Single pulsed-field magnetization on Gd-Ba-Cu-O Bulk HTS assembled for axial-gap type rotating machines

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Abstract. We employed Gd-bulk HTS magnets as rotating poles for a smaller and lighter axial-gap type rotating machine. The bulk was placed between two vortex-type armature coils and cooled down to 77 K under zero-field. Pulsed current was applied to the vortex-type magnetizing coils. The trapped field distribution and transient flux behaviour strongly depend on the radial dimension of the armature vortex-type coil. In the present study, we show that there is an optimal radial dimension of magnetizing coils to the given bulk disk size to give a homogeneously conical distribution of the trapped flux.

1. Introduction

Pulsed field magnetization (PFM) is one of the promising techniques to magnetize a high-temperature superconducting (HTS) bulk magnet. We have studied the PFM of a field-free cooled HTS bulk disk of a melt-textured Gd-Ba-Cu-O inside the applied machines such as motors and generators. For example, in the axial-type rotating machines, the bulk was sandwiched in between a couple of pulsed current vortex-type armature Cu coils [1]. The pulsed current coils generate the magnetic field distribution which is not homogeneous as in the case of a solenoid but conical [2]. The radial dimension of the vortex-type coil was larger than that of bulk HTS. It was found that the trapped magnetic flux was smaller than that obtained with static magnetization in the field cooling mode, which was attributable to a temperature rise caused by the motion of flux lines.

In the present study, we report that there is an optimal radius of the vortex-type magnetizing coil for the selected bulk disk to obtain the conical trapped flux distribution. The transient Hall voltage at the surface of the bulk gives a dynamical motion of flux lines with PFM. The choice of the optimal size of the pulsed Cu coils indicates that the flux promptly penetrates from edge and the flux density at the center surface reaches a maximum around the rise-time of the applied pulsed field. Pinning properties are also reported from the transient behaviour.

2. Samples and experimental methods
Melt-textured Gd-Ba-Cu-O bulk samples (QMG 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, 60 mm in diameter with 19 mm in thickness) were magnetized by using a couple of vortex-type coils. For a comparative study on the PFM geometrical configuration, we prepared three magnetizing coils with different radial dimension. The specifications of vortex-type coil samples are listed in Table 1.

| Specifications of vortex-type coils. |
|-------------------------------------|
| Outer diameter (mm) | Number of turns | Height (mm) | Self-inductance (mH) |
| A | 84 | 200 | 19 | 1.46 |
| B | 60 | 140 | 19 | 0.476 |
| C | 44 | 100 | 19 | 0.175 |

In the geometry A, the dimension of the vortex-type coil was 84 mm in diameter with 19 mm in thickness composed of 10 layers of 20 turn windings with a 2 mm in diameter copper wire. This is the same dimension as designed for the magnetizing coil in an axial-gap type HTS rotating machine [1]. To obtain the conical distribution of the trapped field, we presently used other coils of 60 mm in diameter with 19 mm in thickness (B) and 44 mm in diameter with 19 mm in thickness (C). The HTS bulk sample was sandwiched in between a pair of vortex-type coils (Fig. 1 (a)).

Both bulks and the magnetizing coils were immersed in 77 K. To study the local trace of the dynamical motion of flux lines, we used Hall sensors (Toshiba, THS118). The measurements with these Hall sensors were done on the bulk surface, so the air gap between the sensors and the sample surface was negligible. Fig. 1 (b) shows the positions of five Hall sensors. Sensor 1 was put on the center of the surface of Gd bulk, and two of them were put on with 15 mm separation along the radial direction in the growth sector (GS). The remaining two sensors (sensors 2, 3) were placed with the same distance along the growth sector boundary (GSB) that makes an angle of 135 degree to the line on which both 4 and 5 were at the GS. Then, the remanent field density distribution was measured with a separated Hall probe (F.W Bell BHT 921) scanned at 3 mm above the bulk surface after 3 minutes after the removal of the applied external field. Pulsed-magnetic field was applied once with a pulsed-peak field ($B_p$) 3.4 T around the center of the bulk samples at 77 K. The rise-time of the pulsed field was typically around 5.5 msec.

![Figure 1.](image-url) (a) Illustration of pulsed copper coils and superconducting bulk sample: a couple of vortex-type coils. (b) A drawing of the arrangement of the Hall sensors (Toshiba, THS118).

3. Results and discussions
Figure 2 illustrates the distribution of trapped magnetic flux density after the single pulsed-field experiments with $B_p = 3.4$ T at 77 K. Fig. 2 (a) is the distribution of trapped magnetic flux density excited by the coil A. The shape of distribution of trapped magnetic density projected from the side is trapezoid-like. In other words, the coil A has a large magnetic gradient at the edge; the gradient in the magnetic field at the edge is larger than that at the inner zone around the seeding position. On the other hand, the distribution of a conical trapped magnetic field distribution with a constant magnetic field gradient, in which the maximum field density is observed in the center of the bulk surface, is successfully obtained when a pulsed-field experiment is excited by the coil C, which is shown in Fig. 2 (c). That indicates the gradient in the magnetic field at the edge is the same as that at the inside. It contributes the HTS Bulk rotating machine a smooth rotational motion when used as the rotor pole. Fig. 2 (b) shows that a distribution of magnetic field has an attribute between Fig. 2(a) and Fig. 2(c).

To elucidate the reason of the distribution of trapped field excited by the coils A and C in more detail, we measured up the position-dependent local dynamical motion of flux lines using the Hall sensors during PFM. The vertical dotted lines in the Fig. 3 indicates to the rise-time of the applied field. Fig. 3 (a) shows that the peak value of applying magnetic flux lines at the center of the bulk (sensor 1) is smaller than that at the edge (sensor 3, 5) and at the inner (sensor 2, 4). In addition, according to Fig. 3 (a)-(c), at the edge the amount of the measured magnetic flux lines excited by the coil A is bigger than done by B coil or C coil during around rise-time. Thanks to this, the value of local dynamic magnetic flux lines that penetrate from the edge of the coil A is bigger than excited by the C coil or the B coil. Consequently, this leads the large gradient in the magnetic field at the edge; the projective shape of the distribution from the side view of the excited by the coil A is trapezoid-like.

An excessive integration of applied magnetic flux lines is reduced at the edge when the radius of the magnetizing coils is decreased. This led to a reduction of excessive flux penetration as well as heat generation. The flux density at several points on the GS and GSB also evidenced that the magnetic flux penetrates from the edge with the use of the vortex-type coils since the local dynamic flux density peaks at the inner position (sensor 1, 2, 4) with a delay compared to the local dynamic flux density peaks at the edge (sensor 3, 5). This is a common feature of the magnetization with the use of solenoid-type coils [3]. The GS around the sensor 4 provides a relative weak pinning to the GSB around the sensor 2 from Fig. 3 (a)-(c).

![Figure 2](image-url)
Remarkable feature is that the field flux density around the sensor 1 at the center quickly reaches at the maximum around the rise-time observed at the shunt resistor. Such quick intervention of the flux density was observed at not only the center zone but also around the edge zone. This kind of feature is in much contrast with the previous results by using a solenoid-type magnetizing coil [3]. Thus, the vortex-type coil may be effective to obtain a homogeneous conical shape with moderate radial size of the magnetizing coil as well as an optimized external magnetic flux.

4. Conclusion

The applied vortex-type pulsed copper coils to magnetization of HTS Gd-bulk shows a quick intervention of the external magnetic flux into the center of the bulk. At the edge zone, the flux lines penetrate rapidly and reach the maximum to let the excess flux to exit from the bulk. The GS zone indicates the existence of a weak pinning zone relative to the GSB as has been observed in a conventional pulsed magnetization with a solenoid. The magnetization of a field-free cooled HTS bulk disk sandwiched in between a couple of pulsed vortex-type Cu coils with an optimal radius is useful and may be effective technique for applied bulk HTS for rotating machines such as motor and/or generators. The present work was partially supported by the Ship & Ocean Foundation, Japan.

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