Trapped Field Measurements of Gd-Ba-Cu-O Bulk Superconductor in Controlled Pulse Field Magnetizing

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Abstract. For large-scale electric power application of the melt-processed high temperature superconductor (HTS) bulks, especially at rotating machine, development of trapping much higher magnetic fields by using pulsed magnetization technique is essential. It is difficult to use static field cooling (FCM) technique that is most effective magnetizing method for the general industrial HTS applications, because the FCM requires large-scale superconducting magnets. Because the rise in temperature due to the magnetic flux motion decreases the pinning force, we controlled the magnetic flux penetrating to the bulk for the effective magnetization. A couple of vortex-type copper coils applied a magnetic field to a Gd-Ba-Cu-O bulk, which dimension was 45 mm in diameter and 19 mm in thickness. HTS bulk was magnetized by the controlled pulse field without passive LCR pulse. We controlled waveform by using the discharge current that IGBT chopper in pulse magnetizer intermitted. We applied the pulse magnetic field with the various risetime to the HTS bulk in liquid nitrogen. The various conditions of the controlled waveform pulse to trap well-dressed profile magnetized the Gd-Ba-Cu-O bulk, strongly at 77 K. In the present study, we show several properties which was measured in the PFM of the HTS bulk.

1. Introduction
The high temperature superconductor (HTS) bulks with strong pinning effect trap much higher magnetic fields than usually conventional permanent magnets[1, 2]. To use for the advanced industrial power applications, we are interested in motion of magnetic flux in melt-processed RE-Ba-Cu-O (RE is a rare earth elements) bulk superconductor to use for the advanced industrial power applications. Because superconductors with strong flux pinning force can improve the performance of rotating machines. For the last few years, we have developed axial-gap type synchronous motor by using the large single grain HTS bulks[3]. The pulse field magnetization (PFM) method which we proposed can apply HTS bulk magnet within the motors by using a couple of armature copper coils because it is difficult to apply conventional field cooled magnetization (FCM) in the general industrial applications[4]. The suitable PFM technique is a prerequisite in situ magnetization for the rotating electrical machinery use of HTS bulk.
which are intended to be used as cryo-magnets at temperatures well below 77K. However, pulse magnetic field that the small copper coils generate doesn’t magnetize the HTS bulks effectively. By applying the strong pulsed field, the trapped magnetic flux density distribution was distorted asymmetrically and decreased by a large amount of heat generation which originated in the dynamic flux motion.[4, 5, 6].

Recently, several research groups proposed the new PFM method by multi-pulse technique, named the IMRA and MPSC [7, 8, 9], which methods enhanced trapped magnetic flux density at the bulk centre because of iterative pulsed field application while the trapped peak field was low. However, multi-peak PFM methods require time for magnetizing operation of the motor which includes multiple HTS bulk. For practical HTS bulk magnetizing, we must suppress magnetic flux motion which is generated by the pulsed magnetic field. In general, a magnetizer generates pulse field passively due to LCR circuit load. During turn-on, the magnetic field rises by a passive LCR transient response at pulse magnetizer and excessive $\frac{dB}{dt}$ causes the magnetic flux motion in HTS bulk. Consequently, performed waveform control pulse magnetization (WCPM) which was controlled magnetizing pulse shape actively to generate various $\frac{dB}{dt}$ by using PWM at fixed frequency[10]. In this present, we show the result of WCPM magnetization by single-pulse technique.

2. Experimental procedure
A highly c-axis oriented Gd-Ba-Cu-O bulk sample (GdBa$_2$Cu$_3$O$_{6.9}$ 70.9 wt %, Gd$_2$BaCuO$_5$ 19.2 wt %, Ag 9.4 wt %, Pt 0.5 wt %) which was made by melt growth process was used for measurements. The dimensions of the sample is 45 mm in diameter and 19 mm in thickness. By using the static magnetic field in field-cooled magnetization at 77 K, we obtained the maximum trapped flux density of 1.7 T with a conical distribution on the sample surface.

Trapped magnetic flux density on the growth sector (GS) regions and the growth sector boundaries (GSB) was measured by using five Hall probe (THS118), which was mounted 2 mm above the sample surface. For PFM, the bulk sample was sandwiched with an interval of 5 mm between two vortex-type copper coils of inductance 650 µH with 84 mm in diameter and 20 mm in thickness. The couple of magnetizing coils increased a magnetic field to the conical shape distribution along the central axis of the sample in the maximum flux density. The bulk and copper coils were into the liquid nitrogen. Figure 1 shows schematic illustration of the sample geometry.

It is necessary that a pulse field magnetizer is used to generate electronic impulses with large
Figure 2. PFM circuit for HTS bulk.

Figure 3. Time evolution of the magnetic flux density at $B_{ex} = 5.4$ T for different period of switching. Collector-emitter voltage for IGBT is shown in square wave of inset. The switching period of (a) is different from (b).

energy for many practical applications with HTS bulk. A pulse magnetizer causes intensive flux motion in HTS bulk because the generation of the magnetic field uses electric discharge from LCR circuit. However, we controlled the electrical current flow from the capacitor actively by using the semiconductor chopper so that slow risetime was realized. The pulse waveform is not exponential curve which generates LCR circuit. Our pulse magnetizer is shown in figure 2. The voltage multiplier worked out to maximum 1 kV DC from 100 V AC and the IGBT device discharge energy of 25 kJ that the capacitor bank in magnetizer stores. The low-side switch by IGBT discharged the electric static energy which was charged for the capacitor. For waveform control, the IGBT is used as the chopper, which accomplishes the on-off control of current flowing from the capacitor bank to a couple of vortex pulsed coils. We measured magnetic flux density on the bulk surface during WCPM magnetization.

IGBT require certain turn-on and turn-off times for waveform control. The condition of $di/dt$ and $dv/dt$ are set by the IGBT switching characteristics and must be satisfied during turn-on and turn-off. Protection circuit is normally required to keep the operating $di/dt$ and $dv/dt$ within the allowable limits of IGBT. The RCD (Resistor, capacitor and diode) snubber which was one of the kinds of the snubber circuit brought the lowest impulse noise to our magnetizer. Therefore, we prepared by the RCD snubber circuit because of the IGBT device protection.
3. Results and discussion

Figure 3 shows time evolution of the magnetic flux density on each region of the sample surface while the bulk was once magnetized by WCPM. Inset shows the collector-emitter voltage ($V_{CE}$) signal that needed for the waveform control. Duty ratio of 50% generated the pulse, respectively. The switching period in figure 3 is $T = 1.2$ ms and 4.2 ms, respectively. The high-speed impulses within the external magnetic field and $V_{CE}$ signal are the electric noise which could not be removed due to the snubber circuit among switching. A pulse magnetic field by WCPM causes the minute vibration. This saw wave-shaped vibration may increase $dB/dt$. Because periodic 4.2 ms is slow, the vibration of the external applied magnetic field appears clearly in the curve. The curves of penetrating magnetic field have a vibration corresponding to the external magnetic flux density $B_{ex}$. However, when the curve of $T = 4.2$ ms is compared with the curve of 1.2 ms, the magnetization experiments for the same condition except for the period showed the equivalent magnetic characteristics. Consequently, minute vibration within $B_{ex}$ by WCPM doesn’t influence the magnetic properties.

We measured the strong trapped magnetic flux density and conical distribution when the external pulsed field was around 5.4 T. While the bulk was magnetized by each controlled pulse field of about 5.4 T, figure 4 shows time evolution of the magnetic flux density on the sample surface at centre. During magnetizing, we controlled the waveform of the external applied magnetic field with a constant period which is about 1 ms. In this study, risetime $t_r$ is close from to 20.8 ms, $E = 1.56$ kJ. $t_r = 49.8$ ms, $E = 3.37$ kJ $B_{ex} = 5.4$ T

Figure 4 shows time evolution of the magnetic flux density on each region of the sample surface at centre. During magnetizing, we controlled the waveform of the external applied magnetic field. Inset is time evolution of the magnetic flux density for five seconds.

Figure 5. The comparison of the different duty ratio in the magnetization by the electrostatic energy of $E = 3.06$ kJ. External flux density $B_{ex}$ at duty ratio of 70% and 30% is shown in inset.
the controlled pulse with a constant period is narrow. It is important to study the behavior of the magnetic flux motion in range of this condition for the efficient magnetization.

Though, we may generate advanced pulse waveform for HTS bulk magnetization to suppress the magnetic flux motion which increases magnetization efficiency. In this study, the penetration pulse field with long risetime from $t_r = 10$ ms to 50 ms magnetized the HTS bulk. The time evolution of magnetic flux density with variation of duty ratio and magnetizing electrostatic energy of $E = 3.06$ kJ at the bulk centre is shown in figure 5. All of the curves with various duty ratio increase $dB/dt$ about 1.7 T. The bending exists in the curves of the figure 4 as well. Inset in figure 5 shows the time evolution of $B_{ex}$ which doesn’t include the change of $dB/dt$. The magnetic density of gradient which changes doesn’t depend on magnetization elapsed time and magnitude of the applying or penetrating magnetic flux density. The curve inflections are not measured clearly in other regions on the bulk. Dashed line in figure 5 shows the magnetizing flux density of $B = 1.7$ T by using the static magnetic field in FCM at 77 K. This fact suggests the possibility that the magnetic saturation in the bulk influences the dynamic magnetic flux motion.

4. Conclusion

Gd-Ba-Cu-O bulk was magnetized by using the controlled PFM. The vibration noise within magnetizing field of the controlled waveform, which period is the range from 1 ms to 5 ms, didn’t affect the magnetic flux density distribution. HTS bulk trapped 1.12 T of magnetic flux density with conical distribution. Because of the wide range of the condition in effective magnetization, the controlled period should be set up suitable to increase the trapped magnetic flux density. At that time, PFM by using the novel waveform will show more suitable magnetic characteristics.

Magnitude of the magnetic flux density which is trapped by using the static magnetic field in FCM becomes the boundary of the different $dB/dt$ at PFM process. The boundary exists for the inherent magnetic properties of the bulk. It may provide necessary information to magnetize HTS bulk to understand the penetration magnetic flux motion on the bulk with paying attention to the boundary.

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