Practical Technique of Pulsed Field Magnetization for Bulk HTS Application

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Abstract. We studied a pulsed field magnetization (PFM) of bulk HTS assembled into a synchronous motor as a field-pole. The PFM is essential to apply bulk HTS inside the machine as a practical technique. In the present study, we developed a PFM technique that is a usage of Controlled Magnetic density Distribution Coil (CMDC). The coil is composed of inner vortex coil and outer solenoid. We successfully obtained the trapped flux density with 1.3 T by the step-wise cooling method with CMDC at 38 K in the motor. The bulk was cooled by a condensed neon. In addition, we studied the PFM for Gd-bulk of 140 mm diameter. By using the CMDC, we obtained the trapped flux density distribution with regular shape. In this paper we report these advanced PFM techniques for a practical machinery applications.

1. Introduction

We studied a pulsed field magnetization (PFM) of Bulk HTS assembled into an axial type synchronous motor as a field-pole as shown in figure 1 (a) [1]. The PFM is essential to apply Bulk HTS inside the machine as a practical technique. The trapped flux density and integrated flux, however, are reduced compared to that with field cooling method (FCM). In addition, the trapped flux density distribution is distorted in the a-b growth sector (GS). It is attributed to increase of local temperature due to the resistive force exerted on moving flux line [2]. These problems cause low performance for a machine. Therefore, we need PFM techniques as high trapped flux density with regular magnetic distribution. To solve these problems, we invented many techniques and improved bulks for the PFM, i.e., split vortex-type coil, a bulk impregnated with and U-alloy a stacked bulk etc. [3-9]. A vortex type coil has a structure in which copper wire are wound from the edge to the centre. There is no midair in the centre. The coils are set to a split-type arrangement as shown in figure 1 (b). The advantage of a split-type arrangement is that the vectors of generated magnetic field form the upper coil and lower coil are added and become parallel to the c-axis at the bulk field density [3]. In addition, split-type arrangement is same relationship between armatures and field pole magnet for axial type motor [1]. Thus, the magnetizing coil is shared with armature coil in the motor. A bulk
Impregnation with U-alloy is a post fabrication treatment that improves thermal conductivity of the bulk for PFM. A small hole was artificially drilled into the centre of bulk. An aluminium wire was inserted into the hole and then the sample was subjected to impregnation by using Bi-Sn-Cd alloy. It was found that the alloy impregnation was effective in suppressing the temperature rise and in increasing the trapped flux density [5]. The stacked bulk means two bulks are stacked and layered, with misaligned growth sector boundary by rotating the crystal angle in the a-b plane to one another. As the result, the homogeneous distribution of pinning strength, because there is a GSB region above the GS in the layered bulk structure, the integrated flux was enhanced in the stacked layered bulk with misaligned GSB [6]. The same PFM methods were applied for the bulk field-pole magnets on the rotor in the motor. We obtained the trapped flux density with 1 T [10].

In this present study, we developed a PFM technique that is a usage of Controlled Magnetic density Distribution Coil (CMDC). The coil composed of inner vortex coil and outer solenoid. This coil excels in obtaining the trapped flux density distribution with regular shape. Recently, the ISTEC group in Japan has succeeded in synthesis of growth a larger Bulk HTS disc magnet up to 140 mm in diameter. We expect to develop high performance rotating machines depending on a dense magnetic flux density upon successful magnetization for this bulk. On the other hand, the trapped magnetic flux density of the bulk increased with decreasing cooling down. To realize high performance machine, we change to the cryogen liquid nitrogen to condensed neon in the motor. On both cases, it is difficult to obtain a trapped field distribution with regular shape because of inhomogeneous melt grows crystal, strong pinning force and heat generation during PFM etc. In this paper, we report the advantage of multi-PFM with CMDC for large bulk and machinery.

![Figure 1. (a) The HTS synchronous motor for ship propulsion (b) The arrangement of PFM with split-type vortex coils: a magnetizing coil is shared with an armature coil in the motor.](image)

2. Effect of Vortex-type coil smaller than a bulk’s diameter

We have reported PFM experiment a with split-type vortex coil smaller than bulk’s diameter [6]. That PFM conditions were a GdBaCuO bulk 60 mm in diameter and a split-type vortex coil 44 mm in diameter was used. By using smaller coil, we success to reduce the flux penetration into the periphery of the bulk magnet. As a result, the integrated flux was equal to 90 % of the values obtained in FCM. Moreover we obtained a trapped flux density distribution with regular shape in figure 2 (a). Thereby we interpret that lager transient heat generation due to a mobile flux was decreased around the periphery, since a relatively smaller magnetic flux penetrated into the periphery region in the PFM with a vortex coil which is smaller than the bulk in the PFM with a coil larger than bulk. In this section, we report PFM study for larger bulks with split-type vortex coil smaller than bulk.

The GdBaCuO bulk magnets were 100 mm and 140 mm in diameter and 20 mm thickness. The bulk sample was placed in the air gap between split-type vortex coils 84 mm in diameter and 20 mm in thickness and immersed in liquid nitrogen. PFM conditions were peak field ($B_p$) = 8.5 T and rise time ($T_{rise}$) 5.5 ms. The bulk 100 mm in diameter was applied pulsed magnetic field 7 times and the bulk 140 mm in diameter was 5 times at the centre of bulk surface respectively. After PFM, The trapped flux density distribution was mapped using a Hall sensor (F.W.Bell BHT921) at the distance of 4 mm from the bulk surface. Figure 2 (b) shows trapped flux density distribution for the bulk 100 mm in
diameter. We obtained the trapped flux density distribution with close conical shape by PFM. The maximum trapped flux density was 0.52 T and integrated flux was 1.55 mWb. These values were 27% and 29% compared with FCM, respectively. The trapped flux density distribution of the bulk 140 mm in diameter was shown figure 2 (c). The bulk was magnetized around the centre only. The vortex coil smaller than bulk can magnetize a bulk around the center without any influence around periphery.

![Figure 2](image.png)

**Figure 2.** Trapped flux density distribution of the bulk magnetized at 77 K (a) the bulk 60 mm in diameter and the coil 44 mm in diameter (b) the bulk 100 mm in diameter and the coil 84 mm in diameter (c) the bulk 140 mm in diameter and the coil 84 mm in diameter.

### 3. CMDC (Controlled Magnetic density Distribution Coil) method

We produced the vortex coil which is smaller than a bulk can be magnetized the bulk with high magnetic field and regular distribution around centre with no remarkable trace around periphery. The magnetization coil, however, have to be used as an armature in our motor because additional coils are not necessary. In case of the armature coil smaller than a bulk, the output was decreased because all trapped flux for a bulk can't be used. To solve this problem, we developed a new PFM technique that is a usage of Controlled Magnetic density Distribution Coil (CMDC) [9]. The coil composed of inner vortex coil and outer solenoid, that is, a solenoid coil is formed around a vortex coil, as shown in figure 3 (a). Figure 3 (b) shows the arrangement of CMDC mode A. Mode A is the same as a normal split-type vortex coil whose dimension is same or larger than bulk's, i.e. the CMDC plays a role as an armature coil in the motor. The pulsed current is applied to both solenoid and split-type vortex coils under serial connection. Figure 3 (c) illustrates the mode B whose radial dimension is smaller than the bulk's. The PFM experiments were applied with the coil mode A and coil mode B sequentially.

![Figure 3](image.png)

**Figure 3.** (a) CMDC composed of the outer solenoid and the inner vortex (b) The arrangement of Mode A (use of vortex type coil and solenoid coil: the diameter is same or larger than bulk's) (c) The arrangement of Mode B (only use of Vortex-type coil: the diameter is smaller than bulk).

### 3.1. The PFM for the bulk 60 mm in diameter with CMDC
The GdBaCuO sample was manufactured by Nippon steel Co. The dimensions were 60 mm in diameter with 20 mm thickness. The mode A of CMDC is equal to a vortex coil 84 mm in diameter and mode B is 44 mm in diameter and 20 mm in thickness with a 2mm diameter copper wire. They were immersed in liquid nitrogen. The $B_p$s were 3.5 T ($\Phi 84$) and 6.5 T ($\Phi 44$) at the centre of bulk surface, respectively. These values are the parameters with which the best maxim trapped flux density and integrated flux can be obtained by respective modes. The $T_{rise}$ of pulsed field was typically around 5.5 ms. After PFM process, the trapped flux density distributions were measured with Hall sensor scanned at 3 mm above the sample’s surface. Firstly, the mode A was used 3 times so as to obtain a substantial trapped flux density. Then mode B was used at 4th time. For comparison, pulsed magnetic field was applied with mode A 4 times. Figure 4 (a) shows trapped flux density distribution for the bulk with mode A coil. The maximum trapped flux density was 0.60 T and integrated flux was 0.83 mWb. If the peak field about $B_p = 4$ T with mode A is applied at 4th time, the tapped field distribution is distorted in ab-GS sector and the peak magnetic flux density and integrated flux is decreased[4]. Figure 4 (b) shows the trapped flux density distribution with CMDC method. The maximum trapped flux density was 0.68 T and the integrated flux was 0.84 mWb. As a result we observed an increase of the amount of the maximum trapped flux density and the distribution of trapped flux density close to a regular shape. The decrease of the radial dimension of magnetizing coil contributes to leading the flux lines in the periphery, which brings the flux lines to penetrate into the centre area of the bulk effectively.

![Figure 4](image_url)

**Figure 4.** Trapped flux density distribution at 77 K on the plate which is 3 mm above surface of the bulk (a) applied with the coil mode A only (b) applied with the coil mode A to B.

3.2. The PFM for the bulk 140 mm in diameter with CMDC

Recently, a bulk 140 mm in diameter was fabricated by ISTEC-SRL [11]. We may develop high performance rotating machines depending on a dense magnetic flux density upon successful magnetization for this bulk. Therefore, the PFM can be also convenient and may be installed into the applied machines and system such as synchronous motor.

The dimensions of GdBaCuO sample were 140 mm in diameter and 20 mm thickness. And the CMDC was composed of solenoid coil 140 mm in diameter and vortex coil 100 mm in diameter and 20 mm in thickness with a 2mm diameter copper wire. They were immersed in liquid nitrogen. Firstly, the multi-PFM experiment have done with the mode A. Figure 5 (a) shows trapped flux density distribution for multi-PFM with mode A. The maximum trapped flux density was 0.6 T and the integrated flux was 3.5 mWb at the distance of 4 mm form the bulk surface. It is difficult to obtain the trapped flux density distribution with regular shape even though the bulk applied various pulsed field [12]. In case of lager bulk, the flux is difficult to penetrate the centre of the bulk. In case of strong peak field was applied, the trapped flux density distribution was distorted on the GS form center to edge. Conversely weak peak filed was applied, flux don’t penetrate to the bulk. So, it was difficult to find modified peak field. The PFM conditions that the bulk was magnetize whole area with regular shape by could not be found. AT the next step, we have done multi-PFM with CMDC to magnetize around the centre. Figure 5 (b) exhibits the trapped flux density distribution with CMDC method. The
maximum trapped flux density was 0.6 T and the integrated flux was 3.1 mWb at 4 mm above the sample’s surface. By using CMDC method, we have done a success to obtain the trapped flux density distribution with a regular shape. In contrast, the conventional multi-PFM without CMDC exhibits a substantial deformation of the trapped flux density distribution. The present results indicate that a small sized HTS propulsion motor with high power density may be available due to a high dense magnetic flux form such as a large Bulk HTS.

![Image](image_url)

**Figure 5.** Trapped flux density distribution at 77 K at the distance of 4 mm above the surface of the bulk

(a) multi PFM with mode A 140 mm in diameter (b) multi-PFM with mode A to mode B 100 in diameter

4. CMDC experiment in the motor

Figure 6 (a) illustrates the arrangement of PFM with CMDC in the motor. The bulk HTS motor with a single rotor plate comprised 8 pole-field magnets and 12 armature coils [10]. We have changed a pair of armature coils to CMDCs. Dimensions of GdBaCuO bulk were 60 mm in diameter and 20 mm in thick. In addition, dimensions of CMDC were mode A 84 mm in diameter and mode B 44 mm in diameter and 20 mm in thickness respectively. Bulk magnets were under indirect cooling with condensed neon. The temperature of bulk was measured by thermocouple (Au-0.07 %Fe, Normal silvers). The PFM method was Step-wise cooling method with CMDC method [13-15]. Firstly, Pulsed magnetic field which peak was mode A with 7.7 T and mode B with 9.5 T 2 times, receptivity, was applied at 55 K. the typical $T_{rise}$ were 6.8 ms (mode A) and 3.2 ms (mode B). Secondary, pulsed magnetic field with same CMDC method was applied at 38 K. after PFM experiments, trapped flux density distribution at the distance of 1.3 mm from the surface of bulk was measured along ab-GS. As a result, we obtained the trapped flux density with 1.3 T by the step-wise cooling method with CMDC at 38 K in the motor, as shown in figure 4 (b). Therefore, there are advantages to assemble the CMDC into the motor.

![Image](image_url)

**Figure 6.** (a) The illustrate of PFM with CMDC in the motor: a pair of armature coils changes to CMDCs. (b) Trapped flux density distribution along ab-GS at the distance of 1.3 mm from surface of the bulk.
5. Summary
Employing the bulk HTS for applications such as rotating machine/generator, NMR, sputtering device and magnetic separation etc, the integrated flux with high maximum tapped field density and the distribution with regular shape are required for high performance. In the present study, we have developed a multi-PFM technique that is a usage of Controlled Magnetic density Distribution Coil (CMDC). Thanks to CMDC, we obtained the trapped flux density distribution for the bulk 140 mm in diameter with regular shape. In addition, step-wise cooling method with CMDC, we obtained the trapped flux density with 1.3 T by the step cooling method with CMDC at 38 K in the motor. Therefore we expect our PFM techniques were practical for not only motor but also other applications.

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