Development of Single-phase Bi2223 High Temperature Superconducting Transformer with Protection System for High Frequency and Large Current Source

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Abstract. The authors have been developing a large AC current source with a single-phase Bi2223 superconducting transformer. The authors aim to develop the source of supplying current with the maximum frequency of 1 kHz and the maximum amplitude of 1 kA. However, the conventional transformer has some leakage inductance resulting in large voltage drop, and therefore it was unable to transport the current with high frequency and large amplitude. In this paper, the authors propose a configuration of the transformer with less leakage inductance than inductance of the conventional one. Improved current source has output current with the maximum frequency of 1 kHz and the maximum amplitude of 900 A. In addition, a protection system for normal transition in the transformer is proposed. The authors have proposed the active power method to detect the normal transition. For high frequency and large current, however, the normal transition may be incorrectly detected by using the method due to large AC loss. The authors show a new method to avoid the incorrect detection by an empirical formula based on measurement results of the AC loss. From the experimental results of the normal transition, the authors show that the proposed method is more correct to detect the normal transition than the conventional method.

1. Introduction

The authors have developed a small and light power source that can output a current with the maximum frequency of 1 kHz and the maximum amplitude of 1 kA to measure current conduction characteristics of a high temperature superconducting (HTS) wire [1, 2]. The main part of the source is an HTS transformer. The conventional HTS transformer has some leakage inductance resulting in large voltage drop. In order to achieve the current of 1 kHz and 1 kA\textsubscript{peak}, the leakage inductance must be much reduced. The main cause of the leakage inductance is gap between the primary coil and the secondary coil of the transformer. In this paper, we propose a revised structure that two primary coils with the same height as the secondary coil sandwich the secondary coil in order to reduce the gap. Achieved output current has the maximum frequency of 1 kHz and the maximum amplitude of 900 A.

Also, for the safe operation of the HTS transformer, it is essential to protect the transformer from excessive heating in the normal transition. We have proposed a protection system based on an active power method to detect the normal transition [1, 2]. However, for high frequency and large current, the normal transition may be incorrectly detected by using the method due to large AC loss. In the reference [2], we proposed a countermeasure for the correct detection, however, the calculation formula was complex and...
not enough for the correct detection. We propose a new method to avoid the incorrect detection based on an empirical formula to calculate the active power and show its usefulness by experimental results.

2. Development of single-phase Bi2223 HTS transformer

Figure 1 shows configuration of a proposed single-phase Bi2223 HTS transformer. In order to reduce leakage inductance, the secondary coil was sandwiched by the primary coils so as to minimize gap between the primary coils and secondary one. Height of the primary coils were the same as that of the secondary one. Specifications of the HTS transformer is shown in Table 1. Numbers of the turns were 40 and 1 for the primary coils and secondary coil, respectively. The primary rated current was 25 A\textsubscript{peak} which a small power source with capacity of 3 kW = (100 V \times 30 A) could output. Because the secondary rated current was 1000 A\textsubscript{peak}, required turn ratio was 40. The numbers of turns were the minimum to obtain the ratio. The primary coils and the secondary coil were wound with DI-BSCCO superconductor (Type H). The primary wire was a single wire because the critical current of the wire was 200 A at 77 K and self-field which was larger than the primary rated current 25 A\textsubscript{peak}. The secondary wire was a bundle of 10 wires so that the critical current of the bundle became larger than the secondary rated current 1000 A\textsubscript{peak}.

Table 2 shows the leakage inductance of the developed transformer and the conventional one [2]. The leakage inductance of the HTS transformer was about 1/3 times smaller than that of the conventional one. Table 3 shows the primary currents I\textsubscript{1} (A\textsubscript{rms}) and the primary voltages V\textsubscript{SC1} (V\textsubscript{rms}) for transporting the secondary current of 1 kA\textsubscript{peak} at 60 Hz to the developed transformer and the conventional one. The primary currents were almost same with each other, however, the primary voltage of the developed transformer was about 1/3 times smaller than that of the conventional one due to the reduction of the leakage inductance. As shown in Figure 2, the developed transformer could output the secondary current i\textsubscript{2} of 900 A\textsubscript{peak} at 1 kHz for the primary current i\textsubscript{1} of 22.5 A\textsubscript{peak} and the primary voltage v\textsubscript{SC1} of 141 V\textsubscript{peak} (100 V\textsubscript{rms}) under short-circuiting secondary coil.

Table 1. Specifications of the developed transformer

| Transformer   | Phase | Single |
|---------------|-------|--------|
| Primary rated current (A\textsubscript{peak}) | 25    |
| Primary rated voltage (V\textsubscript{peak})   | 141   |
| Secondary rated current (A\textsubscript{peak}) | 1000  |

| Primary coils | Inner | Outer | Secondary coil |
|---------------|-------|-------|----------------|
| Inner diameter (mm) | 89.0  | 89.6  | 89.3           |
| Outer Diameter (mm) | 89.3  | 89.9  | 89.6           |
| Height (mm)      | 91.0  | 91.0  | 91.0           |
| Number of Turns | 40    | 1     |
| Inductance (mH)  | 52.6  | 0.0293|

Table 2. Leakage inductance

|                           | The conventional transformer (mH) | The developed transformer (mH) |
|---------------------------|----------------------------------|--------------------------------|
|                           | 2.99                             | 0.964                          |
Table 3. Primary currents $I_1$ and primary voltages $V_{SC1}$ for transporting a secondary current of 1 kA$_{peak}$ and 60 Hz

|                      | $I_1$ (A$_{rms}$) | $V_{SC1}$ (V$_{rms}$) |
|----------------------|-------------------|------------------------|
| The conventional    | 17.8              | 21.8                   |
| transformer          |                   |                        |
| The developed        | 18.1              | 7.98                   |
| transformer          |                   |                        |

3. Detection method of normal transition

In reference [2], the authors described that the active power method might cause incorrect detection of the normal transition due to AC loss. Also, the proposed countermeasure in [2] was complex in calculation and not enough for the correct detection. We propose a method to avoid the incorrect detection based on an empirical formula to calculate the active power.

Following equation (1) is to calculate an active power dissipated in the normal area [2].

$$P' = P_T - P_L.$$  

(1)

$P_T$ is the total amount of the active power dissipated in the normal area and AC loss in the transformer, and $P_L$ is the AC loss in the transformer.

The AC loss $P_L$ is calculated by some experiments unlike the method in [2]. $P_L$ is expressed as follows.

$$P_L = k_e I_2^2 f^2 + k_h I_2^2 f,$$  

(2)

where $I_2$ is the root mean square value of the secondary current, $f$ is the frequency and $k_e$ and $k_h$ are proportional coefficients. The first term on the right side shows eddy current loss and the second term shows hysteresis loss. Based on L-type equivalent circuit of the transformer, $I_2 = a I_1$ ($I_1$: the root mean square value of the primary current, $a$:turn ratio) and therefore we approximated the AC loss in the transformer by equation (2). The AC loss is calculated by equation (3).

$$P_L = \frac{1}{T} \int_0^T (v_{SC1} - a v_{SC2}) \cdot i_1 dt,$$  

(3)

where $T$ is a periodic time of the current. By fitting (2) to (3), the coefficient $k_e$ and $k_h$ are determined. The calculated $k_e$ and $k_h$ are shown in Table 4. These are average values in a set of measurements from 60 to 1000 Hz at 900 A$_{peak}$.

4. Experimental results for the detection method

Figure 3 shows that $P_T$ increases with increase of the peak current and the frequency of the secondary...
Table 4. Values of the coefficient \( k_e \) and \( k_h \)

|       | \( k_e \)          | \( k_h \)          |
|-------|--------------------|--------------------|
|       | \( 7.18 \times 10^{-11} \) | \( 4.95 \times 10^{-8} \) |

current due to the AC loss. Figure 4 shows that \( P' \) was suppressed to low values as compared with the \( P_f \) in Figure 3. This means that \( P' \) has little AC loss signal which causes the incorrect detection. Figure 5 shows the threshold value \( P_{th} \) and \( P' \) as function of the secondary current. \( P_{th} \) is the parameter to judge the normal transition. When \( P' \) reaches \( P_{th} \), the transport current is cut off to protect the transformer. \( P_{th} \) must be larger than \( P' \) in the superconducting state and the normal transition must be detected so as to suppress the temperature of the normal area to less than an allowable temperature of the windings of the HTS transformer. \( P_{th} \) in Figure 5 was calculated based on the equations in [3]. The equations in [3] are based on 1 dimensional equation of heat conduction and the equation of the electric circuit. We can obtain the proper threshold to suppress the temperature of the normal area to a specified temperature by the equations. \( P_{th} \) in Figure 5 was calculated so as to suppress the maximum temperature of the normal area to 200 K which was allowable temperature of the windings [4]. The results in Figure 5 show that the proposed method can protect the HTS transformer regardless of the AC loss.

![Figure 3](image-url)  
**Figure 3.** \( P_f \) in transporting currents with various values and frequencies.

![Figure 4](image-url)  
**Figure 4.** \( P' \) in transporting currents with various values and frequencies.
5. Protection tests for the Bi2223 HTS transformer

Protection tests in the normal transition were carried out by using the developed transformer. The protection circuit is shown in Figure 6 [2]. The secondary current was 850 A_{peak} at 1 kHz. The normal transition was occurred by a heater mounted on the secondary coil. When $P'$ reached $P_{th}$, the thyristor switch turned off and the primary and secondary currents were shut off.

The experimental results are shown in Figure 7. Figure 7 (a), (b) and (c) show respectively $P_f$, $P'$ and temperature of the normal area. $P_{th}$ was set at 40 W for this experiment. $P_f$ was about 120 W in the superconducting states, which was greater than 40 W until about 220 s. This means $P_f$ causes the incorrect detection. On the other hand, $P'$ was almost zero in the superconducting state and then it increased when the normal transition occurred at about 220 s. When $P'$ reached 40 W, the transport currents were shut off and the temperature was suppressed less than 160 K. This means the proposed method can protect the HTS transformer correctly in the occurrence of the normal transition regardless of the AC loss.

![Figure 5](image_url)  
**Figure 5.** $P_{th}$ and $P'$ in transporting currents with various values and frequencies.

![Figure 6](image_url)  
**Figure 6.** A protection circuit.
6. Conclusions
The authors developed a power supply with the maximum current of 900 \( A_{\text{peak}} \) and the maximum frequency of 1 kHz by reducing leakage inductance in the HTS transformer based on structural study. For the safe operation of the transformer in the normal transition, we proposed the more correct method to detect the normal transition than the conventional method regardless of the AC loss and showed its usefulness by experimental results. We are studying a more efficient structure of the transformer to achieve the transport current of 1 \( kA_{\text{peak}} \) at 1 kHz.

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References
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