Protection System for Normal Transitions in a Single-phase Bi2223 Full Superconducting Transformer by the Active Power Method under Flowing Currents of Various Frequencies

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Abstract. The authors have developed a large AC current supply with a single-phase Bi2223 full superconducting transformer. The supply is very small and light and can output currents of various values and frequencies. In order to operate the supply safely, a protection system for normal transitions in the transformer is essential. The authors have proposed the system based on the active power method, which detects the normal transitions as dissipated active power in the normal area. Previous studies have shown that the protection system can work well for the transformer in transporting constant current of 60 Hz. The supply is used under transporting currents of various values and frequencies. AC loss and iron loss in the transformer are increased by increasing the value and frequency and then they are detected as active power in a superconducting state. Therefore these losses cause incorrect recognition of the normal transitions. In this paper, the authors propose the system which can detect correctly the normal transitions regardless of the losses. The experimental results show its usefulness for the transformer.

1. Introduction
In recent years, high temperature superconducting (HTS) power applications have been developed [1]. The authors have developed a small and light power source with a single-phase Bi2223 HTS transformer [2]. The power source can supply AC currents of various values and frequencies to measure current conduction characteristics of an HTS wire. For safe operation, it is essential to protect the transformer from excessive heating in normal transitions. The authors have proposed a protection system based on the active power method as a detection method of the normal transitions. This method detects the normal transitions by measuring dissipated active power in normal areas [2-7]. Previous studies have shown that the protection system can work well for the transformer in transporting constant current of 60 Hz [2]. However, the system does not work well in transporting currents of various values and frequencies because AC loss and iron loss in the transformer are increased by increasing the value and frequency. These losses are detected as active power in a superconducting state. Therefore they cause incorrect recognition of the normal transitions. In this paper, the authors propose an improved system which can detect correctly the normal transitions regardless of the losses. Experimental results show the proposed method is useful for detection of the normal transitions and protection of the HTS transformer under flowing currents of various values and frequencies.
2. Active power method

2.1. Iron loss
Specifications and configuration of the developed single-phase Bi2223 HTS transformer is shown in Table 1 and Figure 1, respectively. Its primary and secondary coils are Bi2223 HTS coils with cylindrical and solenoidal shapes. Both coils are co-axially arranged and have an iron core. Only the coils are cooled in liquid nitrogen and the iron core is always in room temperature air.

Figure 2 shows an electric circuit diagram of the developed power source with the HTS transformer, and Figure 3 shows an equivalent circuit of Figure 2 converted to its primary side. In Figures 2 and 3,

- \( v_{sc1} \): primary voltage
- \( v_{sc2} \): secondary voltage
- \( i_1 \): primary current
- \( i_2 \): secondary current
- \( r_1 \): resistance of the primary coil after the normal transitions
- \( r_2 \): resistance of the secondary coil after the normal transitions
- \( L_1 \): self-inductance of the primary coil
- \( L_2 \): self-inductance of the secondary coil
- \( M \): mutual inductance
- \( v_{c1c} \): voltage of a cancel coil
- \( m_1 \): mutual inductance of a cancel coil
- \( a \): turn ratio (= \( N_1/N_2 \), \( N_1 \) and \( N_2 \) are numbers of turns of the primary and secondary coils, respectively)
- \( i_0 \): excitation current
- \( g_0 \): excitation conductance
- \( b_0 \): excitation susceptance
- \( Z \): load impedance

A variable current and variable frequency power supply with a low rated current is connected to the primary side and then a large current is outputted from the secondary side.

| Table 1. Specifications of the Bi2223 HTS transformer |
|-----------------------------------------------|
| Transformer                                   | Single |
| Phase                                         |       |
| Primary rated voltage / current               | 100 Vpeak / 25 A peak |
| Secondary rated voltage / current             | 2.5 Vpeak / 1000 A peak |
| Primary coil                                 |       |
| Inner diameter                                | 100 mm |
| Outer Diameter                                | 110 mm |
| Height                                        | 95 mm  |
| Number of Turns                               | 120    |
| Inductance                                    | 509 mH |
| \( I_C \)                                     | 53 A   |
| (a single tape)                               | 1520 A |
| Secondary coil                                |       |
| Inner diameter                                | 83 mm  |
| Outer Diameter                                | 89 mm  |
| Height                                        | 45 mm  |
| Number of Turns                               | 3      |
| Inductance                                    | 0.325 mH |
| \( I_C \)                                     | 1520 A |
| (a bundle of 8 tapes)                         |       |

Figure 1. Configuration of the HTS transformer.

Figure 2. An electric circuit diagram of the developed power source.

Figure 3. An equivalent circuit of the transformer converted to the primary side.
At first the authors propose the active power method which detects the normal transitions by measuring dissipated active power regardless of the iron loss.

In Figure 3, potential deference $\Delta v$ between $v_{SC1}$ and $v_{SC2}'$ is expressed as follows.

$$
\Delta v = v_{SC1} - v_{SC2}' = r_1 i_1 + (L_1 - aM) \frac{di_1}{dt} + a^2 r_2 i_2' + a^2 \left( L_2 - \frac{M}{a} \right) \frac{di_2'}{dt}.
$$

(1)

The excitation current $i_o$ is very smaller than $i_2'$ and then $i_1$ is approximately derived as follows.

$$
i_1 = i_0 + i_2' \approx i_2' = \frac{i_2}{a}.
$$

(2)

Equation (1) is transformed by equation (2) as follows.

$$
\Delta v = r_1 i_1 + a r_2 i_2 + \left( (L_1 - aM) + a^2 \left( L_2 - \frac{M}{a} \right) \right) \frac{di_1}{dt}
$$

(3)

The cancel coil is an air-core transformer and its output voltage is shown as follows.

$$
v_{CC1} = m_1 \frac{di_1}{dt}.
$$

(4)

Then a resistive voltage is derived as follows.

$$
k = \frac{L_1 + a^2 L_2 - 2aM}{m_1},
$$

(5)

$$
\Delta v' = \Delta v - kv_{CC1} = r_1 i_1 + a r_2 i_2.
$$

(6)

$\Delta v'$ is only the resistive voltage generated the normal transitions. This voltage includes no voltage due to the excitation conductance $g_0$, therefore the normal transitions can be detected by measuring this voltage signal regardless of the iron loss. In order to remove electromagnetic noise in the voltage signal, $\Delta v'$ is converted to an instantaneous active power $P$ and the $P$ is filtered resulting $P_f$ as follows.

$$
P = \Delta v' i_1 = \Delta v' i_2' = r_1 i_1^2 + r_2 i_2'^2,
$$

(7)

$$
P_f = \frac{P}{1 + sT}.
$$

(8)

Equation (8) is expressed by Laplace transform and $T$ is a time constant of the filter.

2.2. AC loss

$P_f$ has no iron loss however it has AC loss signal as the active power signal ($r_1$ and $r_2$ include equivalent resistance of the AC loss). Then the AC loss $P_L$ is calculated and subtracted from equation (8) as follows.

$$
P' = P_f - P_L.
$$

(9)

In order to calculate the AC loss, it is necessary to consider the magnetic field distribution because the AC loss generated in the superconducting wire depends on the magnetic field. The primary and secondary coils are cylindrical and solenoidal shapes, therefore the magnetic field distribution of each coil can be obtained by summing up the magnetic field created by a single circular current loop. The AC loss generated in each turn of the coil can be calculated by using the calculated magnetic flux density. $B_p$ is defined as the maximum value of the magnetic field vertically applied to the turn and $f$ is defined as frequency of the transport current. Hysteresis loss in the AC loss is proportional to $B_p f$.
when the strength of the magnetic field is equal to or greater than a certain value $B_s$, and is proportional to $B_{pk}^3 f$ when it is less than $B_s$, and the coupling loss in the AC loss is proportional to $B_{pk}^2 f^2$. Then the AC loss generated in the entire coil can be obtained as follows [8].

$$P_L = A_{31} \left( \sum_{k=1}^{m} l B_{pk}^3 \right) f + A_{11} \left( \sum_{k=m+1}^{N} l B_{pk} \right) f + A_{22} \left( \sum_{k=1}^{N} l B_{pk}^2 \right) f^2.$$  \hspace{1cm} (10)

- $l$: Length of one turn of the coil,
- $B_{pk}$: The $k$th lowest applied magnetic field in all turns,
- $N$: Number of turns,
- $m$: Number of turns in less magnetic field than $B_s$.

The coefficients $A_{31}$, $A_{11}$, and $A_{22}$ are calculated by least squares method using actual measurement value of the AC loss of each coil. Equation (10) calculates the AC losses in the primary and secondary coils, $P_{L1}$ and $P_{L2}$, respectively, and $P_L = P_{L1} + P_{L2}$.

It was obtained that $B_s=0.12$ mT, $A_{31}=60000$, $A_{11}=0$ and $A_{22}=0.01$ in the primary coil, and $B_s=0.029$ T, $A_{31}=5000$, $A_{11}=5.8$ and $A_{22}=0.1$ in the secondary coil.

Note that the frequency is calculated using the voltage of the cancel coil and the primary current $i_1$ as follows.

$$f = \frac{V_{cc1}}{2 \pi m_1 i_1}.$$  \hspace{1cm} (11)

Capital letters mean root mean square values.

Equation (9) can detect the normal transitions without incorrect detection caused by the iron loss and AC loss.

When $P'$ reaches a specified threshold $P_{th}$ [9], the normal transitions are recognized. The method can detect the normal transitions in the primary and/or secondary coils.

### 3. Energization tests for a Bi2223 HTS transformer

$P_f$ and $P'$ were measured under flowing the secondary currents of various values and frequencies. Figures 4 and 5 show experimental results of $P_f$ and $P'$, respectively.

Figure 4 shows that $P_f$ increased as the value and/or frequency of the current increased because of the AC loss. Whereas $P'$ in Figure 5 was suppressed under about 10 W because the AC loss was removed. It is supposed that the difference under about 10 W occurred because the calculated $B_{pk}$ had some difference from the actual magnetic field which depended on the magnetic characteristics of the

![Figure 4. $P_f$ in transporting currents with various values and frequencies.](image-url)
actual iron core. However $P'$ signal is enough small for detecting the normal transitions in the transformer as mentioned at the next chapter.

![Figure 5. $P'$ in transporting currents with various values and frequencies.](image1)

4. Protection tests for the Bi2223 HTS transformer

![Figure 6. A protection circuit.](image2)

4. Protection tests for the Bi2223 HTS transformer

![Figure 7. A flow chart of the protection system.](image3)
Protection tests for the normal transitions in the transformer was carried out to confirm effectiveness of the proposed method. The protection circuit is shown in Figure 6. Z in Figure 6 was a resistor of 0.3 mΩ. AC current of 25 A_{peak}, 60 Hz and 300 Hz was supplied to the primary coil and then secondary coil outputted a current of 1 kA_{peak}, 60 Hz and 300 Hz. The normal transition was occurred by a heater mounted on a surface of the secondary coil. When \( P' \) reaches a specified threshold \( P_{th} \), the thyristor switch turns off and the primary and secondary currents are shut off. Then joule heating in the normal zone is suppressed and its temperature rise is also suppressed.

Figure 7 shows a flowchart of the protection system. Firstly, \( v_{sc1}, v_{sc2}, i_1, i_2 \) and \( v_{cc1} \) are measured. Secondly, \( f \) and \( P_f \) are calculated by an analog system, and \( P_{L1} \) and \( P_{L2} \) are calculated by a digital system. The analog system deals with all the measured signals which are AC signals for correct calculations. On the other hand, the digital system, which is a highly customizable and flexible system, is for DC signals. Finally, a signal \( P' \) to detect the normal transitions is calculated.

The test results for 60 Hz and 300 Hz are shown in Figures 8 and 9, respectively. A specified threshold \( P_{th} \) has to be set at 50 W for both tests [9]. In Figure 8, (a), (b) and (c) show respectively \( P_f \), \( P' \) and temperature of the normal area. When \( P' \) reached at \( P_{th} = 50 \), the transport currents were shut off and the temperature was suppressed less than 170 K which was under permitted temperature of the coil [10]. In this test, the normal transitions can be detected by \( P_f \) as well as \( P' \) because it was less than \( P_{th} = 50 \) in the superconducting states until about 18 s.

As well as Figure 8, Figure 9(a), (b) and (c) show respectively \( P_f \), \( P' \) and temperature of the normal area, and when \( P' \) reached at \( P_{th} = 50 \), the transport currents were shut off and the temperature was suppressed less than 170 K. However in this case, the normal transitions cannot be detected by \( P_f \) because it was greater than \( P_{th} = 50 \) in the superconducting states until about 3 s. These results show that \( P' \) is useful for detecting the normal transitions in the HTS transformer under flowing currents of various values and frequencies.

![Figure 8. Test results at 1 kA, 60 Hz current.](image1)

![Figure 9. Test results at 1 kA, 300 Hz current.](image2)
5. Conclusions
The authors proposed the improved active power method as a detection method of the normal transitions regardless of the iron loss and AC loss for the Bi2223 HTS transformer. As experimental results for the HTS transformer, it was confirmed that the system could work well even in cases of transporting currents of various values and frequencies.

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