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Critical Current Degradation Analysis in HTS Pancake Coil due to Self Field Effects

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Abstract

Since the discovery of high Tc superconductors, great efforts have been focused to develop high performance HTS 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 reduce the self field effects. In this paper, we calculate the self field effects of a stacked conductor, defining self field factors of normal and parallel magnetic fields to the tape surface. Finally, the critical current degradations in the HTS magnet are explained by the introduced self field factors of the stacked conductor.

Keywords: HTS magnet, Self field effects, Critical current degradation

I. Introduction

HTS magnet development is basically needed for the HTS application to power system devices as well as to the high energy physics. The HTS magnet designers, who design magnet using the short sample test results, however, have always had difficulties in the estimation of the maximum operating current of the designed magnet, due to the degradation of the critical currents in the magnet. Similar situation applies to the HTS electrical bus bar and current leads. Recently, multi-stacked Bi-2223 tapes have a been used for large current carrying bus bar because bus bar has a relatively low self magnetic field. Usually they stack tapes to be a multi-stacked conductor, which is again displaced in a bus bar spacer for large current transportation. The large current inherently generates large self magnetic field, which degrades the critical current of a bus bar. To reduce these self magnetic field effects, some research groups suggested several methods, such as an alternate go-and-return structure and a new stacking method of HTS tapes, of which effects had been verified by experiment [1],[2]. It seems, however, that the anisotropic characteristics of the critical current of HTS tapes require more detailed quantitative analysis to get optimally reduced self field effects in a bus bar system. In this paper, we introduce self field factors of parallel and normal magnetic fields for a rectangularly shaped conductor, and calculate the critical current of it, of which validities are confirmed by ex-

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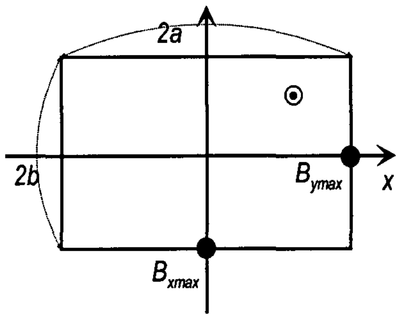


Fig. 1 Cross sectional view of a rectangular conductor (tape) with width $2a$ and height $2b$.

periments in part. Using the introduced self field factors, the self field effects in a single pancake coil will be explained.

II. Self field of a rectangular conductor

Fig. 1 shows a cross sectional view of rectangular conductor with width $2a$, and height $2b$. The magnetic field distribution of Fig. 1 can be described analytically, the formulas of which are as in (1) and (2).

$$B_x = \frac{\mu_0 J}{4\pi}\left[(x-a_1)\ln\left\{\frac{(x-a_1)^2+(y-b_2)^2}{(x-a_1)^2+(y-b_1)^2}\right\} + (x-a_2)\ln\left\{\frac{(x-a_2)^2+(y-b_1)^2}{(x-a_2)^2+(y-b_2)^2}\right\} + 2(y-b_2)\left\{\tan^{-1}\frac{(x-a_1)}{(y-b_2)} - \tan^{-1}\frac{(x-a_2)}{(y-b_2)}\right\} + 2(y-b_1)\left\{\tan^{-1}\frac{(x-a_2)}{(y-b_1)} - \tan^{-1}\frac{(x-a_1)}{(y-b_1)}\right\}\right] \quad (1)$$

$$B_y = \frac{\mu_0 J}{4\pi}\left[(y-b_1)\ln\left\{\frac{(x-a_1)^2+(y-b_1)^2}{(x-a_2)^2+(y-b_1)^2}\right\} + (y-b_2)\ln\left\{\frac{(x-a_2)^2+(y-b_2)^2}{(x-a_1)^2+(y-b_2)^2}\right\} - 2(x-a_2)\left\{\tan^{-1}\frac{(x-b_1)}{(x-a_2)} - \tan^{-1}\frac{(y-b_2)}{(x-a_2)}\right\} - 2(x-a_1)\left\{\tan^{-1}\frac{(x-b_2)}{(x-a_1)} - \tan^{-1}\frac{(y-b_1)}{(x-a_1)}\right\}\right] \quad (2)$$

, where a_1 and a_2 are the x axis coordinates of the left and right side of the conductor, respectively. In figure 1, $a_1 = -a$ and $a_2 = a$. Similarly, b_1 and b_2 are the y axis coordinates of the lower and upper side of the conductor, respectively. In figure 1, $b_1 = -b$ and $b_2 = b$. If we choose the x axis to be parallel, and the y axis normal to the conductor (tape) surface, the maximum parallel component B_{pmax}, and the maximum normal component B_{nmax} always occur at $(0, -b)$, and at $(a, 0)$, respectively. B_{pmax} and B_{nmax} can easily be calculated to be,

$$B_{p\max} = J\cdot a\cdot F_p(\alpha), \quad B_{n\max} = J\cdot a\cdot F_n(\alpha) \quad (3)$$

where,

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

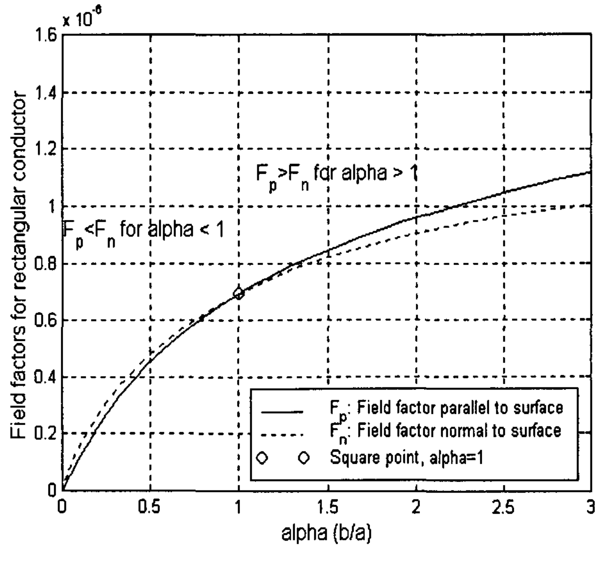


Fig. 2 Self field factors of a rectangular conductor as a function of α.

In the above equation, $\alpha=b/a$, and J is an over all current density across the cross section of the conductor. The field factors F_p for B_{pmax} and F_n for B_{nmax} are functions of α only, and are shown as in Fig. 2. Both F_p and F_n increase as α increases. F_p is less than F_n for $\alpha<1$, and greater than F_n for $\alpha>1$.

III. Critical current degradation of stacked conductors

Fig. 3 shows critical current values of 1, 3, 5, and 7 stacked Bi-2223 tapes. The tapes were fabricated using a typical PIT method. Powders of $Bi_2Sr_2Ca_2Cu_3O_x$ were loaded into silver tubes and then swaged, drawn, and rolled into tapes with a final thickness of 0.14 mm and a width of 3 mm. The fabricated tape is mono-filamentary, and the silver to superconductor ratio was 2.3 to 1. After heat treatment, 10 cm long tapes were stacked as desired, and were subjected to final heat treatment. Without self field effects, the critical current of stacked conductors should be the same as the multiplication of the stacked number by the critical current of one tape. Data in Fig. 3 shows that the critical currents of stacked conductors decrease more as the stacked number increases.

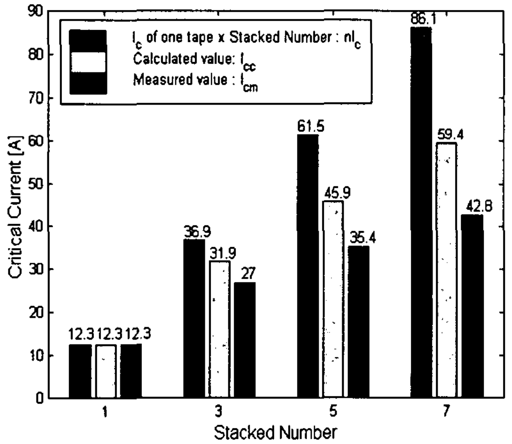
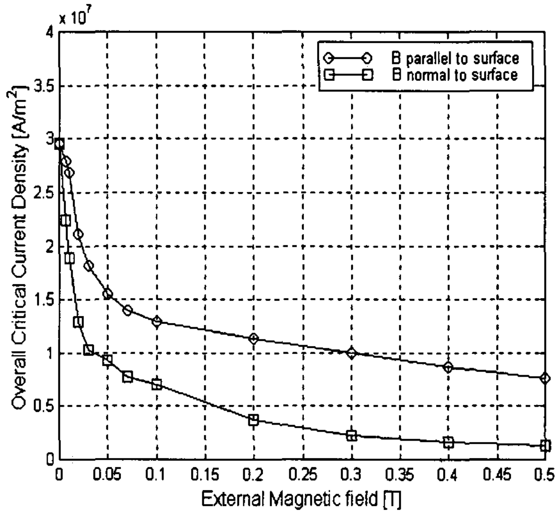
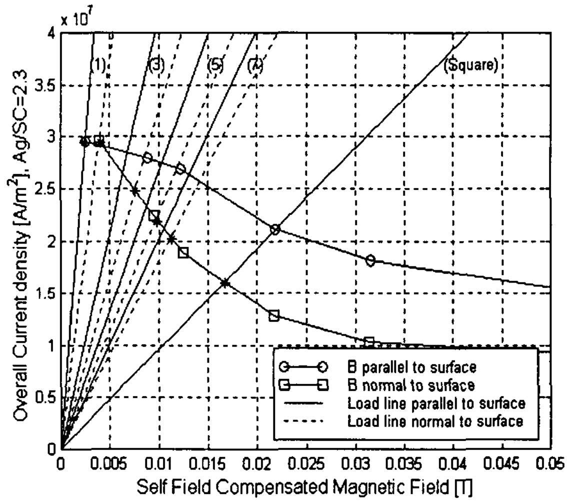


Fig. 3 Critical currents of Bi-2223 stacked superconducting conductors. I_{cc}/nI_c for stacked number 3, 5, and 7 is 0.86, 0.75, and 0.69, respectively, and I_{cm}/nI_c, 0.73, 0.58, and 0.50.

To analyze the self field effects quantitatively, we can use eq. (3) and eq. (4) to define load lines of parallel and normal magnetic fields for arbitrarily shaped rectangular conductors. For 1, 3, 5, and 7



(a)



(b)

Fig. 4 (a) Critical current vs. external magnetic field of one tape (b) Diagram for critical current calculation with load lines and self field compensated magnetic field. (1), (3), (5), and (7) mean stacked number, and each corresponds to α = 0.047, 0.14, 0.23, and 0.33, respectively.

stacked conductors, each has its own load line in the experimentally obtained J_c-B plane to calculate critical currents. The first graph of Fig. 4 is an experimentally obtained J_c-B curve, but in this figure the magnetic field B does not include self magnetic fields: B represents an external magnetic field only. We use self field factors of eq. (3) and (4) to calculate incremental ΔB due to transport current, and add the effects to the external magnetic field data of (a) of Fig. 4. Then we finally obtain (b) of Fig. 4. In this figure, one can find 8 load lines for 1, 3, 5, and 7 stacked conductors, 4 load lines for parallel magnetic fields and the other 4 for normal magnetic fields. It is satisfactory to check that the two critical current densities, determined from the two J_c-B curves and load lines at the beginning of graph (b), coincide each other. As the magnetic field (including self field) increases, critical current density due to normal magnetic field component decreases more than that of parallel magnetic field component. So, load lines of normal magnetic fields with J_c-$B_\perp$ curve determine the critical points rather than those of parallel magnetic fields with J_c-$B_\parallel$. As a result, the asterisked points are used to determine critical current density of the conductors. The results are summarized in Fig. 3 with "Measured values".

As can be seen in the figure, the measured critical currents are still quite a bit smaller than the calculated ones. This is due to the fact that the load lines we have proposed are for the entire conductor, but not for the superconductor only. Note that the y-axis in Fig. 4 is overall current density rather than current density of superconductor only. Therefore, the actual magnetic fields experienced by superconductors in the stacked conductors are higher than the calculated ones, which could explain the discrepancies in Fig. 3. To predict the self field effects more precisely, one needs load lines of superconductor only, which is not a simple problem, especially for multi-filamentary conductors. Fig. 4 demonstrates that to reduce self field effects effectively, we need to minimize the normal magnetic fields on the tape surface. Kato *et al* proposed a new stacking method, which proved to reduce normal magnetic fields effectively [2]. Still, it seems, however, that there should be an optimum tape stacking structure that minimizes the normal magnetic fields the most. The optimum stacking problem in a conductor will be proposed in somewhere else. In this paper, we go to a HTS pancake coil, to analyze the self field effect using the concept introduced above.

IV. Critical current degradation of a single pancake coil

Fig. 5 shows a single pancake coil, which has inner radius of r_1 and outer radius of r_2. Using the geometry of Fig. 1, one can see that the tapes are stacked in the direction of y axis. If the radius of the coil is large enough, the coil can be treated as a straight stacked cable rather than a solenoid. Then, we can use the self field factors to estimate the critical current of the coil. No doubt, α of a pancake coil is much greater than 1, which means $F_p >> F_n$. Therefore, the maximum magnetic field occurs at the point of B_{ymax}, rather than B_{xmax} in Fig. 5. With the experimentally obtained short sample data of HTS tape, one can estimate the critical current of a single pancake coil just like the same way as did in the stacked cable. If the radius of the coil is not large enough to take the coil to be straight, we need to know the details of the magnetic field distribution of the pancake coil itself to estimate the current degradation in it.

V. Conclusion

We introduced self field factors of parallel and normal magnetic fields of a rectangular conductor,

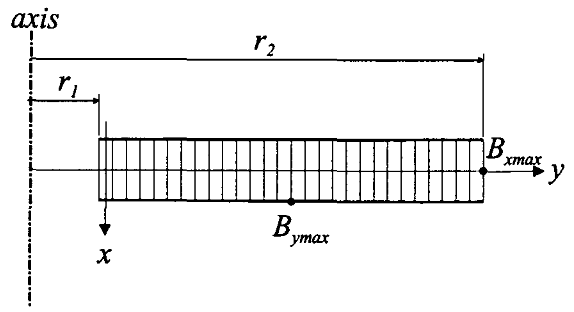


Fig. 5 Cross sectional view of single pancake coil, which has the inner radius of r_1 and outer radius of r_2.

and calculated critical currents of stacked tapes. The calculated values were still larger than the measured ones, which attributes to the fact that we used overall current density to calculate them. To predict critical current degradation due to self field effects more precisely, one needs load lines of superconducting filaments only, the results of which will appear somewhere else.

Finally, we explained the self field effects of a single pancake coil using the self field factors introduced in stacked conductors. The maximum parallel magnetic field experienced in a coil takes place at the middle line of bottom (or top) plate, while the maximum normal magnetic field does at the mid-point of outer surface. In this way we can estimate the critical current density of a single pancake coil, depending on the experimented short sample test results. To estimate the critical current of a magnet more accurately, one need to develop the load lines of a solenoid coil, taking into account of the anisotropic characteristics of HTS tapes.

Acknowledgments

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