Current distribution mapping in insulated (Gd,Y)BCO based stabilizer-free coated conductor after AC over-current test for R-SFCL application

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Abstract. Uniformity of critical current ($I_c$) over long lengths of (GdY)-Ba-Cu-O ((Gd,Y)BCO) -based high temperature superconducting (HTS) tapes after long periods of AC current excitation is an important criterion in their selection for resistive type superconducting fault current limiter (R-SFCL). The present work describes such critical current ($I_c$) uniformity measurements performed over 1m long, stabilizer-free (SF), 12 mm wide, 2nd generation (2G) (Gd,Y)BCO based HTS tape. A non-destructive method using a static hall probe (TapeStar®) with moving HTS tape configuration was employed for estimation of $I_c$ uniformity. Scanning Hall probe microscopy (SHPM) was then used to examine the weak superconducting regions (i.e. less $I_c$) with a static HTS tape. Remanent field distribution on the HTS tape was measured to yield the critical current density distribution. Except for small degradation of $I_c$ at some locations, these studies confirmed near-uniform critical current distribution over meter-long (Gd,Y)BCO tapes, both in virgin state and after exposure to AC over current.

1. Introduction
R-SFCLs based on HTS tapes have the ability to reduce fault current levels (5-10 times higher than its critical current, $I_c$) within the first cycle. The first cycle suppression of fault current by R-SFCL can lead to an increased transient stability of the power system. The first limited peak current of the R-SFCL is much higher than its $I_c$ value and termed as over-current. Stabilizer free (SF) (Gd,Y)BCO based coated conductors (CCs) are being used for R-SFCL, as they have the required normal state resistance without current sharing in the stabilizer layers and low AC losses as well as sufficient mechanical strength and thermal capacity [1]. Uniformity of $I_c$ over long lengths of HTS tapes for use over long periods of AC operation is an important criterion in their selection for R-SFCL. Heat generation occurs in HTS tapes due to non-uniform current flow in the conductor even though it is partially superconductive. Hence, it is necessary to investigate the local degradation of $I_c$ of the HTS tape, if any, after its exposure to AC over-current operations. These studies are useful in predicting the reliable and reproducible performance of R-SFCL based on SF (Gd,Y)BCO tapes. In the present work, such critical current ($I_c$) uniformity measurements are carried over 1m of stabilizer free 12 mm wide 2nd generation (2G) SF (Gd,Y)BCO based HTS tape, before and after AC over-current operation. For this, we employed a non-destructive method using a static hall probe (TapeStar®) with moving HTS tape configuration [2]. Scanning Hall Probe Microscopy (SHPM) was then used to closely examine at the degraded zones by mapping the two dimensional (2D) current density ($J_c$) distributions [3]. Roth et al. and Shiohara et al. [4, 5] reported that SHPM can be used to obtain $J_c$ from the magnetic field
mapping of CCs. 2D current in a superconducting tape generates magnetic field which can be measured by a scanning Hall probe. From the measured magnetic field map, the 2D $J_c$ distribution can be obtained by mathematical models (using Biot-Savart law). Magnetic field mapping using scanning Hall probe microscopy (SHPM) of (Gd,Y)BCO CC is conducted at a fully penetrated state (0.5 T applied perpendicular field). In Tapestar measurement, z-axis (vertical distance between hall sensor array and sample) is fixed but in SHPM technique, z-axis can be changed for better resolution.

2. Non-destructive critical current measurement approach

2.1. Distribution of $I_c$ over long length of virgin 2G (Gd,Y)BCO CC

The specification of the SF 2G (Gd,Y)BCO tape as provided by the manufacturer is given in Table 1. The critical current of the virgin tape was measured using Tapestar.

| Table 1. Specifications of SF 2G (Gd,Y)BCO CC |
|-----------------------------------------------|
| Manufacturer | SuperPower |
| Tape type    | SF12100/ 2G CC |
| HTS material | (Gd,Y)BCO |
| Substrate    | Hastelloy® C276 |
| Over-layer   | Ag |
| Over-layer thickness (μm) | 2 |
| Width (mm)   | 12 |
| Thickness (mm) | 0.105 |
| $I_c$ (A) @ 77 K, self field | 468 |
| $T_c$ (K)    | 90 |
| n-value      | 37.5 |
| Insulation/ thickness (μm) | Kapton polyimide film/ 50 |

The calibration of the Hall array is done based on the geometry of the sensor array, its distance and alignment relative to the tape. The calibration is done by measuring a tape with known $I_c$ and the calibration factor $cf$ derived from the following equation [6].

$$I_c = cf \cdot \frac{1}{(N-1)^{1/2}} \sqrt{\sum_i (B_i - B_{i-1})^2}$$

(1)

where, $N$ is the number of sensors and $B_i$ is the field at sensor $i$. The values of $B$ for the virgin tape can be calculated from the measurements performed by a Hall sensor array across the width of the tape. From these $B$ measurements, local $I_c$ of the tape is then calculated using eqn. (1).
The measured non-destructive $I_c$ values (with suitable cf) over 1m length of the virgin SF (Gd,Y)BCO CC is given in figure 1. The figure 1 shows almost uniform $I_c$ over 1m length with an average $I_c$ of 471 A, maximum $I_c$ of 486 A and a minimum $I_c$ of 437 A with a standard deviation (STDEV) of about 1.98% in the measurement.

2.2 Distribution of $I_c$ over 1m length of AC over-current treated 2G YBCO CC

The HTS tape described in Figure 1 was used for over-current (2 kApeak) testing. At the time of exposure to 2kApeak for 100ms, the tape showed current limiting behavior within 2ms and the 1st limited peak was at 888Apeak as shown in figure 2. Figure 3 shows the measured $I_c$ of the HTS tape after AC over-current test. The tape shows an average $I_c$ of 460 A, maximum $I_c$ of 495 A and minimum $I_c$ of 391A with a standard deviation (STDEV) of about 2%. The result shows nearly uniform $I_c$ over the length after exposure to AC over-current. Some minor $I_c$ degradation observed after over-current exposure may be attributed to conductor vibration (due to huge Lorentz force acting on it for short duration) during AC over-current test. The two red circles marked in figure 3 show the sections with reduced $I_c$. These weaker tape sections were cut for further analysis using SHPM.

3. Scanning hall probe microscopy (SHPM) to check uniform current density distribution after AC-over current test

3.1. Mathematical approach to current density

The relation between current and magnetic field (Ampere’s circuitual law) in the Fourier space from the convolution theorem is used to reconstruct the 2D sheet current density $J_n = \hat{x} j_x + \hat{y} j_y$ from the measured $\hat{z}$ component of magnetic field $B_z$ (at levitation height $z$) and the details are given below [4, 7, 8].

$$ b_z = i \frac{\mu_0}{2k} e^{-ikz} \left( k_y j_x - k_x j_y \right) \quad (2) $$

The 2D current density for closed loop condition is given by

$$ -ik_x j_x - ik_y j_y = 0 \quad (3) $$
where, \( b_z, j_x \) and \( j_y \) are the Fourier transforms of \( B_z, J_x \) and \( J_y \) respectively. Wave numbers \( k_x \) and \( k_y \) are the co-ordinates in the Fourier space and \( k = \left( k_x^2 + k_y^2 \right)^{1/2} \).

Using (2) and (3) we have

\[
j_x = -i \frac{2}{\mu_0 k} e^{ikz} b_z
\]

(4)

\[
j_y = i \frac{2}{\mu_0 k} e^{ikx} b_z
\]

(5)

Here, \( k \) cannot be 0, required by (3), since when \( k_x = k_y = 0, j \) is unpredictable and the magnetic field generated by a homogeneous in-plane current does not have a \( \hat{z} \) component.

3.2. SHPM for current distribution in SF (Gd,Y)BCO CC after AC over-current test

Two pieces of 12mm wide and 14 mm long HTS tape from two weak sections (locations are shown in fig. 3) were studied using Scanning Hall Probe Microscopy. In a rectangular aluminium sample holder of 15cm × 5cm, the sample was fixed using adhesive kapton tape and cooled to 77.3 K in liquid nitrogen, and then the sample was magnetized using an NdFeB permanent magnet with a flux density above 0.5 T at its surface. The 0.5 T magnetic field is more than double the penetration field and hence the persistent current, which is the \( J_c \) of the sample at fully saturated condition, can be obtained. The SHPM measurement was initiated 10 minutes after the removal of the external magnetic field to measure the remanent field related to local \( J_c \). The Hall probe (Arepoc AXIS-3) of 50 \( \mu \)m effective area, was excited by 10 mA \( \text{rms} \) AC current at 20 kHz. The scan was done continuously and the data pick-up frequency corresponds to one data point per 50 \( \mu \)m without much noise. The Hall voltage created by the AC current and DC magnetic field is measured by a Signal Recovery 7280 Lock-in amplifier. The time constant is chosen as high as 10 ms for this measurement to reduce the noise. During the scan, the Hall probe is placed as close as possible to the sample in vertical direction and scanned in the horizontal plane. Remanent field was measured and \( J_c \) distribution was calculated according to the measured field map. Our sample showed a 2D \( J_c \) of 385 A/cm (using average \( I_c \) of 460 A) and the penetration field [9] \( B_p = \frac{\mu_0 J_c}{\pi (1+\ln(w/t))} \) is 160 mT, where \( w \) is the width of the tape (12 mm) and \( t \) is the thickness of the superconducting region (estimated to be 1 \( \mu \)m).

The 3D and 2D (Inset) magnetic field maps of sections 1 & 2 with \( z = 0.45 \) mm were shown in figure 4 (a) & (b) respectively. Figure 4 (c) shows the comparison of magnetic field profile of section 2 along X-direction at \( Y=0 \) and \( Y=2 \) mm locations of figure 4 (b). A defective region with lower flux density is observed in section 2 and marked with a black circle in figure 4 (b), corresponding to the location \((x,y) = (-4,0)\).

With the measured \( B_z \) \((x, y) \) data (fig. 4) and using equations 4 and 5, we calculated the distribution of persistent current \( J_x \) and \( J_y \), as shown in figure 5 (a) and (c) for section 1 and figure 5 (b) and (d) for section 2, respectively. \( J_n \), \( |J_n| = \left( J_x^2 + J_y^2 \right)^{1/2} \) the absolute value of current density of section 1 & 2 are shown in figure 6 (a), & (b) respectively. The peak values for persistent current density of both sections of the tape are around 385 A/cm, except at one location of section 2, which was already marked in \( J_x \) and \( J_y \) map with a black circle in figure 5(b) and 5(d) respectively. The defect of section 2 at \((x, y) = (-4, 0)\) has 15% lower \( J_x \) than its surroundings and similar feature is found in the \( J_n \) map as shown in figure 6(b). Since the defect is significant in section 2 when compared to section 1, the persistent current is forced to detour around the defect region in section 2, thus leaving a pair of positive and negative \( J_x \) traces where current should flow only along \( y \)-direction (longitudinal direction).
Figure 4a. 3D magnetic field map of section 1, where no defects are observed. 2D magnetic field map along X-Y directions (Inset) using SHPM after the AC over current test on SF (Gd,Y)BCO CC.

Figure 4b. 3D magnetic field map of section 2, where one defect is observed and marked by black circle. 2D magnetic field map along X-Y directions with the defect marked by black circle (Inset) using SHPM after the AC over current test on SF (Gd,Y)BCO CC.

Figure 4c. Comparison of magnetic field profile across X direction at y=0 (with defect) and y=2 mm (without defect) locations, using SHPM after the AC over current test on SF (Gd,Y)BCO CC.

Figure 5a. $J_x$ of section 1, where no defects are observed.

Figure 5b. $J_x$ of section 2, where one defect is observed at y=0 and marked by black circle.

Figure 5c. $J_y$ of section 1, where no defects are observed.

Figure 5d. $J_y$ of section 2, where one defect is observed at y=0 and marked by black circle.

Figure 6a. The 2D current density $J_n$ of section 1 for SF (Gd,Y)BCO CC.

Figure 6b. The 2D current density $J_n$ of section 2 for SF (Gd,Y)BCO CC where one defect is observed at y=0 and marked by black circle.
4. Conclusion
A meter-long HTS tape (SF (Gd,Y)BCO CC) has been examined by non-destructive \( I_c \) measurements to evaluate its \( I_c \) uniformity before and after AC over current test. Before AC over current test, an average \( I_c \) of 471 A, maximum \( I_c \) of 486 A and minimum \( I_c \) of 437 A were measured by Tapestar. After AC over-current test, a similar uniform \( I_c \) was measured over the 1 meter length except for two weak sections. The two sections of HTS tape where \( I_c \) degradation is observed were further investigated using SHPM technique to locate the defective region. In one of the sections (section 2), a defect at \((x, y) = (-4, 0)\) with 15% lower \( J_c \) than its surroundings was identified by SHPM. The minor current density reduction at a few locations of the meter-long SF 2G (Gd,Y)BCO CC tape was not found to affect R-SFCL performance due to over-current operation of short duration pulse.

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References
[1] Xie Y Y, Tekletsadik K, Hazelton D and Selvamanickam V 2007 IEEE Trans on Appl. Supercond. 17 (2) 1981-1985.
[2] Wang Y, Lu Y, Xu X, Dai S, Hui D, Xiao L and Lin L 2007 Cryogenics 47 225-231.
[3] Abiru K, Honda Y, Inoue M, Kiss T, Iijima Y, Kakimoto K, Saitoh T, Nakao K and Shiohara Y 2009 Physica C, Supercond. 469 1450–1453.
[4] Roth B J, Sepulveda N G and Wikswo Jr J P 1989 “J. Appl. Phys. 65 361–372.
[5] Shiohara K, Higashikawa K, Inoue M, Kiss T, Iijima Y, Saitoh T, Yoshizumi M and Izumi T 2013 Phys. C, Supercond. 484 139–141.
[6] Tapestar®Theva operation manual, 2012. (Private communication)
[7] Furtner S, Nemetschek R, Semerad R, Sigl G and Prusseit W 2004 Supercond. Sci. Technol. 17 S281–S284.
[8] Li X F, Ben Yahia A, Majkic G and Selvamanickam V 2015 IEEE Trans. Appl. Supercond. 25 9000404.
[9] Brandt E H and Indenbom M 1993 Physical Review B 48 12893-12906.