Manuscript Number: EUCAS180R1

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Article Type: Poster

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Trapped Magnetic Field Measurements on HTS Bulk by Peak Controlled Pulsed Field Magnetization

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Abstract. For the past several years, we have studied the high-temperature superconducting (HTS) synchronous motor assembled with melt-textured Gd-Ba-Cu-O bulk magnets. If the single pulse field magnetizes a bulk effectively, size of electrical motor will become small for the strong magnetic field of the HTS magnets without reducing output power of motor.

In the previous study, we showed that the HTS bulk was magnetized to excellent cone-shape magnetic field distribution by using the waveform control pulse magnetization (WCPM) method. The WCPM technique made possible the active control of the waveform on which magnetic flux motion depended. We generated the pulse waveform with controlled risetime for HTS bulk magnetization to suppress the magnetic flux motion which decreases magnetization efficiency. The pulsed maximum magnetic flux density with slow risetime is not beyond the maximum magnetic flux density which is trapped by the static field magnetization. But, as for applying the pulse which has fast risetime, the magnetic flux which exceed greatly the threshold penetrates the bulk and causes the disorder of the trapped magnetic distribution. This fact suggests the possibility that the threshold at pulsed magnetization influences the dynamic magnetic flux motion.

In this study, Gd-Ba-Cu-O bulk is magnetized by the controlled arbitrary trapezoidal shape pulse, of which the maximum magnetic flux density is controlled not to exceed the threshold. We will present the trapped magnetic characteristics and the technique to generate the controlled pulsed field.

1. Introduction
The further demand for electric power applications for electric rotating machine and industrial magnetic devices existed for many years. However, low residual magnetic flux density suppressed the output of the electric power machinery. The high temperature superconductor (HTS) bulks with strong pinning effect trap much higher magnetic fields than usually conventional permanent magnets[1, 2]. We are interested in motion of magnetic flux in melt-processed RE-Ba-Cu-O (RE is a rare earth elements) bulk superconductor for the advanced industrial power applications, because the trapped magnetic field of the superconductor depends on magnetic flux pinning force. For the last several years, we have developed axial-gap type synchronous motor by using the large single grain HTS bulks[3]. Because it is hard to attach cooled bulk to the general
industrial power applications, it is difficult to apply conventional FCM to HTS bulk. 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[4]. The suitable PFM technique magnetizes HTS bulk of cryo-magnet at temperatures well below 77K in necessary magnetic flux density to use the electrical rotating machinery. 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 transient flux flow upon pulsed field magnetization[4, 5, 6]. To have enough magnetization in utilization, the shielding characteristics associated with the transient heat due to the flux motion have to be overcome[7].

Recently, several research groups proposed the new PFM method by multi-pulse technique, named the IMRA and MPSC[8, 9, 10]. The multi-peak PFM methods enhanced trapped magnetic flux density at the bulk centre because of iterative pulsed field application while peak of the trapped magnetic field was low. However, the method of these magnetization needs long time to magnetize it when we use an electromagnetic machinery including multiple HTS bulk. For practical HTS bulk magnetizing, we must suppress magnetic flux motion which is generated by the pulsed magnetic field. The general pulse magnetizer generates pulse magnetic fields for LCR circuit load. During turn-on, the magnetic field increases for a passive LCR transient response by pulse magnetizer and excessive $dB/dt$ causes the magnetic flux motion in HTS bulk.

So far, researchers magnetized a bulk material by a PFM depending on LCR transient response. However, the trapped magnetic flux density in the bulk may increase when the pulse magnetic field with arbitrary profiles suppresses a magnetic flux motion. Such a pulse magnetic field can come true by waveform control pulse magnetization (WCPM) which is controlled magnetizing pulse shape actively to generate various $dB/dt$ by using PWM at fixed frequency[11]. The controlled period should be set up suitable to increase the trapped magnetic density for the wide range of the condition, which is maximum peak magnetic flux density, rise-time and pulse duration, to obtain effective magnetization. In this present, we show the result of WCPM technique to obtain high magnetization by applying single-pulse with arbitrary waveform.

2. Experimental procedure
It is necessary that a pulse field magnetizer is used to generate electronic impulses with large energy for HTS magnet. The electric discharge from passive LCR circuit causes a magnetic flux motion with a sudden magnetic flux penetration. The state of the magnetic flux penetration can improve by pulse width modulation (PWM) control. The configuration of our WCPM magnetizer by PWM control is shown in figure 1. The voltage multiplier generates up to 1kV DC from 100V AC and discharges energy of up to 25 kJ from the capacitor bank by IGBT. The
To pulse magnetizer

Liq. nitrogen

Vortex-type copper coil

5-Hall sensor

6 mm

2 mm

GSB

1-5 : Hall sensor

GS

GS

GS

GS

To data logger

To MCU

Bulk

Figure 2. Bulk sample configuration for magnetization and measurement. (a) Configuration of coupled pulsed copper coils and superconducting bulk and measurement position of magnetic flux density. (b) Geometry schematic of Hall sensor on the bulk surface.

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. The pulse waveform is arbitrary curve which semiconductor switch of IGBT (which has high input impedance, like MOSFET, and low on-state conduction losses, like bipolar transistor) generates. The gating signal of a IGBT and magnetic flux distribution is shown in ref. [12]. The gate of a IGBT is turned on and off several hundred times while an exponential positive pulse magnetic field is applied. The flywheel diode prevents the reverse voltage from appearing IGBT semiconductor switch by density load of magnetization coils. Besides, the diode supplies the flywheel paths for the load current, when IGBT is in the off-state. While gate signal turned IGBT off, the magnetic field decreasing gently is released. Accordingly, the pulse magnetic field by WCPM causes saw wave-shaped vibration for an instant. But the vibration within applied external magnetic field by WCPM doesn’t influence the magnetic characteristics[12]. The slope of the slight vibration which is not outstanding by high frequency is decided by the duty ratio. The IGBT which a MCU (H8/3052F 16 bit micro controlled unit, Renesas Technology) controls forms a arbitrary pulse magnetic waveform.

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.

During WCPM magnetization, we measured a magnetic flux density on the bulk surface by using a magnetic sensor, which is shown in figure 2. Trapped magnetic flux density on the growth sector (GS) regions and the growth sector boundaries (GSB) was measured by using five Hall probe (THS118, Toshiba). The five Hall sensors were fixed on 2 mm above the sample surface. In addition, the output voltage obtained from a hall sensor put on the bulk centre was fed back to MPU. For PFM, the bulk sample was sandwiched with an interval of 5mm between two vortex-type copper coils of inductance 650 $\mu$H with 84 mm in diameter and 20 mm in thickness. Because a wire is wound up to the center, the vortex-type coil is not hollow unlike a general solenoid coil. Consequently, the magnetic field distribution becomes to the conical shape along the central axis of the vortex-type coil[4, 13]. The couple of magnetizing vortex-type coils increased a magnetic field. The bulk and copper coils were immersed in the liquid nitrogen.
Figure 3. Magnetic flux density on the bulk centre. The electrostatic energy used for an electric discharge is 4 kJ. Inset is time evolution of driving current of the pulse coils.

Figure 4. The time evolution of the magnetic flux penetration by the 2nd duty ratio from 3% to 20%.

3. Results and discussion

In preliminary result, when we applied pulsed magnetic field with the wide range of different maximum peak, it was found at the bulk centre that magnetic flux penetration increased rapidly more than 1.7 T[12]. During risetime of the pulse magnetic field, a point of inflection was found around 1.7 T (see black solid line in figure 3). When the maximum peak of the applied magnetic field was increased or decreased, we got the sudden increase or decrease of the magnetic flux penetration at the threshold which is around a point of inflection. The weak applied magnetic flux density did not penetrate the bulk at magnetic flux density more than 1.7 T. The magnetic flux penetration in the bulk centre that is lower than this point of inflection gave a low trapped magnetic field to the bulk magnet. On the other hand, maximum peak of the magnetic flux penetration exceeded threshold of 1.7 T suddenly when we increased the applied magnetic flux density. The applied magnetic field with maximum peak, which exceeded 1.7 T, magnetized bulk in the conical shape of regular. However, it distorted trap magnetic field distribution to increase magnetic field excessively. Additionally, the static magnetic field of 1.7 T magnetizes this bulk centre with regular conical shape. The existence of the point of inflection suggests that a state of the magnetic flux motion changes at around the threshold of magnetic flux density. In this present study, we show the time evolution of magnetic flux penetration with controlled applied magnetic flux density by WCPM at about 1.7 T.

Figure 3 shows the result of the applied pulse magnetic field to a HTS bulk. The magnetic flux density is measured at bulk centre on sample surface. The energy of 4 kJ is changed to the magnetic field of various waveform for the bulk magnetization. The bulk traps $B_T = 0.488 T$ of magnetic field by the regular magnetization pulse of the exponential shape magnetic field made from LCR circuit for the duration of about 150 ms (gray open circle). The low trapped magnetic flux density shows that the the energy of 4 kJ is too high for bulk trapping in a magnetic field. However, the trapped magnetic flux density increased more than double, because of long risetime[12] and long duration[7] of pulse. Accordingly, we magnetized bulk by using applied magnetic field that did not exceed threshold of 1.7 T by controlling risetime under WCPM. At first, the magnetic fields increase at long risetime by 50% of duty ratios, which traps high magnetic field in previous experiments. When an penetration magnetic field at centre of bulk surface reaches 1.7 T, the magnetizer changes the duty ratio and distorts the pulse waveform for different risetime and duration. The applied magnetic flux density can be controlled by feedback from pulse electric current. While the magnetic field to apply to bulk is suppressed by
Figure 5. Magnetic flux density above the bulk at different threshold to change duty ratio around 1.7 T. 2nd duty ratio is 15%. Trapped magnetic flux density is $B_T = 1.219 T( B_{th} = 1.84 T), 1.223 T(1.7 T)$ and $1.137 T(1.56 T)$, respectively. The impulse vibrations on current are the switching noise of the high voltage.

1.7 T, the magnetic flux penetration to the bulk centre increases via the threshold, because of remanent magnetic flux motion from around circumference of the bulk disk to the centre. As a result, pulse magnetic field for about 450 ms duration is applied. The bulk traps $B_T = 1.157 T$ of high intensity magnetic flux density by the single applied magnetic field of the same energy made from WCPM (black solid line). Inset in figure 3 shows the pulse current waveform, respectively. The minute vibrations on deformation current signal are the switching noise of the high voltage that depends on WCPM. The pulse generator of WCPM produces an arbitrary trapezoidal magnetic waveform by chopping electric charge from capacitor bank. The switching period at waveform are 1 ms, respectively. The duty ratio decides a pulse current waveform because the period short enough does not influence trapped magnetic field[12].

The time evolution of the magnetic flux penetration by the second duty ratios from 3 % to 20 % is shown in figure 4, respectively. Because all pulse is generated by same electrostatic energy, the pulse with low peak has long decay time. The bulk is hard to trap the pulse magnetic field such as 3-5 % of second duty ratio is not beyond 1.7 T in most time. When a magnetization device keeps a magnetic field more than threshold of 1.7 T for a long time, the trapped magnetic flux density increases. While magnetic field is trapped to bulk, the pulse of a low peak invasion magnetic field decays gently. However, the duty ratio more than 18 % increases rapidly magnetic field slopes of the decay. Because magnetic fields in bulk suddenly decrease, the trapped magnetic flux density lowers. In the high magnetic field of penetration, the bulk suppresses the increase of the pulsed magnetic field. There is the crossover of the decay slope at duty ratio 15 %, then the bulk trap 1.223 T of the maximum trapped magnetic field. This is 2.5 times of the trap magnetic field by the LCR pulse and, besides, exceeds greatest
trapped magnetic field 1.12 T which we got in this bulk sample by WCPM. The high magnetic field has a point of inflection after 10-20 ms of the peak. This may originate in the change that is in a state of the magnetic flux motion.

The varying of the magnetic field to switch from the 1st duty ratio to the 2nd duty ratio around the threshold at 1.7 T is shown in figure 5. When the threshold $B_{th}$ changes near 1.7 T, the influence is seen in a trapped magnetic field characteristics. As for three curves in all graphs, the switch threshold of the duty ratio is $B_{th}$ = 1.56 T, 1.70 T and 1.84 T, respectively. Similarly, the trap magnetic field in the bulk centre is 1.137 T, 1.223 T and 1.219 T, and the trapped magnetic field of $B_{th}$ = 1.56 T is lower slightly than others. When the threshold is more than 1.7 T and not too high, the bulk traps high intensity magnetic flux density. According to figure 5(a) and (d), it is thought that the threshold does not influence the invasion of the magnetic field from the outer periphery of the bulk, because each curve does not have a clear difference. It suggests that magnetic flux is easy to move at GSB than GS to be lower peak magnetic flux density. The difference of threshold influences trapped magnetic flux density at GSB and the bulk centre. According to the difference of curves at GSB and centre, characteristics of the magnetic flux motion may change at around 1.7 T as for this bulk.

Sander, et al. said that higher magnetizations were found for the longer pulses at around 77 K[7]. In this study, we applied a long trapezoid-shaped pulse magnetic field near the threshold of 1.7 T which exists while pulse magnetic field increases. The pulse magnetizer uses the feedback from a hall sensor for bulk centre to output constant magnetic field. The information of the magnetic field is given back to MCU through our own isolated 16-bit A/D converter. MCU of the magnetization device attempted the stability of the output pulse by PI control. The magnetic flux density when I applied the pulse magnetic field that a magnetization device feeds back and controlled to bulk is shown in figure 6 and 7.

The magnetizer gave bulk a low pulse magnetic field again after the first pulse magnetic field is reduced because a proportion gain was too big in figure 6. According to figure 3, the exponential pulse magnetic field of 4 kJ magnetized bulk to about 0.5 T. However, these two lumps shape pulse magnetic field magnetized bulk to 0.999 T. While magnetic flux was left in bulk after the first pulse magnetic fields to apply decreased, the 2nd applied pulse added magnetic field to the bulk.

Figure 6. Magnetic flux density on the bulk centre at $B_T = 0.999$ T. Because of the slow control, the magnetic field vibrated widely at around 1.7 T. Inset is magnetizing pulse current.

Figure 7. The magnetization by the pulse magnetic field that kept magnetic flux density for a long time at around 1.7 T. State of the pulse driving current vibration is shown in inset.
Thus pulse field with the lower proportion gain magnetized the HTS bulk. The target of the control magnetic field is 1.7 T. The behavior of the PWM generator of MCU is incomplete, but the figure shows result of the pulse control. The fluctuation of magnetic field to apply will cause local heat in the HTS bulk sample. Notwithstanding, the HTS bulk sample realized trapped magnetic flux density of 1.07 T and regular conical shape distribution because we exceeded heat suppression by this magnetization. In general, the applied magnetic field less than 1.7 T for long pulse duration can scarcely magnetize the bulk. By these novel control waveform, single pulse magnetic field may magnetize HTS bulk as well as the multi-peak PFM method.

4. Conclusion
We demonstrated the pulsed magnetization for Gd-Ba-Cu-O bulk when the slope and the duration was controlled by WCPM. By the pulse magnetic field suppression of the waveform which aimed at the threshold of magnetic flux density, we could improve characteristics of trapped field. The HTS bulk trapped at high magnetic flux density of 1.223 T with conical distribution by the pulse magnetic field of the arbitrary trapezoidal waveform which intensity was controlled to around 1.7 T. It will be important to using strong HTS bulk magnet on power applications that we magnetize HTS bulk with attention for the magnetic inflection point to understand intrusion magnetic flux motion. The magnetized bulk by feedback pulse control from simultaneously measure of applied magnetic field acquired regular magnetic field distribution. Stress to bulk and magnetic machinery will be small because this method magnetizes strongly the bulk in low magnetic field for a long time.

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