Generation of highly stable DC current by using a superconducting transformer

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Abstract. The purpose of this study is to generate a highly stable DC current by using a superconducting transformer. For the first trial stage, a 100 A class superconducting transformer was designed and fabricated for operation at the temperature of liquid nitrogen. The secondary coil of the transformer was wound with a superconducting Bi-2223 tape, and the turn ratio of the primary and secondary windings was about 11:1, which brought an output current of about 80 A by a small varying control current. The control system was constructed with a PC, an AD/DA conversion PCI board and a small current supply. The primary input current was controlled by a normal PID control program. The secondary output current was evaluated by measuring the voltage on a low resistivity shunt. As the result of this study, it was suggested that in the case of small impedance in secondary winding circuit, the DC output current with high stability can be obtained by applying an easy control algorithm to the program running on the controlling PC.

1. Introduction

Recently, many kinds of applications of high-T_c superconductors to electric and electronic area have been studied. One of the noticeable studies is the application of superconducting AC power transformer, on which several achievements have been reported [1]. The results gave us hints on a new application of superconducting oxide materials to a DC power transformer. The purpose of this study is aimed to generate a highly stable DC current by using a superconducting transformer. The large DC current over several hundred amperes with high stability is expected to be used for the generation of highly precise and large magnetic field in the NMR system and other applications. For example, DC output current of the superconducting transformer generates a highly precise magnetic field, which may become an alternative method to the flux pump system for the compensation of decremental persistent current in a HTS magnet system.

For the first trial stage, a 100 A class superconducting transformer was designed and fabricated under the concepts of low-cost, compact and large-capacity system. A compact superconducting transformer for AC use was reported by Otabe *et al.* [2], in which the availability of the system was successfully clarified. In this study, we designed the system with the target of DC use, referring to the

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results reported on the systems for AC use. For the concept of low-cost, we constructed the control system based on a PC, instead of using an exclusive apparatus. In this paper, the details of transformer fabrication and system construction were mentioned. An evaluation and discussion were given based on the structure of the superconducting transformer for highly precise control, and the optimization of the control system.

2. Fabrication

The specifications of the primary and secondary coils of the transformer are listed in table 1. The turn ratio of the primary and secondary windings was about 11:1, which brought an output current of about 80 A by a small varying control current. The secondary coil was wound with a commercial

Table 1. Coil specifications of the superconducting transformer.

	primary	secondary
number of turns	200	18
kind of wires	copper (0.2mmϕ)	Bi-2223 tape
diameter of bobbin [mm]	50	59
height of bobbin [mm]	48	48

superconducting Bi-2223 tape. The specifications of the tape are listed in table 2. Since the allowable bending diameter of the Bi-2223 tape is about 50 mm, the secondary coil was wound on a bakelite bobbin with a slightly larger diameter. In order to increase the mutual inductance M between the primary and secondary coils of the transformer, a normal iron core with a cross-section of 9.6×10^{-4}

Table 2. Specifications of Bi-2223 tape used for the superconducting transformer.

tape width [mm]	4.1 ± 0.2
tape thickness [mm]	0.22 ± 0.02
allowable bending diameter [mm]	50
silver ratio	2.2
critical current [A] (defined with the criterion of 1μV/cm at T = 77 K and self-field)	> 80

m^2 was built in. The whole size of the transformer was about 80 mm × 100 mm × 140 mm and the weight was about 1.5 kg. The transformer was designed for operation at the temperature of liquid nitrogen. Figure 1 shows the image of the transformer.

The control system was constructed with a PC, a 16-bit AD/DA conversion PCI board and a small current supply. The output current (secondary current) of the transformer was evaluated by measuring the voltage on a low resistivity shunt, which was serially connected in secondary winding circuit. The control current (primary current) of transformer was controlled by a normal PID control program written and executed in LabVIEW graphical programming environment (National Instruments) on a PC. With this controlled primary current, the output current was fixed at the target value.

In order to realize an accurate control, the accuracy of the voltage measurement on the shunt is quite important, which means that the shunt having large resistivity is favorable. However, for the purpose of ensuring a small superconducting current damping in the secondary winding circuit, the resistivity value must be kept low enough. In this study, we used a bridge-shaped copper block for the

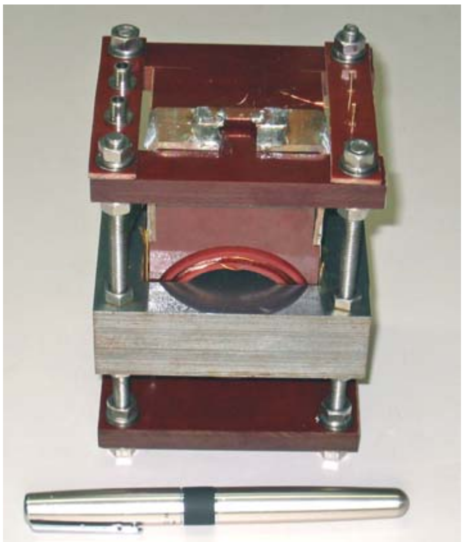

Figure 1. Image of the superconducting transformer. The size is about 80 mm × 100 mm × 140 mm and the weight is about 1.5 kg. The copper bridge on the upper side is used as a shunt for measuring the output current.

shunt, which the resistivity was $4.89 \times 10^{-6}\ \Omega$ at 77K (see figure 1). The voltage on the shunt was amplified to 1000 times by using an isolation amplifier.

3. Results and Discussion

Figure 2 shows the result of the controlled output current (thick line) under the variation of the control current (thin line). The target value of output current was set at 80 A, which is close to the critical current of the Bi-2223 tape used in the transformer. The process of the output current control can be separated into 4 phases along the flow of time, as shown by I – IV in figure 2.

At first phase (phase I), a rapid increase in output current was shown, accompany with a rapid increase in control current. When output current reached the target value, 80 A, then it was controlled as fixed to the target value, by increasing the control current gradually (phase II). Although the variation of output current around target value was controlled within a range less than ± 0.4 %, there is

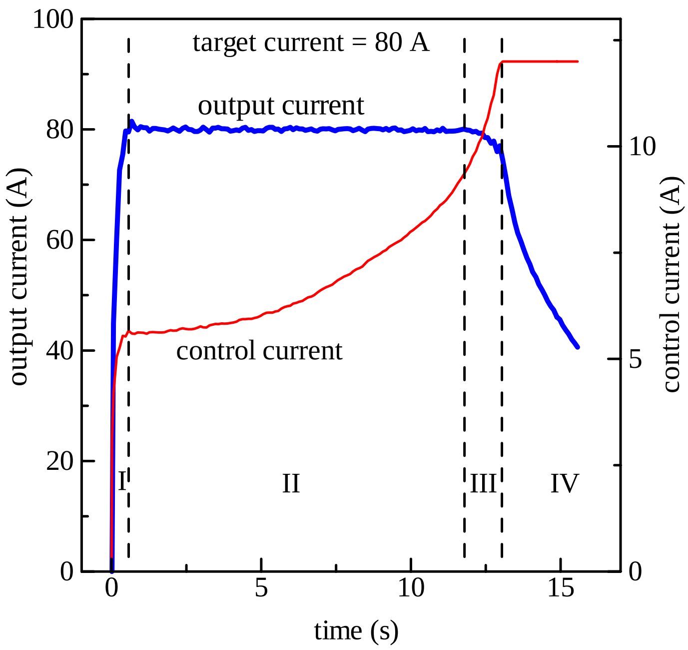

Figure 2. Result of the controlled output current (thick line) under the variation of the control current (thin line).

still a lot of space to reduce the variation to a level below 1 ppm. The large variation was considered to be caused by the electrical noise in the voltage measurement on the shunt, which was used in the feedback control. On the other hand, long duration of phase II is an important factor, while it was limited to a value of about 10 seconds in this study. This is due to the large resistivity serially connected in secondary winding circuit. If we assume the self-inductance and the resistivity in secondary winding circuit are *L* and *R*, respectively, we can get the equation (1):

$$L\frac{\mathrm{d}i}{\mathrm{d}t}+M\frac{\mathrm{d}i_0}{\mathrm{d}t}-Ri=0\ , \tag{1}$$

where i and i_0 are output current and control current, respectively. Since the time differential of i should be zero in phase II, then,

$$i=\frac{M}{R}\frac{\mathrm{d}i_0}{\mathrm{d}t}. \tag{2}$$

This means that if we use a small increase of control current to generate a large output current, *R* should be a sufficient low value, e.g., below 10^{-9} Ω.

For phase III, the increase of control current could no longer keep the output current at the target value. The output current gradually decreased out of control. This was partially caused by a heating effect on Bi-2223 tape, due to the current in primary winding, which may bring a deterioration of critical current in Bi-2223 tape. Finally, the control current reached to the upper limit value, and the output current decayed in the time constant of *L*/*R* (phase IV).

4. Summary

In this study, a low-cost and compact superconducting transformer for DC current generation was fabricated. The secondary coil of the transformer was wound with a superconducting Bi-2223 tape. The control system was constructed with a PC, an AD/DA conversion PCI board and a small current supply, and the control program was written and executed with LabVIEW. As the result of this study, a comparatively stable output current up to 80 A was obtained, with a variation from the target value less than ± 0.4%. In the case of small impedance in secondary winding circuit, it is possible to generate a DC current with high stability and sufficient persistence, by using this system.

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