Waveform control pulse magnetization for HTS bulk magnet

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Abstract. For the past 10 years, we have studied high-temperature superconducting (HTS) bulk magnets for use in electromagnetic rotating machines. If the magnetic field effectively magnetizes the HTS bulk, then the size of the motor and generator can be reduced without a reduction in output. We showed that the melt-textured Gd-Ba-Cu-O HTS bulk effectively traps a high magnetic field using waveform control pulse magnetization (WCPM). WCPM makes it possible to generate any pulsed magnetic field waveform by appropriately changing the duty ratio of the pulse width modulation. By chopping so that the pulsed magnetic field has a period of about 1ms, the WCPM technology enables active control of the rise time and suppresses magnetic flux motion that decreases magnetization efficiency. This method is also useful for any HTS bulk magnet, and the high magnetic flux density is trapped in the HTS bulk by a single pulse magnetic field. We developed a magnetizer that has a feedback system from the penetrated magnetic flux density to realize WCPM. In this research, using only a single pulse magnetic field of WCPM method at 77K, an HTS bulk with a 45mm diameter and 19mm thickness trapped a maximum magnetic field of 1.63T, which is more than 90% of the trapped magnetic flux density by FC magnetization. This result suggests that the pulse magnetizing method can replace the conventional field-cooled method and promote the practical use of HTS magnets for electromagnetic power applications.

1. Introduction
High-efficiency energy consumption is needed for industrial electromagnetic power applications involving rotating machinery. However, the low residual magnetic flux density of magnets complicates the realization of such high efficiencies. A high-temperature superconductor (HTS) bulk with a strong pinning effect can trap much higher magnetic fields than is possible with conventional permanent magnets [1, 2]. Accordingly, the HTS bulk can contribute to the performance enhancement of next-generation electromagnetic rotating machines.

For practical use, a pulsed field magnetizes the HTS bulk installed in an electromagnetic rotating machine using a small metal coil. However, the magnetic flux density that the HTS bulk traps by pulse field magnetization (PFM) is lower than that trapped by field-cooled (FC) magnetization [3]. By applying a strong pulsed field, the trapped magnetic flux density distribution is distorted asymmetrically and it decreases due to the large amount of heat.
generation originating in the dynamic transient flux flow upon pulsed field magnetization [3–5]. The suppression of the trapped magnetic field consisting of the transient heat from the magnetic flux motion must be improved to achieve sufficient magnetization for applications [6]. It is important that HTS motors suppress the magnetic flux motion caused by PFM in order to obtain a high magnetic field, because the trapped magnetic field of the superconductor depends on the magnetic flux pinning force [7]. Therefore, we are interested in the motion of magnetic flux in melt-processed RE-Ba-Cu-O (RE indicates a rare earth element) bulk superconductors for use in advanced industrial power applications. In general, the pulsed field depends on an exponential function that is generated by a passive capacitor discharge. By the multi-peak PFM method, several exponential pulsed fields enhance the trapped magnetic field in the HTS bulk [8,9]. Because the method of magnetization takes a long time to magnetize the HTS bulk, we need a simple and practical magnetization technology to start the HTS motor.

A pulsed field generated by a passive element is not suitable for magnetizing the HTS bulk. Accordingly, we aim to produce a pulsed field that is adapted to the HTS bulk by active control. For the past decade, we have studied a new method of HTS bulk magnetization that uses the pulse magnetic field of an arbitrary waveform that does not depend on the conventional LCR transient response [10–12]. The waveform control pulse magnetization (WCPM) method distorts the pulsed field waveform to suppress discharge using chopping [13]. The single pulse field could suppress the magnetic flux motion and increase the trapped magnetic fields. The melt- textured Gd-Ba-Cu-O bulk was magnetized to an excellent cone-shaped magnetic field distribution. To increase the trapped magnetic flux density by the applied pulse magnetic field, we developed a magnetizer with a feedback circuit that controls the magnetic flux density in the bulk. In our previous work, we used this control to maintain a constant peak current when the penetration magnetic flux density in the HTS bulk exceeded a threshold close to the critical magnetic field [12]. The sequential style feedback control based on this electrical current could not eliminate the influence of the magnetic flux that already penetrated the HTS bulk, so we could not suppress the flux jump. In this study, we applied a magnetizing pulse based on the penetration magnetic flux to the HTS bulk in order to obtain a high magnetic field density, and aimed to suppress the flux jump.

2. Pulse magnetization

When the switch included in the pulse magnetizer is closed, a discharging current flows through the magnetizing coil from the capacitor bank. The discharging current will gently decrease due to the effect of electromagnetic induction if the switch opens. Thus, we can control the pulsed
current by chopping as we repeat the switching operations over a short time. The switching occurs over a short period by applying a high self-induced voltage to the insulated gate bipolar transistor (IGBT) of the chopper. We choose an IGBT that has maximum ratings of DC 1700V/2400A so that the high voltage does not break down the IGBT. Furthermore, we made a snubber circuit for the pulse magnetizer. Accordingly, we switched the chopper with a period of 1ms, the same as in previous work. In this study, we developed pulse magnetizing equipment that controls a pulse magnetic field by feedback input of the penetration magnetic flux. Figure 1 shows an electrical block diagram of the pulse magnetizer developed for the WCPM method. This magnetizing equipment generates maximum DC 1kV from AC 100V. The three parallel IGBTs discharge electrical energy up to 25kJ charged to a capacitor bank of 50,000μF in total. The reverse voltage to be generated between the collector and emitter of the IGBT at the time of chopping would break the IGBT. Therefore, we mounted a flywheel diode and a snubber circuit to protect the IGBT. Figure 2 shows the collector-to-emitter voltage by turning on the IGBT for 100μs following the rise/fall of the gate voltage. At the time of breaking, the switching of IGBT produced a surge voltage of 467V from the capacitor bank voltage of 410V at $t = 0$, and produced a surge of 864V from 780V the same way. The surge voltages are only 12% larger than the capacitor bank voltages. With various methods, our pulse magnetizer can control DC 5kA or 10kA of pulsed current in 1kV or less, without breaking.

The IGBT driver applies a gate voltage to the IGBT according to an input gate signal from a 16-bit micro control unit (MCU). The gate pulse with that duty ratio was changed into a controls magnetizing current. The input gate signal is determined as well as a sequential program by a feedback signal of magnetizing current and magnetic flux density. The 16-bit analog-digital converters (ADCs) measure each of the pulse magnetizing currents and the penetration flux density, and it sends them to the MCU.

The magnetizer for the WCPM method is shown in Fig. 3. A chopper circuit is placed at the bottom of the three levels of structures. The middle layer is the capacitor bank for charging the electric power, and the upper layer is the booster circuit and pulse controller with the MCU. This electronics device limits the charging current, controls the charging voltage, and controls the magnetizing current using commands from the controller automatically.
3. Experiment and result

A highly c-axis oriented Gd-Ba-Cu-O bulk sample (GdBa$_2$Cu$_3$O$_{6.9}$ 70.9wt%, Gd$_2$BaCuO$_5$ 19.2wt%, Ag 9.4wt%, Pt 0.5wt%, QMG, NSSMC) which was made by the melt growth process was used for measurements [11]. The sample was 45mm in diameter and 19mm in thickness. Using the static magnetic field in FC magnetization at 77K, we obtained a maximum trapped flux density of 1.7T with a conical distribution on the sample surface. In this study, the sample was immersed in liquid nitrogen for the pulse magnetization. The magnetic flux motion in the bulk depends on the crystal orientation. Thus, we put five Hall elements on the bulk center, growth sector, growth sector boundary and the outer edges. The details of the sample geometry are shown in Fig. 4. The Hall elements are THS118 (Toshiba) with a GaAs semiconductor type. In this study, we measured the magnetic flux density for feedback to the MCU by using the Hall element in the bulk center. The vortex-type copper coil, which has an inductance of 650$\mu$H, has a diameter of 84mm and a 20mm thickness [3].

We magnetized the HTS bulk sample by WCPM at 77K. The applied pulsed magnetic field generated from the excessive electric power of 12.3kJ was controlled by the feedback of the magnetic flux measured at the HTS bulk surface center in the magnetization, shown in Fig. 5. The chopping period of the applied pulse magnetic field was 1kHz. It is likely that a large number of impulses that are included in the magnetic flux density waveform are due to switching noise by the fluctuation of the high current. However, we consider that the impulses are provided as a result of the feedback control, as we mention it later. When the flux density penetrating the bulk center exceeds a preset threshold, the MCU reduces the duty ratio of the gate pulse sent to the IGBT. In contrast to proportional-integral control in Figs. 6 and 7 of Ref. [12], we tried proportional-derivative (PD) control to follow the steep variation of the magnetic flux. The MCU, which performed PD control by prior input of the proportional gain and the derivative gain, varied the duty ratio depending on the penetration magnetic flux density. In this experiment, we set the integral gain to 0. However, the waveform control signal was integrated every 1ms for chopping. With such a control, the pulse controller suppressed the electric current supplied to the vortex-type copper coils depending on the penetration magnetic flux density, until the pulse magnetization was finished. Because the electrical energy of the capacitor bank was discharged little by little, most of the pulsed magnetic field was generated for 2 seconds. A low pulsed magnetic field continuously was applied for about 4 seconds.

In a previous study, we showed that an instability such as a flux jump occurs around 1.7T of the critical magnetic field by WCPM, which limits the current with the magnetic flux density.
Figure 5. Magnetic flux density on the bulk (a) for short elapsed time from a start of the magnetization, and (b) after 5 seconds elapsing. Both insets show geometry of 1-5 Hall elements.

of the threshold [11, 12]. The magnetic flux motion seems to be strongly inhibited below this threshold, and the magnetic flux density in the bulk increased suddenly when the control did not work. In this study, we set the threshold to 1.8T, which was slightly higher than 1.7T used in Ref. [12]. However, the magnetic field greatly exceeds 1.8T penetrated to the bulk. The reason may be due to the slowness of the integral time of the ADC, which is 1ms on the feedback control. When the penetration magnetic flux density exceeds a critical state, a flux jump will occur. The slow control cannot completely suppress a sudden increase in the magnetic flux density caused by the flux jump. Many of the impulses included within the curves in Fig. 5(a) may be flux jumps that were not suppressed because of incomplete feedback waveform control. Nevertheless, the trapped magnetic field reached 1.63T at the surface center and had a tendency to be distributed into a conical shape. This experimental result for the single PFM realized more than 90% of the magnetic flux density for the critical magnetic field of 1.7T. We consider that the suppression of the incomplete flux jump had the effect of trapping the high magnetic field on the bulk. Otherwise, our HTS bulk might be magnetized by a single WCPM field for approximately 4 seconds, which was generated by an electric power of 12.3kJ. There is a possibility that such an applied magnetic field over a long time would increase the trapped flux density.

4. Summary
We made a pulse magnetizer to magnetize the HTS bulk by the WCPM method. The magnetizing equipment has the ability to measure the magnetic flux density that penetrated the bulk, and the discharge circuit without auto-destruction was possible by the surge voltage. The magnetic flux density at the HTS bulk center fed back to the MCU-controlled amplitude of the pulsed field applied to the Gd-Ba-Cu-O bulk. We magnetized the HTS bulk to 1.63T by a single pulsed field at 77K for the threshold of 1.8T. This magnetizing condition was not able to suppress the flux jump. However, this is beyond 90% of the trapped magnetic flux density by FC magnetization. The very effective magnetizing of the bulk leads to practical uses of HTS materials in electromagnetic power applications. In the future, we will clarify the condition for trapping a high magnetic flux density to various superconducting materials by studying the
details of the magnetizing process together with a trial to suppress the flux jump. And a high magnetic field at a low temperature will be trapped using the single pulse magnetic field of WCPM.

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