Pulsed-Field Magnetization of Bulk HTS magnets in Twinned Rotor Assembly for Axial-type Rotating Machines

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Abstract. We study a pulsed-field magnetization of HTS bulks and application to rotating synchronous machine of axial-gap type. To increase the output performance of the rotating machine, the multiple rotor structure is designed with the alternation of the rotor with Gd-bulks and the fixed armature. Thus, we obtain a redundancy for rotor magnets operation without additional current leads nor slip rings. To assess the present redundancy, we show the result of the pulsed-field magnetization for Gd-bulks in the above mentioned multiple rotor geometry. Two Gd-bulks with 60 mm in diameter and 19 mm thick were inserted into three vortex-type Cu coils, alternatively. They are immersed into liquid nitrogen. The pulsed current was applied to three vortex-type coils as serial. The maximum applied magnetic filed was 5.7 T with the rise time of 6.6 ms. The trapped field for two Gd-bulk were 0.851 T and 0.835 T, respectively. We evidenced it is possible to perform the pulsed field magnetization for two Gd-bulks sandwiched among three armature vortex-type Cu coils, i.e., double layer rotor assembly.

1. Introduction
A small-sized synchronous motor provides a large torque by employing bulk high-temperature superconductor as pole field magnet [1]. Especially, the melt-textured RE-123 (REBa2Cu3Oy; RE: rare earth elements) superconductors have a significant potential for field magnets which may be superior to conventional permanent magnets. Nariki et al [2] developed Gd-Ba-Cu-O bulk superconductors with the trapped magnetic field of 2.7 T at 77 K. Tomita and Murakami reported the melt-textured RE-Ba-Cu-O bulk can trap magnetic fields over 17 T at 29 K [3]. The bulk magnets are magnetized without connecting current leads in contrast to the high-temperature superconducting (HTS) wire winding coils. Therefore, the above results encourage us to develop bulk HTS-rotor field magnet for brush-less rotating machines. The HTS synchronous motor has many striking features, such as small size, lightweight, low vibration, low noise, high power density, and large torque. We have conducted a pulsed field magnetization of HTS bulk with a pair of vortex-type copper coils [4]. Recently, we designed a HTS bulk synchronous motor with Gd-Ba-Cu-O bulk superconductors as 8-poled rotating field magnets. The specific feature is that the rotor field magnets of bulk Gd-Ba-Cu-O are magnetized with magnetic field by pulsed current flow through vortex-type armature copper windings. To increase the output performance of the rotating machine, the multiple rotor structure is formed with keeping the radial dimension with the alternation of the rotor with Gd-bulk and the fixed armature. We report the
merit of pulsed magnetization technique employing the multiple rotor together with a comparative result of the pulsed magnetization employing a single rotor.

2. Samples and experimental methods
Melt-textured Gd-Ba-Cu-O bulk samples (GdBa$_2$Cu$_3$O$_{6.9}$ 70.9 wt.%, Gd$_2$BaCuO$_{5.0}$ 19.2 wt.%, Pt 0.5 wt.%, Ag 9.4 wt.% in composition) were magnetized by using a couple of vortex-type coils and multiple vortex-type coils. Gd-bulks were inserted into vortex-type Cu coils, alternatively. They are immersed into liquid nitrogen. The pulsed current was applied to vortex-type coils as serial. The geometry of the pulsed magnetization measurements is shown in Fig. 1.

![Figure 1](image.png)

Figure 1. Illustration of pulsed copper coils and superconducting bulk samples: a couple of vortex-type coils (A), multiple (twined) vortex-type coils (B).

The pulsed copper coils generates 0.002 T at the centre of the bulk samples when the current flow of 1 A is applied. The dimension of the vortex-type coil was 84 mm in diameter and 19 mm thick, 10 layers of 20 turn windings with a 2 mm copper wire. The HTS bulk sample with a diameter of 60 mm and a thickness of 19 mm was sandwiched in between a pair of vortex-type coils together with a capacitor resonance circuit. The maximum trapped fields at 77 K upon field-cooled magnetization for these samples were 1.8 T. Different multi-pulse magnetization associated with different peak fields were employed. Sample and coils were immersed in Liq. N$_2$. The remanent magnetization was measured with a Hall probe scanned above the sample in a distance ranging 1mm depending on the size of samples.

3. Results and discussions
Figure 2 exhibits the trapped flux distribution for both seed crystal surface and the other surface of single bulk HTS magnet. A series of pulsed magnetic field was applied with the applied peak magnetic field $H_{\text{max}}$ as 7.2 T, 5.7 T, 7.2 T and 5.7 T upon magnetization between a couple of vortex-type coils. The rise time was 5.7 ms. It is worth to note that we employ both the seed surface and the reverse surface of a bulk HTS crystal in the rotating machine. The maximum trapped field at the centre surface of both seed and reverse side of the Gd-bulk were 0.942 T and 0.941 T, respectively.

Figure 3 exhibits the trapped flux distribution, A series of pulsed magnetic field was applied with the applied peak magnetic field $H_{\text{max}}$ as 5.7 T, 4.7 T, 5.7 T and 4.7 T upon magnetization between two couple of vortex-type coils as show in Fig. 1 (B). We have employed a multiple vortex-type coil. The rise time was 6.6 ms. To compare it with the result of a couple of vortex-type coils, we equalized the electric energy saved in the condenser bank prior pulsed magnetization. The maximum trapped field values of a coupled Gd-bulks, i.e., seed surface of the bulk (a), reverse surface (a), seed surface of the bulk (b) and the reverse side (b) were 0.851 T, 0.753 T, 0.835 T and 0.817 T, respectively. There remains considerable difference for trapped field density profile for each Gd-bulk. This is coming from the temperature rise in growth sectors and/or inhomogeneous distribution of the second phase as well as pinning centres. It is possible to recover for the conical shape by changing the condition of how to give the pulse magnetic field as shown in Fig. 4. By increasing the applied peak magnetic field further, the maximum total magnetic flux in multiple sample can be further increased.
Figure 2. The trapped field distributions of single bulk HTS for the pulsed peak field of 5.8 T respectively. The data was taken after the pulsed field was applied with employing a pair of vortex-type coils at 77 K under the magnetization geometry A as shown in Fig. 1.

Figure 3. The trapped magnetic field distributions for the peak pulse fields of 4.7 T respectively. The data was taken after the pulsed field was applied with employing multiple vortex-type coils at 77 K under the magnetization geometry B as shown in Fig. 1.
Figure 4. The trapped magnetic field distributions after another magnetization with a peak pulse field of 5.5 T for seed surface of the bulk (a). The data was taken after single pulsed field was applied after the successive pulsed magnetization as in Fig. 3 with employing multiple vortex-type coils at 77 K.

Figure 5 exhibits the total magnetic flux when magnetizing single bulk and twined bulks with a couple of vortex-type coils and multiple vortex-type coils, respectively. Relatively large value of total magnetic flux was obtained with twin layer with the identically applied electric energy saved in the capacitor bank.

Figure 5. Total magnetic flux and electric energy for single and twinned bulks with vortex-type pulsed copper coils at 77 K

4. Conclusions
In conclusion, we evidenced it is possible to perform the pulsed field magnetization for two Gd-bulks sandwiched among three armature vortex-type Cu coils, i.e., twin layered rotor assembly. Thus, we obtained a redundancy for rotor magnets operation. With the identical electric energy we can obtain better magnetization efficiency and trapped total flux by using a suitable pulse waveform control. This work was supported by the Sasakawa Scientific Research Grant and the Ship & Ocean Foundation Japan.

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