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High Field and High Temperature Characteristics of Small Test Coil Using CVD-YBCO Tape for SMES

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***Abstract*—Magnetic field dependencies of the I_c of the IBAD/CVD-YBCO short tape sample and its small coil sample were measured in high fields, up to 18 T at 77 K. Compared with the I_c of the tape sample, the I_c of the coil sample at 0.1 $\mu V/cm$ showed the same tendency in high fields. If YBCO tape is applied to a high-field coil application, the application should be operated at a temperature which is lower than 77 K. Using long CVD-YBCO tape, six stacked pancake coils were fabricated. Various current tests were conducted using one of these stacked coils. In AC current tests, thermal stability of the YBCO coil was estimated. When the peak values of AC current were 1.2 times higher than the maximum DC current in a thermal stable state, I_{dcmax}, and the average electric field of the coil at the first triangular wave was about 10 times higher than 1 $\mu V/cm$ criterion, the peak values of the built-up voltage did not tend to increase even after the 99th triangular wave current, and thermal run-away in the coil was not observed. In DC current with overlapped pulse current tests, the maximum peak current of the coil in a thermal stable state was obtained as a function of DC current and sweep time. It was 1.3 times higher than I_c and 1.4 times higher than I_{dcmax} in a test condition. These results indicate that the YBCO coil has high potential in short-time, over-current operations at high temperatures. In cases where built-up voltages did not disappear, they began to increase just after the coil currents reverted to the initial DC currents. It was found that DC current influenced the increasing speed of built-up voltages once the pulse current had decreased to zero.**

***Index Terms*—Coil, high magnetic field, high temperature, SMES, YBCO.**

I. Introduction

SUPERCONDUCTING magnetic energy storage (SMES) has been developed for power system control as a national project in Japan. In the project, an SMES system of 10 MVA–20 MJ for load fluctuation compensation is manufactured and will be installed in an actual field test site, and its power system control technology will be verified, in order to put the SMES into practical use for power system control. Moreover, an HTS coil, a converter, power leads, and a cryo-cooler will be also developed, in order to reduce the overall cost of the SMES system and improve its reliability. Regarding the HTS coil, a coil for SMES using a YBCO coated conductor has been developed for this purpose [1], in collaboration with another national project in Japan (Research and Development of Fundamental Technologies for Superconductivity Applications).

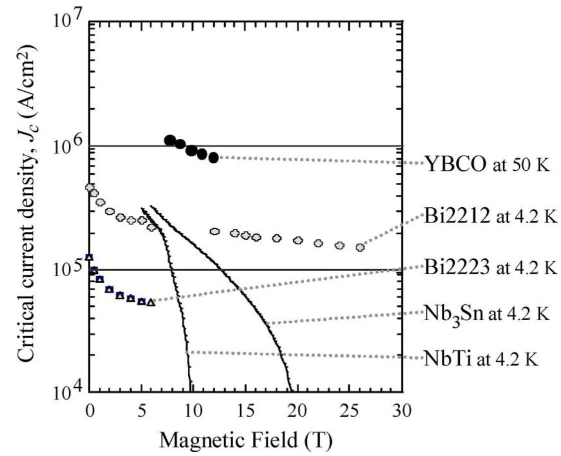

Fig. 1. Comparison of critical current density, J_c of NbTi, Nb_3Sn, Bi2223, Bi2212 and YBCO superconductors in high magnetic field. Temperature is 4.2 K except for YBCO.

Critical current density, J_c of NbTi, Nb3Sn, Bi2223, Bi2212 and YBCO superconductors in high magnetic fields are compared in Fig. 1. This figure shows that YBCO coated conductors have much higher transport properties in high magnetic fields, even at high temperatures, than conventional metallic superconductors and other HTS conductors. Taking this advantage of YBCO coated conductors, a YBCO coil for SMES, applied at a higher temperature than that of boiling helium and applied in a higher magnetic field than that applied to NbTi, can be compact and used in high-temperature operations [2]. These applications lead to lower cost and higher reliability, which are required for SMES.

From this viewpoint, we have been investigating high magnetic field and high temperature characteristics of YBCO coils.

All test samples in this report were fabricated by depositing a YBCO layer on a Hastelloy substrate with PLD-CeO_2 and IBAD-$Gd_2Zr_2O_7$ buffer layers by a multi-stage metal-organic chemical vapor deposition (CVD) technique [3]–[5], and by sputtering silver as a protective and stabilizing layer.

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TABLE I
SPECIFICATIONS OF THE SHORT YBCO TAPE SAMPLE

Thickness	Substrate	Hastelloy C276	100 μm
	Buffer layer	IBAD-$Gd_2Zr_2O_7$	1 μm
		PLD-CeO_2	0.4 μm
	Superconducting layer	CVD-YBCO	1.1 μm
	Protective layer	Ag	10 μm
Width			10 mm
Total Length			100 mm
Critical current @ 77 K, s.f.			80 A

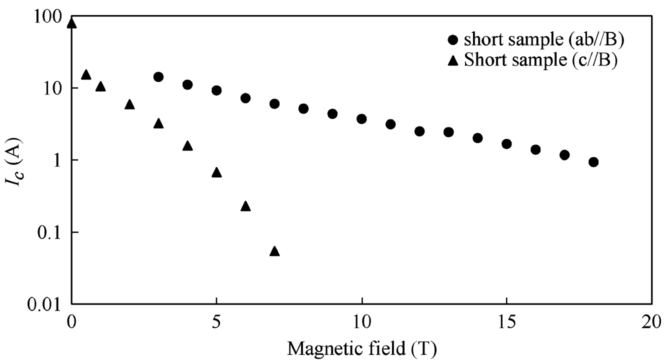

Fig. 2. Magnetic field dependencies of I_c of the IBAD/CVD-YBCO short tape sample. External magnetic fields were applied to the sample parallel and perpendicularly to its ab-plane.

II. High Field Characteristics of YBCO Tape and Coil

A. Short YBCO Tape

The specifications of a short IBAD/CVD-YBCO tape sample for high magnetic field tests are summarized in Table I. We applied a transport current without narrowing the 10 mm width of the YBCO tape sample (having an I_c of 100 A class at 77 K and self-field). This approach enabled us to estimate macroscopic characteristics of YBCO tape in high fields for power applications.

Fig. 2 shows the I_c of the IBAD/CVD-YBCO short tape sample measured in high fields of up to 18 T at 77 K. External magnetic fields were applied to the sample parallel and perpendicularly to its ab-plane. The I_c at a perpendicular field of 5 T was about one hundredth-part of the Ic at 0 T, and the I_c at a parallel field of 5 T was about one tenth-part of that. The I_c at 18 T was decreased to 1 A even in parallel fields. If YBCO tape is applied to a high-field coil application, a coil application should be operated at a temperature which is lower than 77 K.

B. Small YBCO Coil

IBAD/CVD-YBCO tape was wound into the test sample of a small YBCO coil. The specifications of the coil sample are summarized in Table II, and its appearance is shown in Fig. 3. The I_c of the coil sample was measured at 77 K in external magnetic fields. External magnetic fields were applied to the coil parallel to its ab-plane. Magnetic field dependency of critical current, I_c at the electric field of 0.1 $\mu\mathrm{V/cm}$ was shown in Fig. 4. The I_c value at a parallel field of 11 T was decreased to 2.5 A. Compared with the I_c of the tape sample, the I_c of the coil at 0.1 $\mu\mathrm{V/cm}$ showed the same tendency in high fields.

TABLE II
SPECIFICATIONS OF THE YBCO COIL SAMPLE

Tape type	IBAD/ CVD-YBCO
Width	10 mm
Thickness	0.12 mm
Length	0.15 m
Coil Type	Single solenoid
Number of layers	1
Number of turns	3
Inner diameter	ϕ 36 mm
Outer diameter	ϕ 37 mm
Height	30 mm
Inductance	0.25 μH

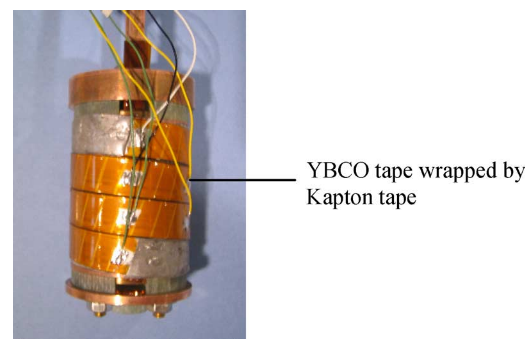

Fig. 3. The appearance of the IBAD/CVD-YBCO coil sample before impregnated.

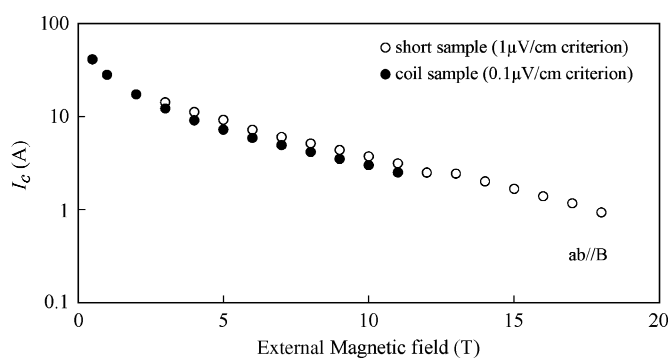

Fig. 4. Magnetic field dependency of I_c of the IBAD/CVD-YBCO coil sample compared with the short tape sample. External magnetic fields were applied to the coil sample parallel to its axis.

III. High Temperature Characteristics of YBCO Coil

A. Test Coil Sample

Using long CVD-YBCO tape, six stacked pancake coils were fabricated. The specifications of the coils are summarized in Table III and their appearance is shown in Fig. 5. The coils were excited at 65 K in decompressed liquid nitrogen, where their operating current was 85 A. The excited maximum field of the coils was 0.65 T at the conductor.

Various current tests, such as AC currents, and DC currents with overlapped pulse currents, were conducted using one of these stacked coils. The I_c of the coil at 77 K and self-field was

TABLE III
SPECIFICATIONS OF THE YBCO COIL SAMPLE

YBCO type	IBAD/ CVD-YBCO tape
Tape size	10 mm-width, 81 m-length
Coil Type	Single pancake
Number of Turns	520 turns
Number of Coils	6 (stacked)
Inner diameter	ϕ 36 mm
Outer diameter	ϕ 64 mm
Height	77 mm
Self inductance	5.5 mH
Maximum field	0.65 T @ 65 K

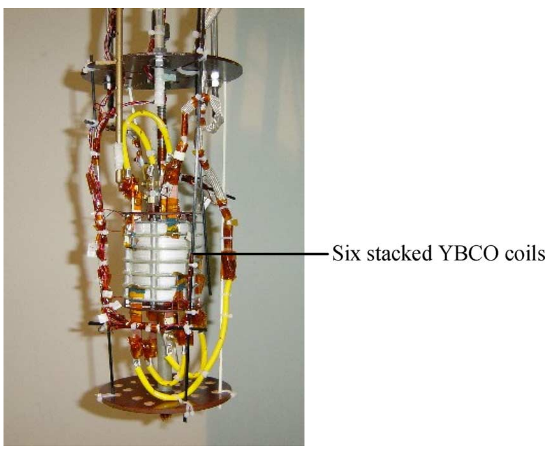

Fig. 5. The appearance of six stacked pancake coils, using long IBAD/CVD-YBCO tape.

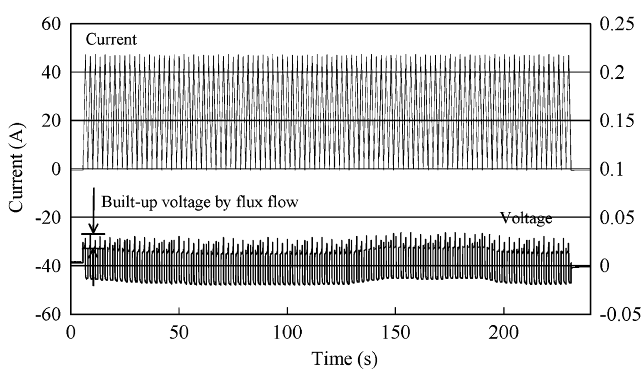

Fig. 6. Transitions of the coil voltage and current in an AC current test, and the coil's thermal stable state.

43 A, and the maximum DC current in a thermal stable state at 77 K, I_{dcmax} was 39 A.

B. AC Current Test

The end-to-end voltages of the coil were measured as AC currents excited the coil. The waveform of the AC currents was triangular, and the sweep-up and sweep-down times were both 1 s.

Fig. 6 shows transitions of the coil voltage and current, when the peak values of the AC current were 47 A which was 1.2 times higher than I_{dcmax}. Built-up voltage at the first triangular wave was 0.02 V, which was about ten times higher than the average electric field criterion of the coil, 1 $\mu\mathrm{V/cm}$. In this case, the peak of the built-up voltage did not tend to increase even after the 99th triangular wave current, and thermal run-away in the coil was not observed.

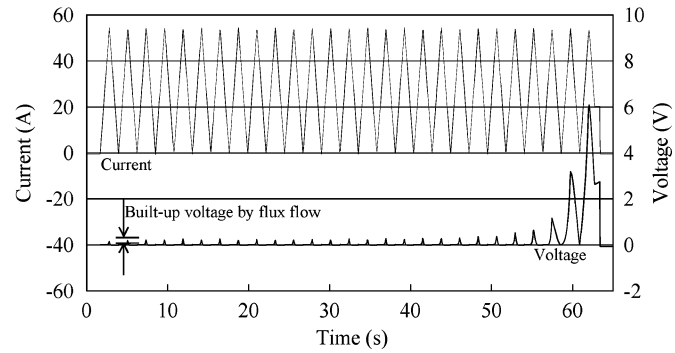

Fig. 7. Transitions of the coil voltage and current in an AC current test, and the coil's thermal unstable state.

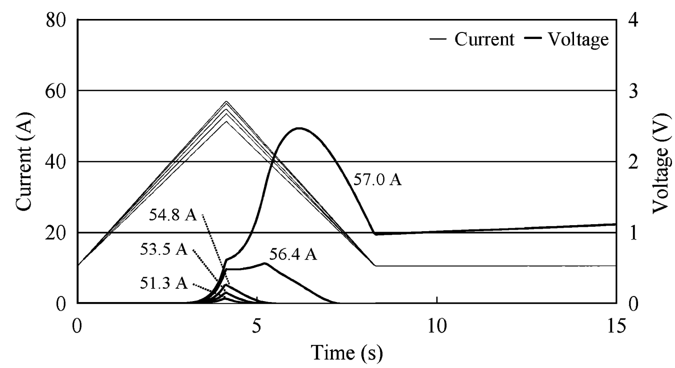

Fig. 8. Behaviors of built-up voltages of the coil in DC currents overlapped with pulse currents tests.

Fig. 7 shows transitions of the coil voltage and current, when the peak values of the AC current were 54 A which was 1.4 times higher than I_{dcmax}. Built-up voltage at the first triangular wave was 0.15 V, which was about a hundred times higher than the average electric field criterion of the coil, 1 $\mu\mathrm{V/cm}$. In this case, the peak of the built-up voltage increased gradually and was over 6 V at the 27th triangular wave current, just before its current was damped. Tendency for thermal run-away in the coil was observed.

C. DC Current With Overlapped Pulse Current Test

DC current with overlapped pulse current tests were conducted in order to evaluate the short-time overloaded characteristics of the YBCO coil. Fig. 8 shows the outcome of these tests. After the coil was excited by a DC current, 10 A, which was about one-fourth of the I_c, it was overlapped with the pulse currents, whose peak values were 51.3, 53.5, 54.8, 56.4, and 57.0 A. The sweep-up and sweep-down times were both 4 s. The transition of the currents and the voltages are shown in this figure. As far as pulse currents were 56.4 A, the built-up voltages disappeared. In the case of a pulse current of 57.0 A, the built-up voltage began to decrease from the point of 2.5 V, 35 A, but stopped to decrease and began to increase due to the DC current, even after the pulse current decreased to zero. The maximum

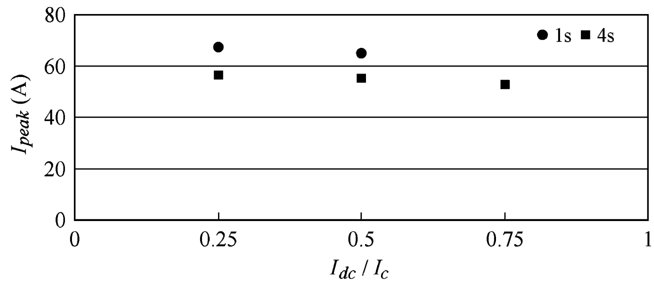

Fig. 9. Maximum peak current versus DC current and sweep time relationship of the coil within a thermal stable state.

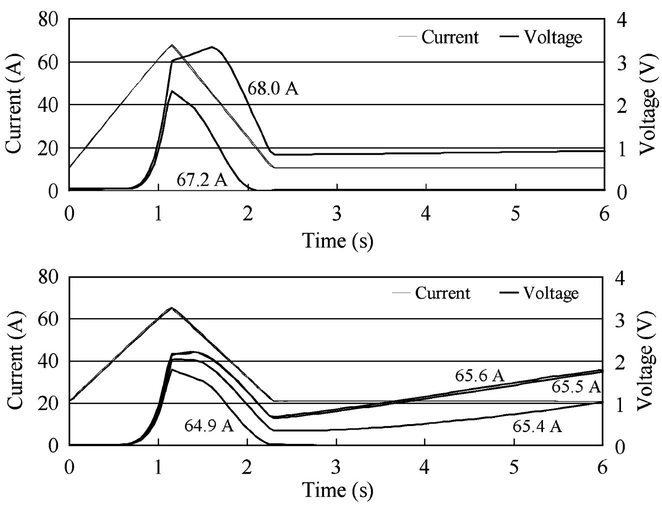

Fig. 10. Voltage transitions in the cases of 10 A and 20 A DC currents after pulse currents decreased to zero.

peak current of the coil in a thermal stable state was obtained: it was 1.3 times higher than I_c and 1.4 times higher than I_{dcmax}.

The maximum peak currents were obtained by the same method in cases where DC currents were one-fourth, one-half, and three-fourths I_c, and sweep-up times were 1 s and 4 s (as shown in Fig. 9). The lower the DC currents were, the higher the peak currents were, and the peak currents of a sweep-time of 1 s were much higher than those where the sweep time was 4 s. These results indicate that the YBCO coil has high potential in short-time, over-current operations at high temperatures.

Fig. 10 shows voltage transitions in the cases of 10 A and 20 A DC, which were one-fourth and one-half of the I_c respectively, in the DC current with overlapped pulse current tests. The sweep-up and sweep-down times were 1 s and 1 s in both cases. In cases where built-up voltages did not disappear, the built-up voltages began to increase just after the coil currents reverted to the initial DC currents. Voltage increasing speed was about 0.03 V/s and about 0.3V/s in the cases of 10 A and 20 A DC, respectively. Although the voltage of 20 A DC was lower than that of 10 A DC at the points where pulse currents were decreased to the initial DC currents, the voltage increasing speed of 20 A DC was much higher than that of 10 A DC. These results indicate that DC current influences the increasing speed of built-up voltages once the pulse current has decreased to zero.

IV. Conclusion

The I_c of the IBAD/CVD-YBCO short tape sample and its coil sample as a function of high magnetic field of up to 18 T at 77 K were obtained. If YBCO tape is applied to a high-field coil application, the application should be operated at a temperature which is lower than 77 K.

Using long CVD-YBCO tape, six stacked pancake coils were fabricated. Thermal stability was estimated using one of the stacked coils. When the peak values of AC current were 1.2 times higher than I_{dcmax}, and the average electric field of the coil at the first triangular wave was about 10 times higher than 1 $\mu\mathrm{V/cm}$ criterion, the peak values of the built-up voltage did not tend to increase even after the 99th triangular wave current, and thermal run-away was not observed.

In the DC current with overlapped pulse current tests, the maximum peak current of the coil in a thermal stable state was obtained as a function of DC current and sweep time. It was confirmed that the YBCO coil had high potential in short-time, over-current operations at high temperatures.

In cases where built-up voltages did not disappear, they began to increase just after the coil currents reverted to the initial DC currents. It was found that DC current influenced the increasing speed of built-up voltages once the pulse current had decreased to zero.

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