transition so far [5]. For safe operation of the transformer, the normal transition in the transformer must be detected without delay because the normal transition causes serious accidents, such as degradation or burnout of the superconducting wire [6,7]. Our previously proposed method can detect the normal transition early, even when the normal transition occurs at only one tape in a bundle of insulated HTS tapes [5]. However, we could not identify the normally transitioned HTS tape in the bundle conductor. If the identification is achieved, causes of the normal transition can be discovered. Therefore, in

this paper, we propose an improved method for identifying the normally transitioned HTS tape in the bundle conductor. The method is based on measuring the active power of each HTS tape in real time. We show the applicability of the proposed method to the HTS transformer via experiments. Section 2 describes the newly proposed method for a bundle superconductor that consists of some insulated HTS tapes. Section 3 describes experiments to verify the method for the HTS transformer and discussions on the results.

2. Identification Method of the Normal Transition in a Bundle Superconductor

Figure 1 shows an equivalent circuit converted to the primary side of an HTS transformer of which the secondary coil is wound with a bundle conductor, and Table 1 lists parameters in Fig. 1. In Table 1, prime means conversion to the primary side, for example, $i'_{21} = i_{21}/a$ (a : turn ratio). The primary and secondary coils consist of HTS tapes. The number of secondary HTS tapes is nine, corresponding to the experiments described in Section 3. Each of the nine secondary windings is electrically isolated and connected in parallel. The parallel HTS tapes in Fig. 1 are tapes 1 ~ 9 from the top. It is assumed that the normal transition occurs in only tape 1. Then the following equation is obtained.

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$$v_1 - v'_{21} = \Delta v_1 = r_{1AC}i_1 + r'_{21AC}i'_{21} + r'_{21}i'_{21} + l_1 di_1/dt + l'_{21} di'_{21}/dt. \quad (1)$$

Since voltages of the cancel coils satisfy $v_{cc1} = m_1 di_1/dt$ and $v_{cc21} = m_{21} di'_{21}/dt$, the resistive voltage is derived as follows:

$$\begin{aligned} \Delta v'_1 &= \Delta v_1 - k_1 v_{cc1} - k_{21} v_{cc21} \\ &= r_{1AC}i_1 + r'_{21AC}i'_{21} + r'_{21}i'_{21}, \end{aligned} \quad (2)$$

where $k_1 = l_1/m_1$, l'_{21}/m_{21} .

Multiplying Equation (2) by flowing current through tape 1, the signal becomes an active power.

$$P_1 = \Delta v'_1 i'_{21}, \quad (3)$$

$$P'_1 = P_1/(1 + sT). \quad (4)$$

Equation (4) shows a filtered signal by a primary lowpass filter for enhancing SN ratio, which is expressed by the

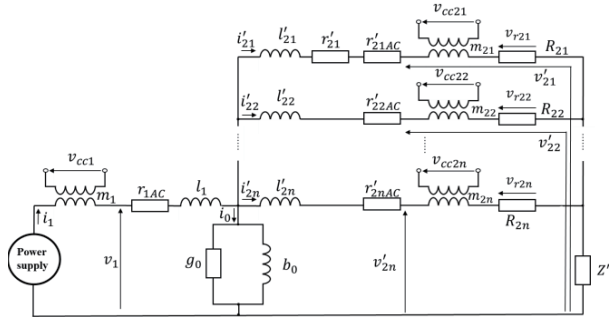


Fig. 1 An equivalent circuit converted to a primary side of an HTS transformer.

Table 1 Parameters in Fig. 1.

v_1	primary voltage	v'_{2n}	each secondary voltage of each secondary tape
i_1	primary current	i'_{2n}	each secondary current of each secondary tape
l_1	primary leakage inductance	l'_{2n}	each secondary leakage inductance for each secondary tape
v_{cc1}	voltage of the primary side cancel coil	v_{cc2n}	each voltage of each secondary side cancel coil
m_1	mutual inductance of the primary side cancel coil	m_{2n}	each mutual inductance of the secondary side cancel coil
r_{1AC}	equivalent resistance of the AC losses in the primary winding	r'_{2nAC}	equivalent resistance of the AC losses in the secondary winding
v_{r2n}	each voltage of each current lead	R_{2n}	each resistance of each current lead
Z'	load impedance	r'_{21}	resistance of the normal area of tape 1

* n is the number of each tape ($n = 1 \sim 9$).

Laplace transform, and T is a time constant of the filter. When normal transitions occur, P'_1 increases rapidly because the resistive voltage of $r'_{21}i'_{21}$ is generated, therefore P'_1 is a detection parameter of the normal transition. The active power of each secondary tape ($P'_1 \sim P'_9$) is measured, resulting in identifying the normally transited HTS tape.

3. Experiments

3.1 Experimental setup

To verify the proposed method, we conducted experiments for identifying the normally transited HTS tape in the HTS transformer. Specifications of the test transformer are listed in Table 2. The transformer can output a maximum current of 1 kApeak at 1 kHz. Figure 2 shows images of the transformer, whereas Fig. 3 shows the configuration of the transformer [2]. The primary and secondary coils consist of 4.2 mm-wide silver-sheathed BSCCO tapes (DI-BSCCO Type H, Sumitomo Electric Industries, Ltd.). To reduce leakage inductances, the secondary winding was sandwiched by the primary winding to minimize gaps between the primary and secondary windings [2]. The secondary coil was wound with a bundle of nine insulated HTS tapes, consisting of vertically stacked nine single-layer coils [2]. The active power is calculated by measuring each secondary voltage v'_{2n} and current i_{2n} , and cancel coil voltage v_{cc2n} . The secondary voltage is measured by voltage terminals of each HTS tape and, the current is

Table 2 Specifications of the transformer.

	Primary coil	Secondary coil
Inner diameter (mm)		89.0
Outer diameter (mm)		90.4
Height (mm)	95	95
Number of Turns	40	1
Self-inductance (mH)	34.0	0.116
Mutual-inductance (mH)		0.85
I_C (A)	159	1990

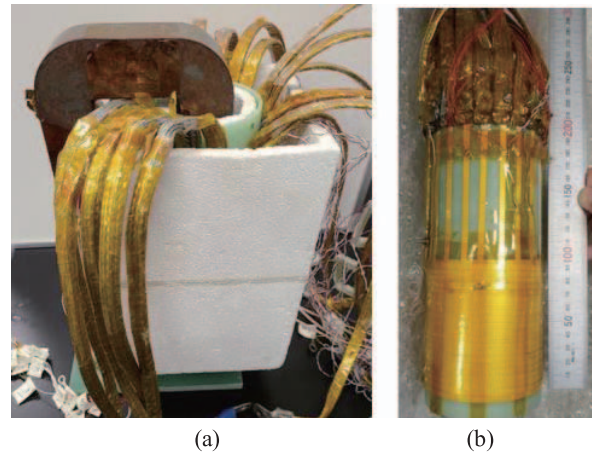


Fig. 2 HTS transformer: (a) a fully assembled transformer, (b) the windings of the transformer.

measured by a four-probe method to a current lead of each HTS tape. The cancel coil voltage is measured by a small air-core transformer (Fig. 4). Magnetic flux from a current lead of the primary coil penetrates a secondary rectangular coil, and then the open-circuit voltage of the secondary coil is v_{cc2n} . To calculate the active power in real time, calculators by analog electronic circuits were fabricated. Figure 5 shows a circuit of the calculator, consisting of operation amplifiers, ICs (integrated circuits) and passive elements.

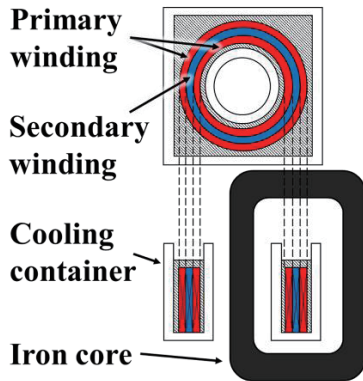


Fig. 3 HTS transformer configuration.

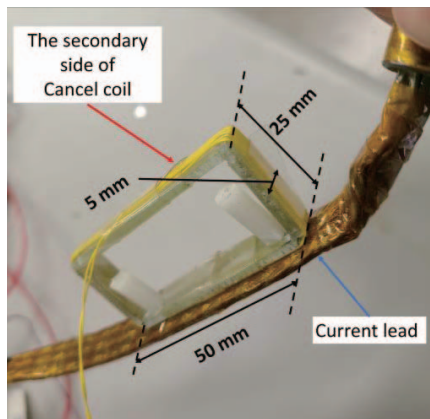


Fig. 4 The cancel coil.

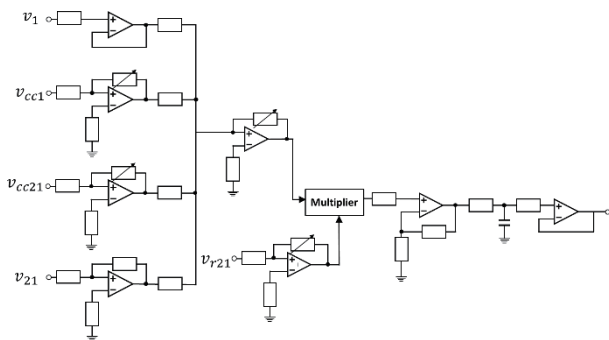


Fig. 5 A circuit of the active power calculator.

3.2 Experiments

We performed experiments on identifying the normal transition in the secondary coil to verify the newly proposed method. The transformer was cooled at 77 K by liquid nitrogen in a cooling container (Figs. 2 and 3). The normal transition was induced by a heater mounted on tape 4 during outputting of the secondary current of 1 kA_{peak} at 1 kHz. Temperature waveforms of the tapes and all active power signals ($P'_1 \sim P'_9$) before and after the normal transition were measured.

3.3 Results and discussions

Figure 6 shows experiment results for the normal transition at tape 4. Figure 6(a) is temperature waveforms of four tapes, which are tape 2 ~ 5. The temperature of tape 4 increased gradually by the mounted heater, and the temperatures of other tapes were constantly 77 K. Owing to the lack of measurement terminals of our data logger, the temperatures of the four tapes were measured as functions of time in real time. However, we confirmed that the temperatures of other tapes were constantly 77 K by the other

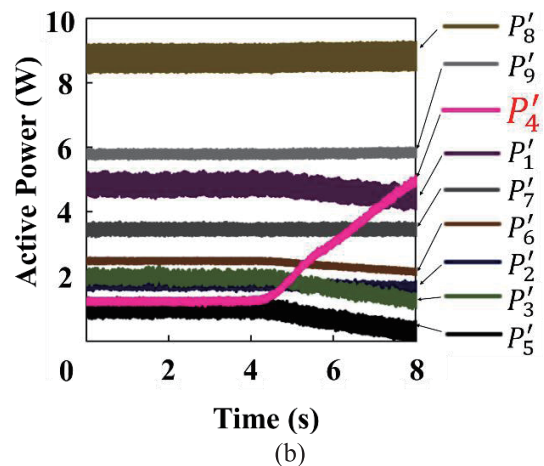
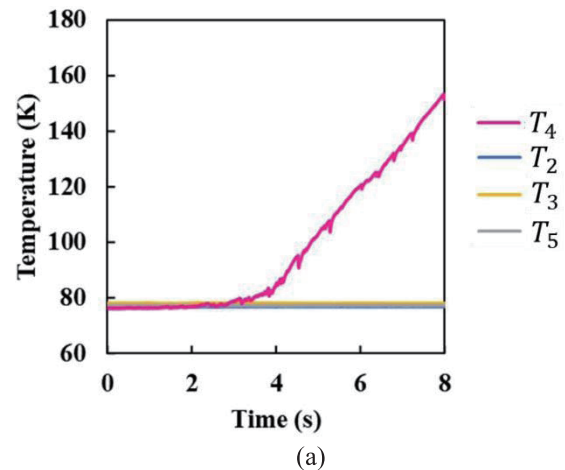


Fig. 6 Experiment results for: (a) the temperature of the normal area of some tapes including tape 4; (b) all active power in the secondary HTS tapes.

Table 3 The transport current of each HTS tape.

i_{21}	170 A _{peak}	i_{26}	83 A _{peak}
i_{22}	90 A _{peak}	i_{27}	112 A _{peak}
i_{23}	80 A _{peak}	i_{28}	182 A _{peak}
i_{24}	65 A _{peak}	i_{29}	170 A _{peak}
i_{25}	63 A _{peak}		

measurement tool. Figure 6(b) shows all active powers ($P'_1 \sim P'_9$) in the secondary HTS tapes. Only P'_4 , colored in pink, increased gradually. This means only tape 4 was normally transitioned. The results show that the proposed method identified the normally transitioned tape, which means that the method can detect the normal transition of the bundle conductor of HTS tapes early [5].

All active powers were different from each other before 4 s (when the normal transition occurred) as shown in Fig. 6(b). The difference is due to different AC loss [8] in each HTS tape and signals due to a few effects of mutual inductances among tapes. The proposed method measures those signals and the active power generated by the normal transitions. To investigate the active power signals, the transport current of each secondary tape was measured. Table 3 shows the measurement results. The order of the magnitude of the active power was almost consistent with that of the current. The differences among the currents are due to drift by different inductance of each tape and joint resistance of the terminals for the coil winding. In Fig. 6(b), some of the active power values gradually decreased, and the others were almost constant after 4 s. This is supposed to be due to the change in AC losses and some mutual voltages by current-sharing after the normal transition. In the future, we will investigate the trend of the active powers.

4. Conclusion

The identification method of the normally transitioned HTS tape in the secondary coil of the HTS transformer that was wound with a bundle of some HTS tapes was de-

scribed. The method was based on the measurement of the active power in each HTS tape. We conducted the experiments for the HTS transformer and showed the feasibility of identifying the normally transitioned HTS tape as well as detecting the normal transition early.

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