Early Detection of Normal Transitions in a High Temperature Superconducting Transformer Wound with a Plurality of HTS Tapes Using the Active Power Method

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Abstract. The authors have been developing an AC power source with a high temperature superconducting (HTS) transformer which is small in size and can supply large AC current. The HTS transformer needs a detection system of normal transitions for high reliability. The authors have reported the active power method as the detection system. However, the conventional method could not detect early the normal transition in a secondary coil of the transformer which was wound with a bundle of some HTS tapes since resistive voltage in the normal area is too small due to current sharing among the HTS tapes. In this paper, the authors propose a method to detect the normal transitions in the bundle conductor by improving the active power method. The early and correct detection can be achieved by measuring each active power of each HTS tape. In order to measure the active power, current leads are attached independently to all the HTS tapes. The current leads enable to measure the resistive voltage in each HTS tape, and each active power can be measured. The proposed method works well when even one of secondary tapes transits to the normal conducting state. Experimental results show the usefulness of the proposed method.

1. Introduction
The authors have reported the active power method as the detection system of the normal transitions so far [1, 2]. The authors also have presented a small and lightweight AC current supply to grasp current conduction characteristics of an HTS sample tape [1-3]. The supply has an HTS transformer of which secondary coil is wound with a bundle of some HTS tapes [1-3]. For safe operation of the transformer, normal transitions in the transformer must be detected without any delay. However, resistive voltages due to the normal transitions become very small in the bundle wire by current sharing among the HTS tapes. Therefore the normal transitions in the secondary coil are difficult to be detected by the conventional active power method. In this paper, the authors propose an improved method to detect the normal transitions in the secondary coil. If the active power consumed in each secondary tape can be measured, the normal transitions in the secondary coil can be detected regardless of the current sharing. In order to achieve the measurement, secondary current leads are connected independently to all secondary tapes. The current leads enable to measure the voltage of each tape. The active power consumed in each tape can be detected by using the voltage of each tape. The authors show its usefulness through experiments for a hybrid HTS transformer [2] as a test sample.
2. Detection method of normal transitions in a bundle superconductor

Figure 1 shows an equivalent circuit converted to a primary side of a hybrid HTS transformer of which primary coil is a copper coil and secondary coil is wound with a bundle of HTS tapes, and Table 1 shows parameters in the figure. Number of the secondary HTS tapes is two for simplification. In the conventional active power method, the voltage signal “$v_{SC1} - v'_{SC2}$” is calculated to detect the normal transitions [2]. When only one secondary tape transits to the normal state, the current through the tape decreases by current sharing. Then the voltage signal “$v_{SC1} - v'_{SC2}$” has a much smaller resistive voltage than the inductive voltage. Also in order to detect the resistive voltage, the inductive voltages of the both two tapes must be canceled. However the both inductive voltages are difficult to be derived from the voltage signal “$v_{SC1} - v'_{SC2}$” unless the currents $\beta_i i'_2$ and $\beta_2 i'_2$ are independently measured. Therefore the normal transitions in the secondary coil are difficult to be detected by the conventional active power method when even one of secondary tapes is in the superconducting state.

The authors propose an improved method by connecting a current lead to each secondary tape and measuring each voltage of each secondary tape. Figure 2 shows an improved circuit for the detection of the normal transitions in a bundle wire. Newly added parameters in the figure are shown in Table 2. Each secondary tape is connected to each current lead of which resistance is $r'_2$. The current leads are what a current lead connecting the secondary coil and the load is divided into two, therefore $R' = R'_{21} R'_{22} / (R'_{21} + R'_{22})$.

![Figure 1](image1.png)

**Table 1. Parameters in Figure 1.**

| $v_{SC1}$ | : primary voltage | $v'_{SC2}$ | : secondary voltage |
| --- | --- | --- | --- |
| $i_1$ | : primary current | $R'$ | : resistance of a current lead connecting the secondary coil and the load |
| $r_1$ | : primary resistance | $Z'$ | : load impedance |
| $l_1$ | : primary leakage inductance | $i_0$ | : excitation current |
| $r'_{21}$ | : resistance of the normal area | $g_0$ | : excitation conductance |
| $l'_{21}$ and $l'_{22}$ | : each secondary leakage inductance for each secondary tape | $b_0$ | : excitation susceptance |
| $\beta_1 i'_2$ and $\beta_2 i'_2$ | : each secondary current for each secondary tape, \((\beta_1, \beta_2): \text{coefficients, } \beta_1 + \beta_2 = 1, \beta_1 > 0, \beta_2 > 0) \}
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Figure 2. An improved circuit for the detection of the normal transitions in a bundle wire.

Table 2. Newly added parameters in Figure 2.

| Parameter        | Description                                      |
|------------------|--------------------------------------------------|
| \(v_{CC1}\)      | voltage of the cancel coil                       |
| \(m_i\)          | mutual inductance of the cancel coil              |
| \(R'_{21}\) and \(R'_{22}\) | each resistance of each current lead               |
| \(v'_{SC21}\) and \(v'_{SC22}\) | each secondary voltage of each secondary tape |

Following equations are obtained from Figure 2.

\[
v_{SC1} - v'_{SC21} = \Delta v_1 = r_1 i_1 + l_1 \frac{di_1}{dt} + \beta_i l'_2 i_2 + r'_{21} \beta_1 i_2.
\]  
(1)

\[
v_{SC1} - v'_{SC22} = \Delta v_2 = r_1 i_1 + l_1 \frac{di_1}{dt} + l'_2 \beta_2 i_2.
\]  
(2)

A following equation is derived from summation of (1) and (2).

\[
\Delta v_1 + \Delta v_2 = 2 r_1 i_1 + 2 l_1 \frac{di_1}{dt} + (\beta_1 l'_2 + \beta_2 l'_2) \frac{d^2 i_2}{dt^2} + r'_{21} \beta_1 i_2.
\]  
(3)

Since \(\beta_1 + \beta_2 = 1, l'_2 = l'_2\) and \(i'_2 = i_1\), equation (3) is expressed as a following equation.

\[
\Delta v_1 + \Delta v_2 = 2 r_1 i_1 + (2 l_1 + l'_2) \frac{di_1}{dt} + r'_{21} \beta_1 i_2.
\]  
(4)

Since \(r_1\) is a known resistance and a voltage of the cancel coil \(v_{CC1} = m_i \frac{di_1}{dt}\), the resistive voltage is derived as a following equation.

\[
\Delta v = \Delta v_1 + \Delta v_2 - k v_{CC1} = 2 r_1 i_1 = r'_{21} \beta_1 i_2,
\]  
(5)

where \(k = (2 l_1 + l'_2)/m_i\).

The active power \(P\) is calculated as follows [2].

\[
P = \Delta vi_1 = r'_{21} \beta_1 i_1^2 = r_2 \beta_1 i_2^2.
\]  
(6)
\[ p' = \frac{p}{1 + sT}, \quad (7) \]

where \( r'_{21} = a^2 r_{21}, \quad i_2 = a i_1 \) (\( a \): turn ratio). \( P \) is an instantaneous active power in the normal area and \( p' \) is a filtered \( P \) by a low pass filter to reduce superposed noise. Equation (7) is expressed by Laplace transform and \( T \) is a time constant of the filter. \( p' \) is a parameter to detect the normal transitions.

This method is useful for 3 or more secondary tapes as well.

3. Experimental results

The authors carried out experiments on the detection of the normal transitions in the secondary coil. Configuration and specifications of the test transformer are shown in Figure 3 and Table 3, respectively. The primary and secondary coils are respectively a copper and YBCO ones. The YBCO secondary cable is a bundle of two YBCO tapes (Tape 1 and Tape 2) which are SCS4050 by Superpower. Width of the tape is 4 mm and thickness is 0.05 mm. The secondary coil was cooled at 77 K in LN2. Amplitude of the secondary transport current was 100 Apeak and frequency 60 Hz. A heater was installed on each tape to cause the normal transitions.

\( v_{SC1}, v'_{SC1}, v_{SC2}, i_{CC1} \) and \( i_1 \) were measured to calculate the equations from (1) to (7). The measurement and calculation were carried out by NI cRIO with FPGA chassis by National Instruments. Calculation programs of the equations from (1) to (7) were prepared by using LabVIEW software and the programs were written in the FPGA. Specifications of voltage input modules in the system were as follows: Maximum input voltage \( \pm 10 \) V, Sampling rate 1 MS/s, Resolution 16-bit. Since \( v_{SC1} \) was larger than 10 V, \( v_{SC1}/10 \) was inputted to the module by a voltage divider.

Figure 4 shows experimental results for the normal transitions at only tape 1. The normal transitions occurred at 10 s. Temperature \( T_1 \) in the normal area of tape 1 increased gradually and temperature \( T_2 \) of tape 2 was kept at 77 K. Then \( p' \) increased gradually as well as \( T_1 \). The temperature and active power slowly increased since the current of tape 1 decreased after the normal transitions.

Figure 5 shows experimental results for the normal transitions at both two tapes. The normal transitions occurred at 11 s. Both temperatures \( T_1 \) and \( T_2 \) increased rapidly compared to Figure 4 and \( p' \) increased as well as the both temperatures. The temperatures and active power increased rapidly.

| Table 3. Transformer Specifications. |
|------------------------------------|
| Primary coil                     | Secondary coil               |
| (copper)                          | (YBCO (SCS4050))             |
| Inner diameter                    | 54.0 mm                      | 89.0 mm                      |
| Outer diameter                    | 58.0 mm                      | 89.4 mm                      |
| Height                            | 220.0 mm                     | 25.0 mm                      |
| Number of turns                   | 120                           | 2                            |
| Resistance                        | 392 mΩ                        | -                            |
| Self-inductance                   | 395.9 mH                      | 0.168 mH                     |
| Mutual inductance                 | -                             | 6.55 mH                      |
| Critical currents                 | -                             | 96, 95 A                     |
| (Tape 1, Tape 2)                  | (A bundle of 2 tapes)         |
since the currents of tape 1 and 2 were constant before and after the normal transitions. In Figure 4, the temperature of tape 1 was around 160 K at 20 s, and \( P' \) is 1 W. In Figure 5, the temperatures of both tapes are around 200 K at 20 s, and \( P' \) is 13 W. This is because the normal area was heated by the

![Figure 4](image1.png)

**Figure 4.** Experimental results for the normal transitions at tape 1.

![Figure 5](image2.png)

**Figure 5.** Experimental results for the normal transitions at tapes 1 and 2.

![Figure 6](image3.png)

**Figure 6.** Experimental results obtained by the conventional active power method shown in figure 1 for the normal transitions at tape 1.
mounted heater and consumed active power in the area, and amount of heat by the heater was larger than that by the consumed active power.

The results show that the proposed method works well when even one of secondary tapes transits to the normal conducting state. This means the proposed method can detect early the normal transitions. The method is suitable for a bundle secondary conductor of the HTS transformer.

Figure 6 shows experimental results obtained by the conventional active power method shown in Figure 1 for the normal transitions at only tape 1 [2]. The normal transitions occurred at 10.5 s. $P'$ was almost -0.5 W in both the superconducting and normal state nevertheless temperature $T_1$ increased. As mentioned above, the results show that the normal transitions in the secondary coil are difficult to be detected by the conventional active power method. The $P'$ was not 0 W but -0.5 W since the inductive voltages were not completely canceled.

4. Conclusion
The normal transitions in the secondary coil of the HTS transformer which is wound with a bundle of some HTS tapes are difficult to be detected by the conventional active power method. In this paper, the authors proposed the improve active power method to detect the normal transitions in the secondary coil. The method is based on measurement of each voltage of each HTS tape. The authors carried out some experiments for the test HTS transformer and showed its feasibility of the early detection of the normal transitions.

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