Self Field Effect Analysis of Bi-2223 Tape-Stacked-Cable with Constant Current Density Assumption

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In this paper, we analyze self field effects of Bi-2223 tape-stacked cable assuming constant current density in the cross section of stacked cable. Generally, the critical current of Bi-2223 tape-stacked-cable is much less than the total summation of critical currents of each tape, which is mainly due to the self magnetic fields of the cable itself. Therefore, to predict the critical current of Bi-2223 tape-stacked-cable, we need to analyze the self field effects of the stacked cable as well as the critical current density data (J_c) of one tape. To make it more complex, the critical current degradation of a Bi-2223 tape is an-isotropic; the critical current is lower in the normal magnetic field(to the tape surface) than in the parallel field. In the paper, a novel approach to predict the critical current of a Bi-2223 tape-stacked-cable from a J_c-B curve of one tape is presented with the assumption of constant current density across the stacked cable. The approach basically includes the load analysis of the stacked tapes, and its usefulness is confirmed by the experimental data.

Keywords : self-field effect, HTS tape, J_c degradation

1. INTRODUCTION

So far, many efforts have been focused to develop high performance HTS (High Temperature Superconductor) magnets for the ultimate applications to power system devices. Magnet designers, however, have had difficulties in the estimation of the maximum operating current of the designed magnet from the tested short sample data, due to the degradation of the critical current density in the magnet. Similar story applies to the HTS electrical bus bar. It has been found that the critical current of Bi-2223 stacked tapes is much less than the total summation of critical currents of each tape, which is mainly attributed to the self magnetic fields. Furthermore, since the critical current degradation of Bi-2223 tape is greater in the normal magnetic field (to the tape surface) than in the parallel one, detailed magnetic field configurations are required to estimate the self field effects. In this paper, we suggest a load line analysis method, which predicts the critical current of stacked cable from an experimental critical current characteristic curve (Jc -B) of a single tape. The load lines can be defined using either overall current density or superconductor current density with the assumption of constant current density across the stacked cable. In this paper, the critical current calculation procedures for both cases are described and the experimentally obtained critical currents are compared with the calculated ones to show the usefulness of the suggested load line methods.

2. THEORY AND EXPERIMENTS

2.1. Load lines of stacked tapes using overall current density

The concepts of load lines using overall current density were introduced in Ref. [1], and we repeat them here briefly to further the idea to the load lines using superconductor current density only. Bi-2223 superconductor is usually rolled into a tape to have a final rectangular cross sectional shape. Current in the tape, of course, generates self field magnetic field around it, and the magnetic field distributions depend on the rectangular shape. Fig.1 shows a cross sectional view of a mono-filamentary conductor of which width and height are $2a$ and $2b$, respectively. It also shows that its filament has width of $2a_f$ and height of $2b_f$ If the current is distributed uniformly on all over the conductor, B_{xmax}, and B_{ymax}, the maximum magnetic field of x and y component, always occur at $(0,-b)$, and $(a,0)$, respectively. , B_{xmax} and B_{ymax} are calculated to be [1],

$$B_{x\max} = J \cdot a \cdot F_p(\alpha), \qquad B_{y\max} = J \cdot a \cdot F_n(\alpha) \tag{1}$$

where,

$$F_p(\alpha) = \frac{\mu_0}{2\pi} \cdot \left[\ln(1+4\alpha^2) + 4\alpha \cdot \tan^{-1}\left(\frac{1}{2\alpha}\right) \right] \tag{2}$$

$$F_n(\alpha) = \frac{\mu_0}{2\pi} \cdot \left[\alpha \cdot \ln\left(\frac{4+\alpha^2}{\alpha^2}\right) + 4 \cdot \tan^{-1}\left(\frac{\alpha}{2}\right) \right] \tag{3}$$

, and $\alpha = b/a$. J is an over all current density across the cross section of a conductor. Maximum magnetic fields described in (1) are functions of overall current density and the field factor F, which depends on only geometrical configuration of the tape. F_p and F_n in (2) and (3) are field factors for parallel and normal component to the tape surface. For a given specific shape factor α, field factor is fixed, and we define (1) as load lines using overall current density. Both F_p and F_n increases as α increases. The detailed configurations of F_p and F_n as a function of α are described in [1].

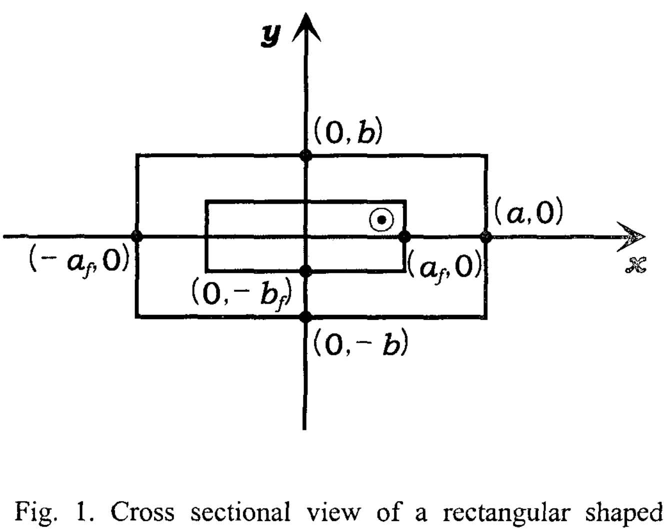

Fig. 1. Cross sectional view of a rectangular shaped mono-filamentary tape.

2.2. Load lines of stacked tapes using superconductor current density

Load lines introduced in the previous section are defined using overall current density across the conductor. The actual magnetic fields experienced by the superconductor in a tape, however, might be higher than the calculated ones from the previously introduced load lines. To predict the self field effects more precisely, one needs the load lines of superconductor only. Since maximum magnetic field locations vary as we stack the tapes, we need to define field factors for the newly stacked tapes. Basically, one can calculate magnetic field distributions of stacked tapes analytically [3], and can decide field factors for any point in a conductor. Our interesting point is, of course, the maximum magnetic field points for B_x and B_y. It can be induced that the maximum magnetic field point for B_x always occur at bottom of the lowest filament as can be seen in Fig. 2 and 3. The maximum magnetic field point for B_y is, however, depends on the stacked number of the tapes. For the odd-stacked tapes, the maximum B_y occurs at the right side of the mid-plane in the central filament (Fig. 2). For the even-stacked tapes, the maximum B_y occurs at right side of the two central filaments (See the dark short solid lines in Fig. 3.), which depends on the filament shape. Basically, the field factors of stacked tapes can be calculated by superposing the field factors of each rectangles with proper sign.

For odd-stacked tapes, the field factor F_x and F_y are :

$$F_x = F_p(\alpha_1) - F_p(\alpha_2) + F_p(\alpha_3) - F_p(\alpha_4) + \cdots \tag{4}$$

$$F_y = F_n(\alpha_1) - F_n(\alpha_2) + F_n(\alpha_3) - F_n(\alpha_4) + \cdots \tag{5}$$

, where $\alpha_1 = b_f/a_f$, $\alpha_2 = (b+b_f)/a_f$, $\alpha_3 = (2b+b_f)/a_f$, and $\alpha_4 = (3b+b_f)/a_f$ and so on. For even-stacked tapes, the field factor F_x can be expressed as

$$F_x = -F_p(\alpha_1) + F_p(\alpha_2) - F_p(\alpha_3) + F_p(\alpha_4) + \cdots \tag{6}$$

, where $\alpha_1 = (b-b_f)/a_f$, $\alpha_2 = (b+b_f)/a_f$, $\alpha_3 = (2b+b_f)/a_f$, and $\alpha_4 = (3b+b_f)/a_f$ and so on. The location of B_{ymax}, however, is not at $(a_f, 0)$, but does vary along the dark solid line as in Fig. 3, depending on the shape of the conductor. In this case, we cannot use (3) for the field factor calculation but have to find maximum magnetic field point and derive new formula, referring to the analytic expression of rectangular-shaped conductor [1],[2]. If we put prime notation on the newly derived field factor as F_n', which is too lengthy to include, F_y for the even-stacked tapes is

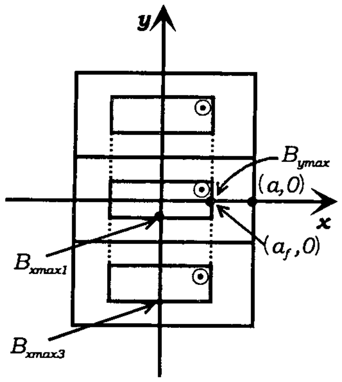

Fig. 2. Cross sectional view of odd-stacked tapes. B_{xmax} occurs at (0, $-b_f$), for one tape, and at (0, $2b+b_f$) for three stacked tapes and so on. B_{ymax} occurs at (a_f, 0) for both one and three stacked tapes.

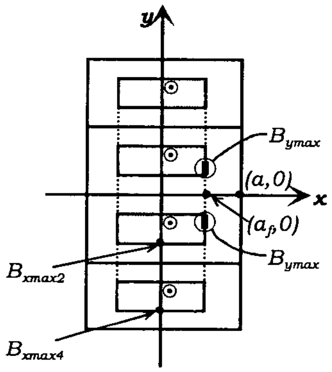

Fig. 3. Cross sectional view of even-stacked tapes. B_{xmax} occurs at (0, $b-b_f$), for two stacked tapes, and at (0, $3b+b_f$). B_{ymax} occurs at dark solid lines, depending on the tape shape.

$$F_y = F'_n(\alpha_1) - F'_n(\alpha_2) + F'_n(\alpha_3) - F'_n(\alpha_4) + \cdots \quad (7)$$

, where α_1, α_2, α_3, and α_4 are the newly defined variables. The maximum magnetic fields of B_{xmax} and B_{ymax} are calculated as in (1), but one should replace the overall current density and a (half of the conductor width) by the superconductor current density and a_f (half of the filament width).

Fig. 4 shows the calculated curves of the above mentioned field factors as a function of stacked number for a specific tape size, which is described in Table 1. Also in the figure is the field factors using overall current density, which is based on (2) and (3). One can notice that the field factors using superconductor current density is smaller than those of overall current density,

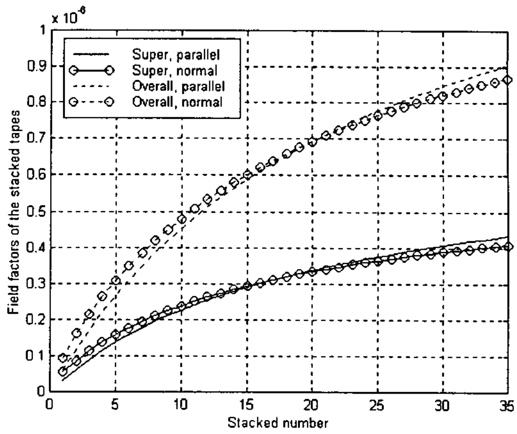

Fig. 4. Calculated field factors *vs.* stacked number. The solid ones are from using supercoductor current density, and the dotted ones, overall current density. The circled ones are the normal magnetic field factor to the tape surface.

which was expected from the minus terms in (4) through (7). But the maximum magnetic fields are usually quite the reverse because the superconductor current density is as many times larger as the overall current density, depending on the silver to superconductor ratio of the conductor.

2.3. Generation of J_c *vs.* self-field compensated magnetic field

To do load line analysis, one needs critical current density *vs* .self field compensated magnetic field characteristic curve. The dotted lines in Fig. 5 are the experimentally obtained J_c-B curves for parallel (square) and normal (circled) magnetic fields to the tape surface. We used self field factors to calculate the incremental ΔB due to transport current, and added the effects to the external magnetic field. The solid ones are finally obtained J_c *vs.* self field compensated magnetic fields. To see the compensated effects more clearly, we added the enlargement inside the main box with the magnetic field range of 0 - 0.02[T].

3. EXPERIMENTAL AND DISCUSSION

Table 1 and Fig. 6 illustrate the size and cross sectional shape of BSCCO-2223 tape, used in J_c measurement. Field factor calculations of Fig. 4 and J_c - B curve of Fig. 5 were made from the data of Tape 2. For Tape 1, after heat treatment of long tape, we cut the tape into 10 cm long. The tapes were stacked as desired, and were subjected to final heat treatment. For Tape 2, we cut the tape after final heat treatment, and stacked them, and fastened using silver wire.

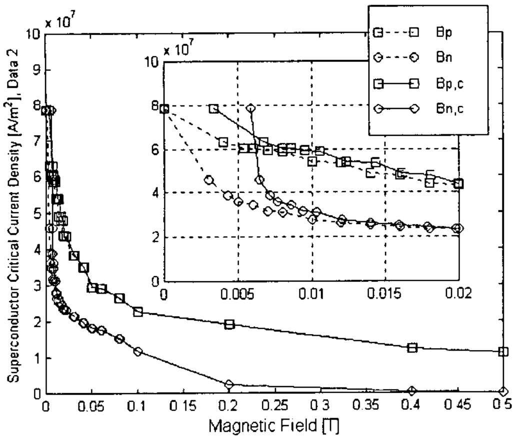

Fig. 5. Superconductor critical current density *vs.* external (dotted line) and self field compensated (solid line) magnetic field. Subscript 'c' in the legend means compensation. Inside the box is the enlargement of the range of 0 – 0.02 [T].

Table 1. Size of the BSCCO-2223 tapes in [mm]

	Tape 1	Tape 2
Width of the tape ($2a$)	3.0	3.2
Height of the tape($2b$)	0.14	0.16
Width of the filament ($2a_f$)	2.5	2.7
Height of the filament ($2b_f$)	0.06	0.07

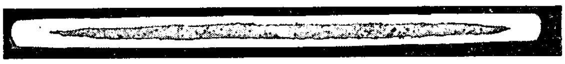

Fig. 6. Cross sectional view of mono-filamentary BSCOO-2223 Tape 2.

Fig. 7 and 8 shows load lines of Tape 2 with the self field compensated magnetic fields. One can find 18 load lines for 1-9 stacked tapes, 9 load lines for parallel magnetic fields (dotted), and the other 9 for normal magnetic fields (solid) to the tape surface. As the magnetic fields increases, the critical current decrease due to normal magnetic field is larger than that the decrease due to parallel magnetic field. Therefore, load lines of normal magnetic fields with J_c-$B_\perp$ determine the critical points rather than those of parallel magnetic fields with J_c-$B_\parallel$. Finally obtained critical points are the asterisked points in Fig. 7 and 8. With these points, one can calculate the critical currents of any numbered stacked tapes, which are summarized in Table 2 and 3. The I_{cc1} and I_{cc2} are the calculated critical currents using overall (Fig. 7) and superconductor (Fig. 8) current density, respectively, and I_m is the measured one. As the stacked number increases, the measured critical current decreases dramatically, and

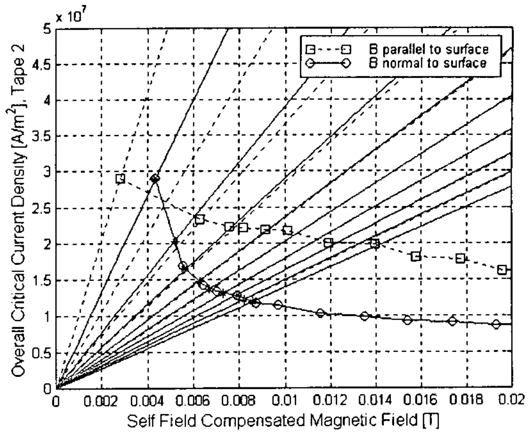

Fig. 7. Load lines with J_c *vs.* B (Self field compensated field) of Tape 2 using overall current density.

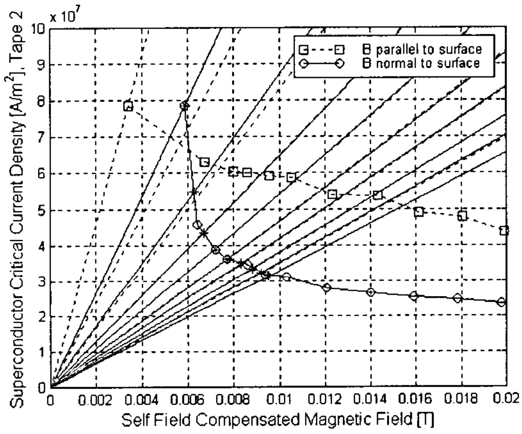

Fig. 8. Load lines with J_c *vs.* B (Self field compensated field) of Tape 2 using superconductor current density.

the calculated ones, I_{cc1} and I_{cc2}, trace the decreasing trends quite well, but the absolute magnitude still have discrepancies to explain the critical current degradation after the stacking. For Tape1, the I_{cc1} and I_{cc2} are much smaller than the current $N\times I_c$, multiplication of the stacked number by the critical current of one tape, but still larger than the measured ones. For Tape 2, the I_{cc1} and I_{cc2} are also much smaller than the current $N\times I_c$,, but, in this case, smaller than the measured ones. Notice that Tape1 was subjected to final heat treatment after stacking, which might mean that the stacked tapes have no gape between the tapes. But for Tape 2, we stacked tapes after final heat treatment, and packed by using silver wire. We found small gaps between the stacked tapes, and the calculation shows that there are 10-20% increases in critical current by introducing 0.1 mm gap between the tapes. That can explain the large measured current density of Tape 2, in part. Further more, after removing the stacked tapes one by one, we found that

Table 2. Critical currents of stacked tapes of Tape 1.

Stacked Number (N)	$N \times I_c$	I_{cc1}	I_{cc2}	I_m
1	12.3	12.3	12.3	12.3
3	36.9	31.9	30.7	27.0
5	61.5	45.9	45.0	35.4
7	86.1	59.4	58.2	42.8

I_{cc1}: Calculated critical current using overall current density
I_{cc2}: Calculated critical current using superconductor current density
I_m: Measured critical current

Table 3. Critical currents of stacked tapes of Tape 2.

Stacked Number (N)	$N \times I_c$	I_{cc1}	I_{cc2}	I_m
1	14.8	14.8	14.8	14.8
2	29.6	20.8	20.7	25.2
3	44.4	25.3	24.6	34.5
4	59.2	30.1	29.3	47.3
5	74.0	34.9	34.0	56.7
6	88.8	40.3	39.7	64.2
7	103.6	45.7	44.4	73.6

I_{cc1}: Calculated critical current using overall current density
I_{cc2}: Calculated critical current using superconductor current density
I_m: Measured critical current

each critical current of stacked tape of Tape 2 varies 14-19 [A], while we used 14.8 [A] for the generation of J_c-B curve. Finally, the filament cross sectional shape is not strictly rectangular as shown in Fig. 6, which causes errors to determine the filament sizes. It is thought that the above described reasons result in the higher measured values than the calculated ones in Tape2-stacked cables.

Table 2 and 3 shows that I_{cc2} always has smaller values than I_{cc1} as expected, but the differences between them are quite negligible for these specific cases. Actually, the differences between I_{cc1} and I_{cc2} depend the relative sizes of the tape and filaments. It is believed that for Bi-2223 stacked cables, however, considering the usual cross sectional shape of the tape, the differences between I_{cc1} and I_{cc2} could be small in most cases. Therefore, we conclude that load line analysis for self-field effects of stacked cables can be performed with (1) - (3), which use overall current density rather than (4) - (7), which use the relatively complicated superconductor current density.

4. CONCLUSION

Load line analysis of Bi-2223 stacked tapes for the estimation of critical current degradation due to self field was performed with the assumption of constant current density across the stacked cable. The load lines were defined using either overall current or superconductor current density by introducing respective self field factors. The calculated critical currents using the suggested load line analysis showed some discrepancies from the measured values, which could be explained by the non-uniform current density along the tape, the gaps between the tapes of stacked cable, and the non-rectangular shape of the filaments. With these causes fixed, however, the load line analysis can explain the self field degraded tendencies of stacked tapes quite well, and can be used when estimating the critical current of stacked tapes. It is believed that the critical current of multi-filamentary tape-stacked cable can also be estimated using the suggested load line analysis with overall current density. Finally, to predict the self field effect more precisely, we need to calculate the critical current density distribution across the stacked tapes.

ACKNOWLEDGMENTS

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