Detection of normal transitions in a hybrid single-phase Bi2223 high temperature superconducting transformer by using the active power method and a magnetic flux detection coil

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Abstract. The authors have been developing a hybrid single-phase Bi2223 high temperature superconducting (HTS) transformer used in the AC current source with rated current of over 500A. Its primary coil is a copper coil and secondary coil is a Bi2223 HTS coil. In this paper, the authors propose a new detection method of normal transitions in the secondary coil by using the active power method and a magnetic flux detection coil attached on the inside of the secondary coil. In the proposed method, the normal transitions are detected by measuring active power dissipated in the secondary coil, and induced voltage of the magnetic flux detection coil by a primary and leakage flux of the secondary coil enables to calculate the active power dissipated in only the secondary coil. As experimental results for a hybrid single-phase Bi2223 HTS transformer, it was found that the proposed method enabled to detect the normal transitions in its secondary superconducting coil.

1. Introduction
The authors have been developing a small and light AC power source with a hybrid single-phase Bi2223 HTS transformer for supplying a large current. The transformer consists of a primary copper coil and a secondary Bi2223 HTS coil. It is important to detect normal transitions in the secondary coil to protect from excessive heating in the normal area. The authors have presented the active power method as a detection method of the normal transitions in a superconducting coil [1]. In the active power method, the normal transitions are detected as active power signal in the superconducting coil. The hybrid transformer has a primary copper coil and an iron core and therefore no-load losses are always consumed in the transformer. Then the conventional active power method cannot detect accurately the normal transitions due to the no-load losses [1].

The authors propose a new detection method by using the active power method and a magnetic flux detection coil attached on the inside of the secondary coil. The magnetic flux detection coil contributes to measure active power dissipated in only the secondary coil. This paper shows usefulness of the proposed method for detection of the normal transitions in the hybrid HTS transformer.

2. Protection tests for a hybrid single-phase Bi2223 HTS transformer

2.1. Principle of detection of normal transitions by using a magnetic flux detection coil
In the Hybrid single-phase Bi2223 HTS transformer, copper loss in the primary coil and iron loss are always consumed as no-load losses in the transformer. In conventional active power method, no-load
losses are regarded as active power due to the normal transitions, therefore false detections may happen.
In the proposed method, the voltage of the magnetic flux detection coil enables to calculate the active power dissipated in only the secondary coil. 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,

\[ v_1 : \text{primary voltage,} \quad i_1 : \text{primary current,} \quad r_1 : \text{primary resistance,} \]
\[ x_1 : \text{leakage primary reactance,} \quad i_0 : \text{excitation current,} \quad g_0 : \text{excitation conductance,} \]
\[ b_0 : \text{excitation susceptance,} \quad i_2 : \text{secondary current,} \quad x_2 : \text{leakage secondary reactance,} \]
\[ r_2 : \text{secondary resistance generated after the normal transitions,} \]
\[ v_{sc2} : \text{secondary voltage,} \quad Z : \text{secondary load impedance,} \]
\[ a : \text{turn ratio of the primary coil and secondary coil,} \]
\[ a' : \text{turn ratio of the magnetic flux detection coil and the secondary coil (} a = a' \text{),} \]
\[ v_f : \text{voltage of the magnetic flux detection coil.} \]

As shown in Figure 1, the magnetic flux detection coil is mounted according to the secondary coil on the inside of the bobbin and therefore it generates an induced voltage by a primary flux and leakage flux of the secondary coil. Then \( a'v_f \), which is a conversion voltage on primary side of \( v_f \), is shown in Figure 2. Also the turn ratio \( a \) equals to \( a' \). A secondary resistive voltage is detected by difference between \( a'v_f \) and \( av_{sc2} \) (a conversion voltage on primary side of \( v_{sc2} \)) and active power dissipated in the secondary coil is calculated as follows.

\[
P_2 = \left( a'v_f - av_{sc2} \right) \frac{i_2}{a} = \left( a^2 r_2 - \frac{i_2}{a} \right) = r_2 l_2^2.
\]  

(1)

In this method, the active power \( P_2 \) is not affected by the signal of primary winding resistance \( r_1 \) and excitation conductance \( g_0 \). Moreover, the protection system becomes more simple than the conventional one because the detection can be achieved by measuring only three signals of the secondary voltage, the secondary current and the voltage of the magnetic flux detection coil.

2.2. Protection tests of the hybrid HTS transformer

In order to verify the above method, detection and protection tests for a hybrid single-phase Bi2223 HTS transformer were carried out. The configuration and specifications of a hybrid single-phase Bi2223 HTS transformer are shown in Figure 3 and Table 1. The primary copper coil is a square shape solenoid coil to suppress a leakage flux and the secondary HTS coil is a cylindrical solenoid coil to suppress bending
stress. The cooling container is made of styrene foam and has a cylindrical bore for the iron core and then only the secondary HTS coil is cooled in liquid nitrogen. A protection circuit is shown in Figure 4. In order to reduce an electromagnetic noise in calculated $P_2$, it is filtered by a low pass filter. The resultant active power “$P_2'$” reaches a specified threshold $P_{th}'$, the thyristor switches are turned off and transport current is shut off.

In the protection tests of the transformer, transport current of 21 Apeak, 60 Hz was supplied to the primary coil and then a current of 500 Apeak was supplied to the secondary coil. The secondary side circuit of the transformer was connected to a resistor of 1.1 mΩ (=Z). The normal transitions were occurred by a heater mounted on the secondary one. The tests for normal transitions in the secondary coil was carried out and the results are shown in Figure 5. Figures 5 (a)-(d) show expanded waveforms for time axes in a superconducting state. Figure 5 (a) shows the primary current of 21 Apeak, 60 Hz and (b) shows the secondary current of 500 Apeak, 60 Hz, which was transformed according to the turn ratio of the transformer as mentioned above. Figure 5 (c) show the voltage across the secondary coil and it equals to the voltage of the connected resistor. Figure (d) shows the voltage across the magnetic flux detection coil and it is the induced voltage by a primary flux and leakage one of the secondary coil. Figure 5 (e) shows the active power signal $P_2'$ in the secondary coil before and after the normal transition. In a superconducting state until about 150 s, $P_2'$ was constant with a small value. Then it increased drastically because the secondary resistance generated by the normal transition. It does not have no-load losses and therefore the normal transition can be detected with a higher SN ratio than that of the conventional method [1]. The thyristor switches were turned off when $P_2'$ reached a specified threshold $P_{th} = 25$ W [2]. Figure 5 (f) shows temperature of the normal zone near the heater on the secondary coil. The maximum temperature of the secondary coil was suppressed to 178K which was lower than permissive temperature [3].

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

**Figure 3.** Configuration of the hybrid single-phase Bi2223 HTS transformer.

**Table 1.** Specifications of a hybrid single-phase Bi2223 HTS transformer.

| Primary coil (Copper) | Secondary coil (Bi-2223) |
|-----------------------|--------------------------|
| Height 220 mm         | Height 60 mm             |
| (One side length)     | (Inner diameter) 89 mm   |
| Number of Turns 120   | Number of Turns 5        |
| $I_C$ (at 77 K, self-field) | $760$ A |

![A protection circuit.](image)

**Figure 4.** A protection circuit.
From the test results, it was verified that the protection system based on the proposed method worked successfully for the hybrid HTS transformer. The small value shown in Figure 5 (e) in the superconducting state is supposed to be a signal due to AC loss in the secondary coil. The signal is much smaller than the threshold $P_{th'}$ and therefore it causes no false detection.

![Graphs of test results](image)

**Figure 5.** Test results for the hybrid single-phase Bi2223 HTS transformer.

### 3. Conclusions

The authors proposed a detection and protection system which consists of the active power method using the magnetic flux detection coil for normal transitions in a hybrid single-phase HTS transformer. The system can detect only the normal transitions in the secondary HTS coil regardless of the resistance of the primary copper coil and iron loss. They verified usefulness of the system for the hybrid HTS transformer through the experimental results.

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### References

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