Study on a Magnetic Flux Detection Coil for Detection of Normal Transitions in a Hybrid Single-phase Bi2223 Superconducting Transformer by the Active Power Method

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Abstract. The authors have been developing a small and light power source with a hybrid single-phase Bi2223 high temperature superconducting (HTS) transformer. The transformer consists of a primary copper coil and a secondary Bi2223 superconducting coil and can output current of 500 A. For safe operation of the transformer, it is important to detect normal transitions in the transformer and to protect it from excessive heating in the normal area. The authors have presented a protection system based on the active power method and magnetic flux detection coil. However, in the conventional method, the active power does not become zero in a superconducting state due to AC loss and therefore incorrect recognition may be caused. In this paper, the authors propose a method to reduce the loss signals by configuration and mounting position of the magnetic flux detection coil. Through experimental results for a hybrid single-phase Bi2223 superconducting transformer, the authors show that the proposed method can detect the normal transitions more accurately than the conventional one.

1. Introduction
The authors have been developing a hybrid single-phase Bi2223 HTS transformer [1] used in the small and light AC current source [1-3]. The transformer consists of a primary copper coil and a secondary Bi2223 HTS coil and the transformer can output current of 500 A. For safe operation of the transformer, it is necessary to detect normal transitions in the secondary coil to protect from excessive heating in the normal area. The authors have presented a protection system based on the active power method and a magnetic flux detection coil attached on the inside of the secondary coil [1]. In this protection system, the normal transitions are detected by measuring active power dissipated in the only secondary coil. However, in the conventional method, the active power does not become zero in a superconducting state due to AC loss and therefore the conventional detection method has a possibility of incorrect detection of the normal transitions.

The authors propose a method to reduce the loss signals by configuration and mounting position of the magnetic flux detection coil. The magnetic flux detection coil has only one turn and is mounted on the center of the outside of the secondary coil to measure the magnetic flux which causes much AC loss. In this paper, the authors show that the proposed method can detect the normal transitions more accurately than the conventional one through experimental results for a hybrid single-phase Bi2223 HTS transformer.
2. Protection tests for a hybrid single-phase Bi2223 HTS transformer

2.1. Configuration and mounting position of a magnetic flux detection coil

In the conventional detection method of the normal transitions, the active power dissipated in the only secondary coil can be calculated by the magnetic flux detection coil which is mounted according to the secondary coil on the inside of the bobbin [1]. Mounting position of the magnetic flux detection coil and an equivalent circuit converted to the primary side of the hybrid single-phase Bi2223 HTS transformer are shown in Figures 1 and 2, respectively. In Figure 2,

\( v_1 \): primary voltage,
\( i_1 \): primary current,
\( r_1 \): primary resistance,
\( x_l \): leakage primary reactance,
\( i_0 \): excitation current,
\( g_0 \): excitation conductance,
\( b_0 \): excitation susceptance,
\( i_2 \): secondary current,
\( x_2 \): leakage secondary reactance,
\( r_2 \): secondary resistance generated after the normal transitions,
\( v_{sc2} \): secondary voltage,
\( Z \): secondary load impedance,
\( a \): turn ratio of the primary coil and secondary coil,
\( a' \): turn ratio of the primary coil and magnetic flux detection coil,
\( v_f \): voltage of the magnetic flux detection coil.

A secondary resistive voltage is detected by difference between \( a'v_f \) and \( av_{sc2} \) and active power dissipated in the secondary coil is calculated as follows.

\[
P_2 = (a'v_f - av_{sc2}) \frac{i_2}{a} = (a^2r_2 \frac{i_2}{a}) \frac{i_2}{a} = r_2i_2^2. \tag{1}
\]

\[
P'_2 = \frac{P_2}{1 + sT}. \tag{2}
\]

In order to reduce an electromagnetic noise, \( P_2 \) is filtered resulting in \( P'_2 \), which is expressed by Laplace transform and \( T \) is a time constant of the filter.

In the conventional method, \( P'_2 \) has some AC loss signals which cause false detection of the normal transitions. Therefore the authors propose an improved magnetic flux detection coil with only one turn which is mounted on the center of the outside of the secondary coil as shown in Figure 3. The magnetic flux detection coil can detect most of the flux applied to HTS wire vertically. Much of AC loss is hysteresis loss caused by time varying of the vertical magnetic flux. As the result, the one turn coil can measure much of AC loss in the secondary coil and therefore \( a'v_f \) has more AC loss signals than that of the conventional detection coil. Then \( a'v_f \) becomes close to \( av_{sc2} \) in equation (1) and the AC loss signals in \( P'_2 \) is reduced.
2.2. Comparison of the conventional magnetic flux detection coil and the improved one

In order to verify the proposed method, $P'_{2}$ s were measured as a function of transport current from 100 to 500 A$_{peak}$ for a hybrid single-phase Bi2223 HTS transformer. Configuration and specifications of the HTS transformer are shown in Figure 4 and Table 1, respectively [1]. Experimental results are shown in Figure 5. $P'_{2}$ measured by the improved method was under about 1/3 of that measured by the conventional one. The results show that the proposed method is effective for reducing the AC loss signals.

![Figure 3. Magnetic flux detection coil with one turn mounted on the center of the secondary coil](image)

![Figure 4. Configuration of the hybrid single-phase Bi2223 HTS transformer.](image)

![Figure 5. $P'_{2}$ as a function of transport current.](image)
2.3. Detection and protection tests of a hybrid HTS transformer

Detection and protection tests for the HTS transformer were carried out by the proposed method. A protection circuit is shown in Figure 6. \( P'_2 \) reaches a specified threshold \( P_{th} \), the thyristor switches are turned off and transport current is shut off.

![Figure 6. A protection circuit.](image)

Figure 7. Test results for the hybrid single-phase Bi2223 HTS transformer.

![Figure 7. Test results for the hybrid single-phase Bi2223 HTS transformer.](image)
The normal transitions were occurred by a heater mounted on the uppermost turn of the secondary coil under transporting the secondary current of 500 A\textsubscript{peak} and 60 Hz. The heater has width of 12 mm and height of 4.2 mm. Figure 7 shows the experimental results. Figures 7 (a)-(c) show expanded waveforms for time axes in a superconducting state. Figures 7 (a) and (b) show the primary current of 21 A\textsubscript{peak}, 60 Hz and the secondary current of 500 A\textsubscript{peak}, 60 Hz, respectively. Figure 7 (c) shows the voltage across the secondary coil which equals to the voltage of the connected resistor. Figures 7 (d) and (e) show the active power signal $P'_2$ in the secondary coil before and after the normal transition for the conventional method and the proposed one, respectively. In a superconducting state until about 20 s, $P'_2$ measured by the proposed method was smaller than that by the conventional one. This shows that the proposed method can reduce the loss signals more than the conventional one as mentioned above and therefore the normal transitions can be detected with a higher SN ratio than that of the conventional method [1]. The thyristor switches were turned off when $P'_2$ measured by the proposed method reached a specified threshold $P_{th}=10$ W [4]. Figure 7 (f) shows temperature of the normal zone near the heater on the secondary coil. The maximum temperature of the secondary coil was suppressed to 122 K which was lower than permissive temperature [5].

The test results show that the proposed method can detect the normal transitions more correctly than the conventional one.

3. Conclusion
The authors have proposed the active power method using a magnetic flux detection coil as a detection method of the normal transitions. In this paper, they proposed a method to reduce loss signals included in the active power in a superconducting state by configuration and mounting position of the magnetic flux detection coil. This method made SN ratio of the detection signal higher than that of the conventional one. Experimental results verified the improvement of the method for hybrid HTS transformer. The authors will study on more correct detection.

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