Basic study for a large AC current supply with a single phase air-core Bi2223 high temperature superconducting transformer

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Abstract. The authors have been developing a compact power supply with a single-phase Bi2223 high temperature superconducting (HTS) transformer. The conventional transformer has an iron-core for enhancing magnetic coupling between its primary coil and secondary one. However, the iron-core has great majority of size and weight of the transformer and therefore it is desirable to be removed for a smaller and lighter transformer. In this paper, the authors propose an air-core HTS transformer for a more compact power supply than the conventional one. As experimental results, it is shown that appropriate design of the air-core transformer has a possibility to decrease the weight and volume of the large AC current supply.

1. Introduction
It is very important to grasp current conduction characteristics of high temperature superconductors for developing high temperature superconducting (HTS) apparatus such as HTS electric cables, motors and SMES. HTS tapes used in the apparatus have large critical currents and therefore a large current supply is needed to grasp the current conduction characteristics. However, commercial power supplies especially for large AC current are generally very large and heavy and are difficult to handle in ordinary laboratories. The authors have been developing a compact power supply with a single-phase Bi2223 HTS transformer [1]. Some HTS transformers have been developed for large power supply such as a distribution power grid [2] and railway rolling stock [3]. The transformer for the compact power supply is different from these transformers in that it is used for very low voltage and large current. From viewpoint of the very low voltage, in this paper, the authors study a possibility of an air-core transformer which has no iron-core resulting in a more compact supply. The air-core transformer needs larger excitation current than that of a general iron-core transformer, however the current is originally small due to the very low voltage. Also no copper loss is consumed in the transformer unlike a general transformer with copper windings. Therefore the transformer has a possibility to make the supply small and light without increasing loss. The authors show comparison of current carrying properties of an air-core transformer and a conventional iron-core one. As experimental results, it is shown that appropriate design of the air-core transformer has a possibility to decrease the weight and volume of the large AC current supply.
2. **A compact power supply with a single-phase Bi2223 HTS transformer**

Figure 1 shows an overview of a proposed compact power supply with a single-phase Bi2223 HTS transformer. Number of turns of its primary coil is more than those of its secondary coil. A power supply connected to the primary coil of the transformer supplies small current $i_1$ to the primary coil and then the secondary coil outputs large current $i_2$ to a load $Z$ which is a superconducting wire. The primary power supply is a variable voltage and variable frequency (VVVF) one and the transformer can output a large current with variable frequency.

Figure 2 shows an overview of a conventional HTS transformer with an iron-core. The primary and secondary coils are Bi2223 HTS coils with cylindrical and solenoidal shapes. They are wound with DI-BSCCO Type H fabricated by Sumitomo Electric Industries, Ltd. Specifications of the wire is shown in Table 1. Both coils are co-axially arranged and have an iron core. Only the coils were cooled in liquid nitrogen and the iron core was always in room temperature air. Specifications of the transformer are shown in Table 2 [1]

Figure 3 shows an overview of the iron-core. Its shape was decided so that space for the cooling container was secured. The iron-core was made by layering oriented steel sheets. The steel sheet has thickness of 0.3 mm, density of 7,650 kg/m$^3$, iron loss less than 1.1 W/kg at 1.7 T and 50 Hz, and saturation magnetic flux density of over 1.88 T. Weight of the iron-core is 10 kg which is great part of that of the transformer 12.6 kg.

Figure 4 shows an overview of a proposed air-core HTS transformer and its specifications are shown in Table 2. Its structure is almost same as that of the iron-core transformer but it has no iron-core and its cooling container has no cylindrical bore. Weight and volume of the air-core transformer are respectively 2.6 kg and $4.2 \times 10^{-3}$ m$^3$, which are only about 20 % and 36 % of those of the iron-core transformer, respectively.

| Table 1. Specifications of the DI-BSCCO Type H wire |
|-----------------------------------------------|
| Width                           | 4.3 mm |
| Thickness                       | 0.23 mm|
| Critical current (at 77 K, Self-field) | 143 A  |

![Figure 1. An overview of a compact power supply with a single-phase Bi2223 HTS transformer.](image-url)
**Figure 2.** An overview of an HTS transformer with an iron-core.

**Figure 3.** An overview of the iron-core.

**Figure 4.** An overview of an air-core HTS transformer.

**Table 2.** Specifications of a single-phase Bi2223 HTS transformer.

|                        | Primary coil | Secondary coil |
|------------------------|--------------|----------------|
| Number of turns        | 120          | 5              |
| Inductance             |              |                |
| Iron-core              | 448 mH       | 760 μH         |
| Air-core               | 1208 μH      | 2.67 μH        |
| $I_C$                  | 143 A        | 760 A          |

Volume: $11.8 \times 10^{-3}$ m$^3$
Weight: 12.6 kg
3. **Current carrying tests**  
The authors carried out experiments to measure current ratio $i_2/i_1$ and losses of the air-core transformer compared with the iron-core one.

A test circuit is shown in Figure 5. A VVVF power amplifier supplied current to the transformer. A resistor ($= Z, 13 \, \mu\Omega$) was connected to the secondary coil. The transformer was cooled at 77 K in liquid nitrogen.

Losses of the transformers were measured as follows.

$$P_1 = \frac{1}{T} \int_0^T v_1 \times i_1 \, dt$$  
$$P_2 = \frac{1}{T} \int_0^T v_2 \times i_2 \, dt$$  
$$P_T = P_1 - P_2$$

$P_1$ is summation of loss in a transformer and that in a load resistor, $P_2$ is loss in the load and $P_T$ is loss in the transformer. The losses were measured for secondary currents of 10 A to 200 A, 60 Hz, and 60 Hz to 1 kHz, 200 A. As shown in Figure 5, the currents were measured by non-contact type current sensors (Hall sensors), and data of the currents and voltages were acquired by a digital oscilloscope through isolation amplifiers.

Experimental results for measuring current ratio are shown in Figures 6 and 7. Current ratio $i_2/i_1$ was 24 for the iron-core transformer shown in Figure 6 and 12.5 for the air-core transformer shown in Figure 7. The current ratio of the air-core transformer was about half of that of the iron-core one because magnetic coupling of the air-core transformer was reduced due to no iron-core. Therefore the air-core transformer needed about twice primary current for same secondary current compared with the iron-core one.

Experimental results for measuring losses are shown in Figures 8 and 9. Figure 8 shows losses of the air-core transformer and iron-core one as functions of the secondary current and Figure 9 shows losses of those transformers as functions of frequency. The air-core transformer needed about twice primary current as mentioned above, however, the loss of the air-core transformer was slightly different from that of the iron-core one. The iron-core transformer has iron loss in its iron-core and AC loss in its superconducting winding and the air-core transformer has only AC loss. Moreover, leakage magnetic flux of the air-core transformer is larger than that of the iron-core one. Therefore it is supposed that AC loss in the air-core transformer was larger than that in the iron-core one and then total loss in the iron-core transformer was almost same as that in the air-core one. Hereafter the authors will analyze these losses in detail.

![Figure 5. A test circuit.](image-url)
Figure 6. Experimental results for measuring current ratio of the iron-core transformer.

Figure 7. Experimental results for measuring current ratio of the air-core transformer.

Figure 8. Losses of the air-core transformer and iron-core one as functions of the secondary current.

Figure 9. Losses of the air-core transformer and iron-core one as functions of frequency.
This study shows that appropriate design of the air-core transformer has a possibility to decrease the weight and volume of the large AC current supply because the loss of the transformer with and without the iron core in this study was equivalent. Therefore the authors will study the appropriate design hereafter.

4. Conclusion
The authors have been developing a compact power supply with a single-phase Bi2223 HTS transformer for outputting a large AC current. In this paper, the authors measured current carrying characteristics of an air-core HTS transformer. Compared with an iron-core transformer, the air-core transformer with same primary and secondary coils as those of the iron-core one had almost same loss and 36% volume and 20% weight. That shows the air-core transformer is supposed to be useful for a highly efficient and compact supply. Hereafter the authors will analyze losses in the air-core transformer in detail and study on the appropriate design of the air-core transformer for a more compact supply.

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References
[1] Nanato N, Kobayashi Y 2014 Quench Detection and Protection for High Temperature Superconducting Transformers by Using the Active Power Method Physics Procedia 58 264
[2] Iwakuma M et. al. 2015 Development of a 3φ-66/6.9 kV-2 MVA REBCO Superconducting Transformer IEEE Trans. Appl. Supercond. 25 Art. no. 5500206
[3] Kamijo H et. al. 2007 Tests of Superconducting Traction Transformer for Railway Rolling Stock IEEE Trans. Appl. Supercond. 17 1927