

Study of an Air-Core High Temperature Superconducting Current Transformer for Large Current Supply^{*)}

Hokuto YAMADA, Nozomu NANATO¹⁾, Keisuke SHIRAI and Tetsuhiro OBANA²⁾

Okayama University, 3-1-1 Tsushima-naka, Kita-ku, Okayama 700-8530, Japan

¹⁾*Okayama University of Science, 1-1 Ridai-cho, Kita-ku, Okayama 700-0005, Japan*

²⁾*National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan*

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Large AC current supply is essential for measuring the current transport characteristics of superconducting wires, such as AC loss in helical coil conductors. Commercial current supplies are generally too large and heavy, and therefore, they are inconvenient to use with the superconducting wires. The authors have been studying a small and lightweight large current supply with a high temperature superconducting (HTS) current transformer. An air-core HTS current transformer is suitable for the miniaturization of AC supply because this transformer does not have an iron core and thus does not have large volume and heavy weight. In this paper, we report that the current supply with the air-core HTS current transformer can output large current with high frequency by using the resonance phenomenon. Furthermore, we provide a method for the detection of normal transitions in the transformer by measuring the current transformation ratio of its primary and secondary currents. This detection method is composed of a simple measurement system, and experimental results show the usefulness of this detection method for the air-core transformer.

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1. Introduction

High temperature superconducting (HTS) tapes are expected as next generation materials for a fusion reactor [1]. To measure the current transport characteristics of HTS tapes used in the helical coil of the fusion reactor and other superconducting apparatus, we have been developing small and lightweight AC current supplies with HTS current transformers [2–4]. Figure 1 shows the configuration of the current supply for measuring the current transport characteristics of an HTS tape. A small primary current i_1 is applied to the primary coil, and a large secondary current i_2 is outputted from the secondary coil to the HTS sample tape through the HTS transformer. Our goal is to achieve $i_2 = 1 \text{ kA}_{\text{peak}}$ at 1 kHz for measuring the current transport characteristics such as AC loss [5]. One of our developed transformers was an air-core HTS current transformer [4, 6], which was small and lightweight because it had no iron core. The air-core transformer can output a current with a maximum amplitude of $1 \text{ kA}_{\text{peak}}$ at 60 Hz [6]. However, this transformer has weak magnetic coupling and large leakage inductance. Therefore, it cannot output a large current at high frequencies. This means that the voltage drop of the leakage inductance becomes very large at high frequencies and exceeds the rated voltage of the primary power supply. The resonance phenomenon

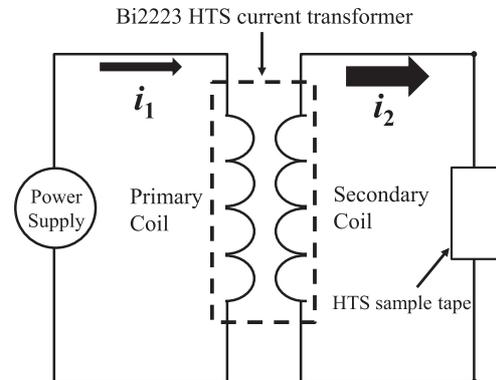


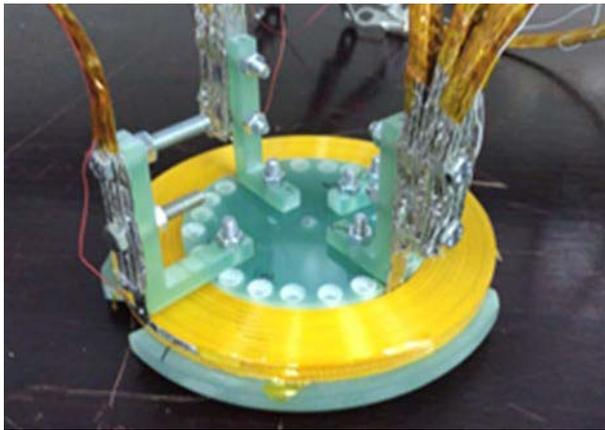
Fig. 1 Configuration of the current supply for measuring current transport characteristics of an HTS tape.

is useful for reducing this voltage drop [7]. An optimized variable capacitor is installed on the HTS transformer, and then, the output current is expected to become larger than that of the conventional current supply.

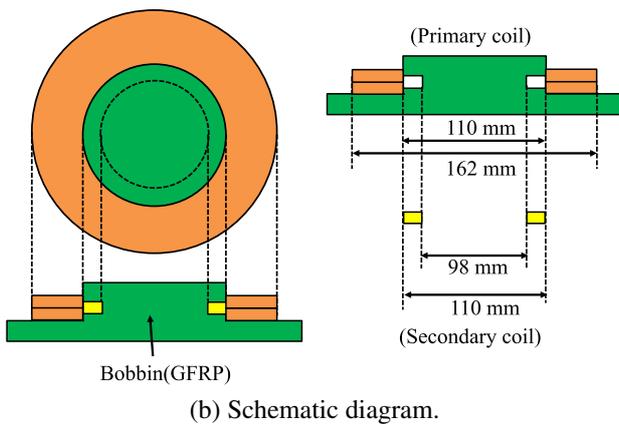
Additionally, the detection of normal transitions in the HTS transformer is important for the safe operation of the current supply [8, 9]. We have developed an active power method for monitoring normal transitions [2, 3]. The air-core transformer has low exciting impedance, and therefore, the secondary current decreases during normal transitions in the secondary coil because of current sharing. By monitoring current sharing, it is expected that normal tran-

author's e-mail: p7hh7xdm@s.okayama-u.ac.jp

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(a) Photograph.



(b) Schematic diagram.

Fig. 2 Structure of the air-core transformer.

sitions can be detected using a simpler system than that of the active power method.

In this paper, we report the characteristics of the large output current achieved using the resonance phenomenon between the leakage inductance and installed capacitor and report the detection method of normal transitions in the secondary coil by monitoring the transformation ratio of the primary and secondary currents.

2. Structure of the Air-Core Transformer

The structure of the air-core transformer is shown in Fig. 2 and its specifications are shown in Table 1. The primary coil, indicated by the orange region in Fig. 2 (b), was composed of two single pancake coils and was wound with DI-BSCCO Type H tape manufactured by Sumitomo Electric Industries, Ltd. The secondary coil, indicated by the yellow region in Fig. 2 (b), was also a single pancake coil wound with a bundle of ten Type H tapes to ensure an output current of a maximum amplitude of $1 \text{ kA}_{\text{peak}}$. The primary and secondary coils were assembled in a coaxial structure to enhance magnetic coupling between the coils. The turns ratio of the transformer was 200 and the current ratio was approximately 34 at 60 Hz. The volume of the

Table 1 Specifications of the air-core transformer.

	Primary coil	Secondary coil
Inner diameter	110 mm	98 mm
Outer Diameter	162 mm	110 mm
Height	9 mm	4.5 mm
Number of Turns	200	1
Self-inductance	7390 μH	0.699 μH
Mutual inductance	35.22 μH	
I_c	76.2 A	1900 A
Superconducting wire	DI-BSCCO Type H	DI-BSCCO Type H

transformer was 1/20 and its weight was 1/3 that of the previously used iron-core transformer [2]. The magnetic field was less than 1 mT at 100 mm from the transformer and almost zero at a distance over 300 mm. Therefore, the magnetic field from the transformer had almost no effect on its surroundings.

3. Improvement of Current Transport Characteristics Using Resonance Phenomenon

Since the air-core transformer has larger leakage inductance than that of an iron-core transformer [2], the voltage drop of the leakage inductance is large at high frequencies, which restrains the output current. We adopted a resonant circuit to reduce the voltage drop [7]. The equivalent circuit, converted to the primary side of the transformer with a resonant capacitor whose capacitance is C , is shown in Fig. 3. The secondary side is short-circuited, assuming that a short HTS sample is connected to the secondary coil, as shown in Fig. 1. The capacitor is connected in series with the primary coil. L_1 and L_2 are the self-inductances of the primary and secondary coils, respectively, M is the mutual inductance, and is the turns ratio. When the impedance of the equivalent circuit becomes zero, the voltage drop is smallest. The impedance Z of the equivalent circuit is shown as follows:

$$Z = j\omega\{L_1 - M^2/L_2 - 1/(\omega^2 C)\}, \quad (1)$$

where j is the imaginary unit and ω is angular frequency. C is determined such that the impedance $Z = 0$, minimizing the voltage drop.

Examples of experimental results of current transport tests are shown in Fig. 4. The transformer was cooled in LN_2 and the power supply applied v_1 to the primary coil, which equaled $20 V_{\text{peak}}$ at 1 kHz. Figures 4 (a) and (b) show the secondary current without and with the resonant capacitor, respectively. The secondary current was $20 A_{\text{peak}}$ without the capacitor and $330 A_{\text{peak}}$ with the capacitor (16.5 times larger). Because the value of C was slightly different from the exact value needed to resonate, $v_1 (= 20 V_{\text{peak}})$ was slightly higher. However, when flowing the current of $330 A_{\text{peak}}$ without the capacitor, needs to

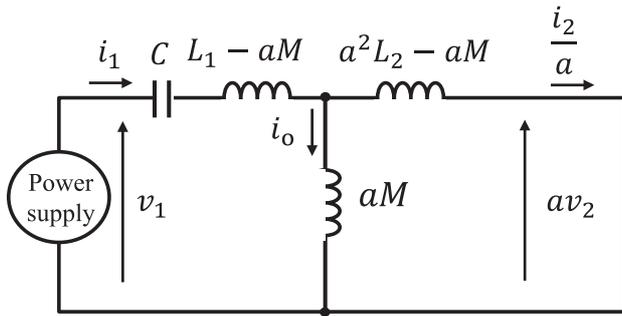


Fig. 3 An equivalent circuit converted to the primary side of an air-core HTS transformer connected with a resonant capacitor.

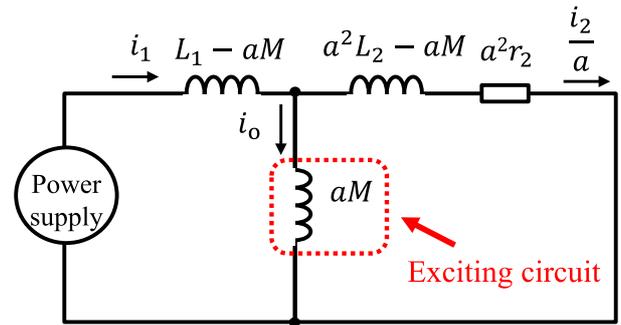


Fig. 5 The equivalent circuit converted to the primary side of the air-core HTS transformer.

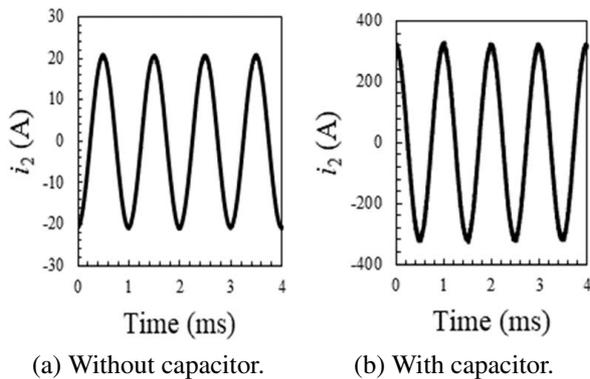


Fig. 4 Comparison of the secondary current.

be approximately $330 V_{peak}$. The voltage was reduced to approximately 6% by the resonant circuit and was small enough to output a large current. These results show that the voltage drop was reduced by the resonant circuit. The transformer can output a large current at various frequencies by using a variable capacitor. We achieved a secondary current up to $i_2 = 330 A_{peak}$ at 1 kHz with the resonant circuit as shown in Fig. 4 (b). Since temperature of the transformer rose due to AC loss in flowing the current of over $330 A_{peak}$, our goal of $1 kA_{peak}$ could not be achieved. Hereafter, we will study the cooling structure of the transformer and how to reduce AC loss.

4. Detection of Normal Transitions in the Secondary Coil of the Air-Core Transformer

Normal transitions in the HTS transformer may cause serious damage to HTS windings, such as burnout of the wire and deterioration of superconducting characteristics [9]. For safe operation of the transformer, it is important to develop a protection system for normal transitions. Early and clear detection of normal transitions is especially important for the system. The air-core transformer has low exciting impedance and therefore a secondary current decrease during normal transitions in the secondary coil by current sharing. An equivalent circuit, converted to the pri-

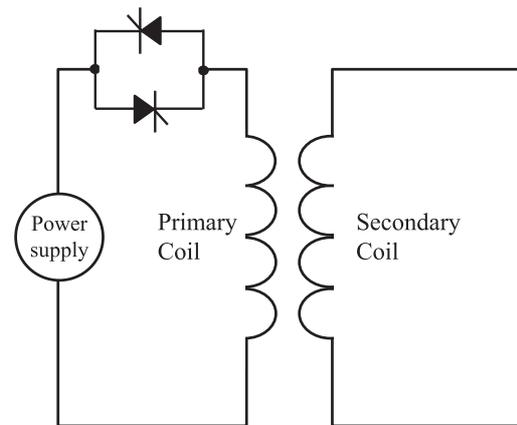


Fig. 6 A test circuit for the detection of the normal transitions in the secondary coil.

mary side of the air-core transformer, is shown in Fig. 5. The impedance of the exciting circuit of the air-core transformer is much lower than that of the iron-core one. When normal transitions with a resistance r_2 generate in the secondary coil, i_2 decreases and the exciting current i_0 increases due to current sharing. Therefore, the current ratio i_2/i_1 decreases during normal transitions. Monitoring the current ratio is a simpler detection method than the active power method [2, 3].

In order to verify this detection method, a detection test of the normal transitions in the secondary coil was carried out. A test circuit is shown in Fig. 6. The transformer was cooled in LN_2 and the secondary coil was short-circuited. The power supply provided a constant primary current of $28 A_{peak}$ at 60 Hz and a secondary current of $939 A_{peak}$ was outputted. The normal transitions occurred in the secondary coil by a heater mounted on its windings. When i_2/i_1 became lower than a specified threshold, the thyristor switch turned off and the transport current shut down [2, 3].

Experimental results are shown in Fig. 7. Figures 7 (a), (b), (c), and (d) show the envelope of the primary current I_1 , the envelope of the secondary current I_2 , I_2/I_1 and the temperature of the normal area T_2 , respectively. The

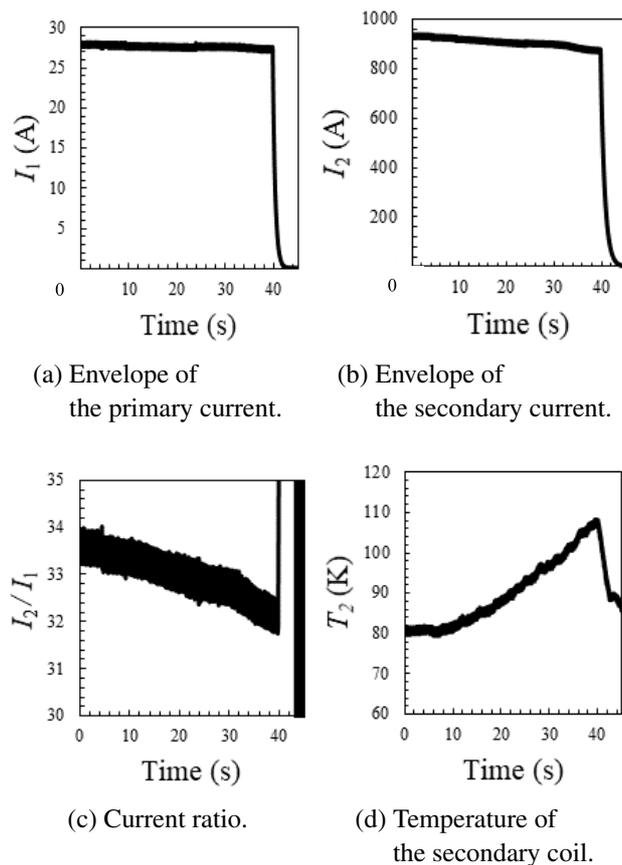


Fig. 7 The result of the experiment.

current ratio shown in Fig. 7 (c) was calculated using the envelopes of the primary and secondary currents to avoid dividing by zero. The primary and secondary currents, shown in Figs. 7 (a) and (b), respectively, were measured by current sensors CT6862 and CT6865 by HIOKI E.E. CORPORATION, respectively, and an envelope measurement circuit. The normal transitions occurred at about 4 s. Then, T_2 and I_2 gradually increased and decreased, respectively, as shown in Figs. 7 (d) and (b). I_1 was almost constant and I_2/I_1 gradually decreased, as shown in Figs. 7 (a) and 7 (c), respectively. These results indicate that the normal transitions in the secondary coil can be detected by monitoring the current ratio. When the current ratio reached the threshold of 32, the primary and secondary currents were shut down by switching off the thyristor. The threshold of 32 was determined by coupled analysis of the heat conduction equation and an electric circuit equation [10]. During this process, the maximum temperature of the normal area was 108 K, which was sufficiently low compared to the permissive temperature of

the HTS wire 200 K [11]. This method was useful for protecting the transformer from damage due to excessive temperature rise. The primary coil is monitored by the active power method.

5. Conclusions

We proposed a small and lightweight power supply with an air-core HTS current transformer as the large current supply. The air-core transformer had a large leakage inductance that interferes with a large output current at high frequencies, however, it was shown that a large output current was achieved by a resonant circuit with an optimum variable capacitor.

Furthermore, we showed a method for detection of normal transitions in the secondary coil of the transformer, that monitored the current ratio. The proposed method was realized by monitoring the primary and secondary currents and therefore the detection system was composed of a simple system.

Acknowledgements

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