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Cabling Method for High Current Conductors Made of HTS Tapes

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***Abstract*—A small-scale test of a twisted stacked-tape conductor made of coated YBCO tapes was performed using four-tape cable. The critical current degradation and current distribution of this four-tape conductor was evaluated by taking account the twist-strain, the self-field and the termination resistance. The critical current degradation for the tested YBCO tape may be explained by the perpendicular self-field effect solo. The critical currents of the twisted stacked-tape conductor with four-tape cable have been confirmed not to degrade up to 120 mm twist pitch length. This type of conductor design is proposed to make it possible to fabricate highly compact, high current cables from multiple flat HTS tapes.**

***Index Terms*— HTS, twist, cable, critical current, self-field.**

I. INTRODUCTION

New electric power and magnet applications of High Temperature Superconductors (HTS) require development of cables capable of carrying high current, often at high magnetic fields. The present flat shapes of both 1G and 2G tapes are not ideal for bundling together to carry high currents. Cables carrying about 1-3 kA have already been demonstrated by helically winding the tapes on a tube former [1], [2]. This approach is not adequate for much higher current cables. Other methods are also under development such as ROEBEL Assembled Coated Conductor [3]. This geometry reduces AC losses, but it also is not easily scalable to very high currents and results in low overall current density.

Recently we have started development of a twisted, stacked-tape geometry to provide a more simple and scalable cabling method [4]. Coated YBCO tape has good mechanical properties to torsional strains [5], [6]. Typically 2G YBCO tape is deposited on a base Ni alloy substrate with additional insulating buffer layers below the YBCO layer and a thin silver layer above the YBCO layer [7]. If desired, thin copper may be deposited over the assembly. The silver side of the tape thus has better electrical transverse conductivity than the substrate side. This asymmetric conductivity is unique compared with other superconductors, and requires special technologies for joints and terminations. In this paper characteristics of the twisted stacked-tape conductor are discussed with critical current degradation, current distribution, termination resistance, self-field, and twist-pitch effect.

II. TWISTED STACKED-TAPE CONDUCTOR

A. Cabling Concept

Freestanding flat tapes are torsionally twisted along the axis of the stack without an external tensile or compressive longitudinal-force, as shown in Fig.1. This cabling method is conceptually different from the existing lapped type cabling. The method allows development of high current, compact conductors for various applications such as power transmission cables and high field magnets. The twisted stacked-tape cable may be enclosed by an electrically conducting conduit as a stabilizer and supporting structure. There are a few options to make the twisted stacked-tape conductor: 1) Stack and twist, then clad, 2) Stack and clad, then twist, or 3) Stack, and then embed in helical open grooves on a structured conduit. Multi-stage cabling of this basic conductor allows developing high current conductors such as a cable-in-conduit conductor.

Fig. 1. Schematic illustrations of twisted stacked-HTS tape conductor.

B. Torsion Twist Strain

The amount of twist is limited to the range of strain tolerances of the tape superconductors. We have reported a torsional twist strain effect on the critical current of a thin HTS tape [4]. It has been described by longitudinal strains taking into account the internal shortening compressive strains accompanied with the tensile longitudinal strains due to a torsional twist.

Schematic illustrations of a twisted single flat tape, and a twisted stacked-tape cable are shown in Fig. 2. In these figures torsional twists are applied to thin rectangular tapes (width w and thickness t) of the length L. During the twisting process, the HTS tapes experience torsional twisting strains. The twisting strain of a tape located at the distance h from the z-axis is approximately described by the axial longitudinal strains ε_{xh} as a function of the distance x from the center axis of each tape as;

$$\varepsilon_{xh} = \frac{\theta^2}{2}\left(x^2 - \frac{w^2}{12}\right), \qquad (\theta = \phi / L) \tag{1}$$

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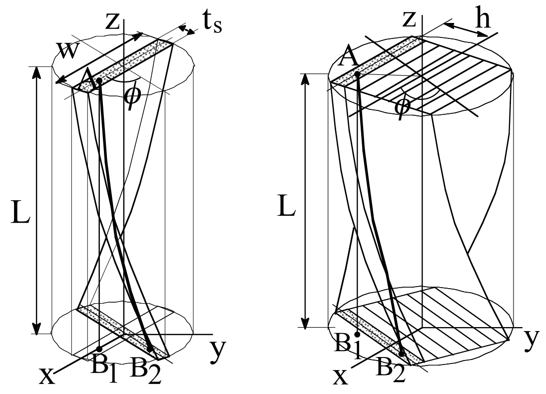
The axial longitudinal strains ε_{xh} does not depend on the tape location h. Therefore any tape in a stacked-tape cable experience the same longitudinal strain distribution as that of the single twisted tape.



(a) (b)

Fig. 2. Schematic illustrations of (a) a single twisted thin rectangular tape, and (b) Twisted stacked-tape cable.

C. *Critical Current*

The critical current of a twisted tape is given by a summation of critical current densities $j_c(\varepsilon_{xh})$ over the tape cross-section of the width w and the thickness t_s, corresponding to the strain distribution given by equation (1). The total critical current I_c of a stacked cable composed of n tapes is given a function of the axial longitudinal strain by

$$I_c = n\, t_s \int_{-\frac{w}{2}}^{\frac{w}{2}} j_c(\varepsilon_{xh})\, dx\,. \qquad (2)$$

Note that more accurately $j_c(\varepsilon_{xh})$ also depends on the field.

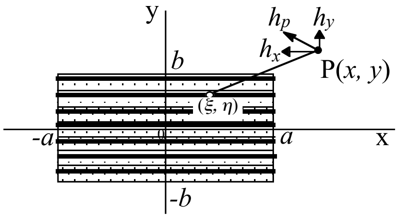


Fig. 3. Magnetic self-field of a stacked tape conductor.

D. *Magnetic Self-Field*

The magnetic self-field of a stacked tape conductor can be analytically calculated for an infinitively long conductor. Fig. 3 shows a cross-section ($2a$ x $2b$) of a stacked tape conductor in an x-y plain. The current flows along the z-axis. An infinite line-conductor of the cross-section $d\xi$ x $d\eta$ at (ξ, η) carrying a current i (A) produces the magnetic field strength h_p at P(x, y). The field strength component h_x and h_y of h_p are easily obtained by Ampere's law [8] as;

$$\begin{aligned} h_x &= -\frac{i\,(y-\eta)}{2\pi\{(x-\xi)^2+(y-\eta)^2\}}\, d\xi\, d\eta \\ h_y &= \frac{i\,(x-\xi)}{2\pi\{(x-\xi)^2+(y-\eta)^2\}}\, d\xi\, d\eta \end{aligned} \qquad (3)$$

The field components are integrated along the conductor of each tape where the current locally flows. The integration can be solved analytically. In this paper, for simplification, we expect the current to flow uniformly over the stacked conductor cross-section of $2a$ x $2b$. The field components H_x and H_y at P(x, y) due to the total cable current I (A) are given as,

$$\begin{aligned} H_x &= -\frac{I}{8\pi ab}\int_{-a}^{a}\int_{-b}^{b} \frac{i\,(y-\eta)}{(x-\xi)^2+(y-\eta)^2}\, d\xi\, d\eta \\ &= -\frac{I}{8\pi ab}\left\{\frac{x+a}{2}\ln\frac{(x+a)^2+(y+b)^2}{(x+a)^2+(y-b)^2} - \frac{x-a}{2}\ln\frac{(x-a)^2+(y+b)^2}{(x-a)^2+(y-b)^2}\right. \\ &\quad +(y+b)\left(\arctan\frac{(x+a)}{(y+b)} - \arctan\frac{(x-a)}{(y+b)}\right) \\ &\quad \left. -(y-b)\left(\arctan\frac{(x+a)}{(y-b)} - \arctan\frac{(x-a)}{(y-b)}\right)\right\} \end{aligned} \qquad (4)$$

$$\begin{aligned} H_y &= \frac{I}{8\pi ab}\int_{-a}^{a}\int_{-b}^{b} \frac{i\,(x-\xi)}{(x-\xi)^2+(y-\eta)^2}\, d\xi\, d\eta \\ &= \frac{I}{8\pi ab}\left\{\frac{y+b}{2}\ln\frac{(x+a)^2+(y+b)^2}{(x-a)^2+(y+b)^2} - \frac{y-b}{2}\ln\frac{(y-b)^2+(x+a)^2}{(y-b)^2+(x-a)^2}\right. \\ &\quad +(x+a)\left(\arctan\frac{(y+b)}{(x+a)} - \arctan\frac{(y-b)}{(x+a)}\right) \\ &\quad \left. -(x-a)\left(\arctan\frac{(y+b)}{(x-a)} - \arctan\frac{(y-b)}{(x-a)}\right)\right\} \end{aligned} \qquad (5)$$

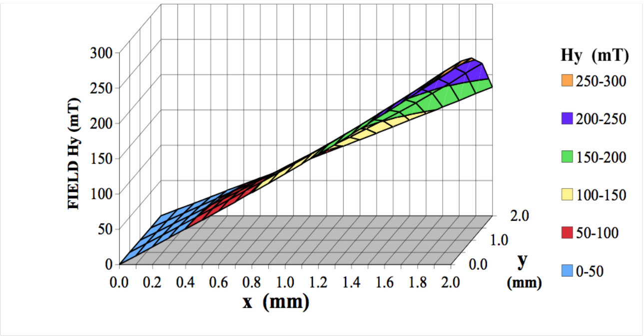


Fig. 4. Perpendicular field H_y calculated from (5) for a 40-tape stacked conductor made of 4 mm width, 0.1 mm thick tapes at the current 3.2 kA.

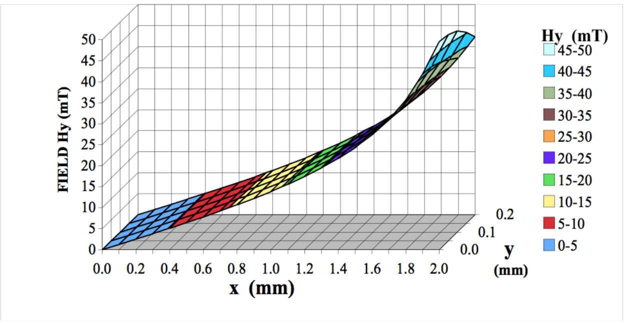


Fig. 5. Perpendicular field H_y calculated from (5) for a 4-tape stacked conductor made of 4 mm width, 0.1 mm thick tapes at the current 253 A.

The critical current of coated YBCO tape is very sensitive to the magnetic field perpendicular to the tape plane ($H\perp ab$ plane). Fig. 4 shows the perpendicular field H_y calculated from (5) for a 40-tape stacked conductor made of 4 mm width, 0.1 mm thick tapes at the current 3.2 kA (a=2 mm, b=2 mm, and I=3.2 kA). The figure shows a quarter of the stacked cable cross-section. The maximum field H_y is about 275 mT at the edge of the center tape among the stacked tapes.

Fig. 5 shows the similar field distribution, but for a 4-tape cable with the current of 253 A (a=2 mm, b=0.2 mm, and I=253 A). The maximum perpendicular field H_y is about 50 mT. The self-field results in a noticeable degradation of the cable critical current as discussed below.

III. EXPERIMENTAL

Torsion twist tests of a twisted stacked-tape conductor were performed with a 4-tape cable made of coated YBCO tapes made by SuperPower, Inc. The YBCO tape was a 2G Type SCS 4050 on 50 μm nickel alloy (Hastelloy®) substrate with a surrounding copper stabilizer. The tape width and thickness were 4.05 mm and 0.128 mm, respectively.

During the twisting cable test, the following tests were carried out: 1. Critical current test of each tape. 2. Critical current tests of the 4-tape stacked-cable with various twist pitches. 3. Critical current tests of the 4-tape cable separated with 4 mm spacers between tapes. 4. Current distribution measurements among 4 tapes. 5. Termination resistance measurement of each tape.

The twist cable test device was similar to the one reported in [4]. The test tapes were total 440 mm in length including a 50 mm termination at each end. Voltage taps to measure the critical current were provided on each tape of the cable with a voltage tap separation of 300 mm. The lower termination of the sample is fixed, while the upper termination was mounted on a rotatable current lead. All experiments were performed in liquid nitrogen (77 K) without externally applied magnetic fields. Joint resistances of each tape were measured after cable tests by cutting the tapes at the middle of the cable.

To measure current distributions of a 4-tape cable, a Hall current sensor device was developed. The current sensor was composed of a C-shape magnetic core (11 mm x 6.4 mm x 3.0 mm thickness) made of stainless steel 430 A with a Hall sensor (F. W. Bell FH-301-020). Four Hall current sensors were assembled on a 32 mm diameter G10 rod. The current sensor assembly was mounted between the lower termination and the lower voltage taps. Each tape conductor was passed through the center hole of the magnetic core. The tape currents were evaluated from the hall voltage after calibration.

IV. RESULTS AND DISCUSSION

The voltages of individual tapes of an untwisted YBCO 4-tape stacked cable were measured with the voltage tap separation of 300 mm, and are shown as a function of the total cable current in Fig. 6 (a). The voltages of 4 tapes were simultaneously recorded during charging. At the same time the current of each tape was measured by the Hall current sensor as shown in Fig. 6 (b). The individual currents flowing in the stacked tapes were quite different. The non-uniform current distribution seems to mainly result from the termination resistance deviations. Tape #1 was charged much quicker than the others, especially Tape #2. When Tape #1 reached about 20 μV (corresponding to 0.66 μV/m), the current of Tape #2 increased sharply. As shown later, the termination resistance of Tape #2 was much higher than the others.

Even if the 4-tapes were stacked tightly (no spacer, unsoldered), the voltage of each tape was different as seen in Fig. 6 (a). Sharing currents of a few amperes might occur through the contact resistance between tapes during the transition. They could be negligible to the critical current. The cable critical currents evaluated at the criteria of 100 μV/m (30 μV for the 300 mm voltage-tap separation) from these individual tape voltages of Tape #1, #2, #3 and #4 were 248 A, 258 A, 254 A and 250 A, respectively. These critical currents (average 253 A) were about 24% lower than 331 A expected from the sum of the individual tape values. The critical current of Tape #1, #2, #3 and #4 measured each one separately were 82 A, 82 A, 84 A, and 83 A, respectively.

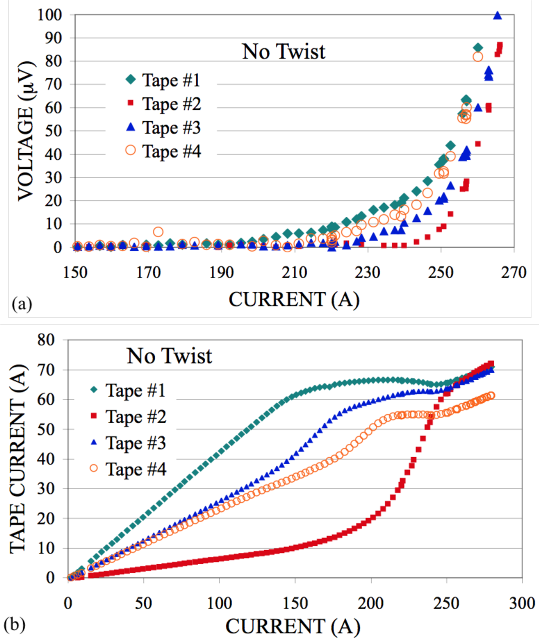


Fig. 6. Charging behaviors of a 4-tape YBCO cable: (a) Tape voltages and (b) Tape currents of 4-tape tightly stacked cable as a function of the total current before twisting.

Termination resistances of the upper and lower joints of each tape were measured after the cable tests with a portion of copper lead. The total (upper and lower values) termination resistance results of Tape #1, #2, #3 and #4 were 0.67 μΩ, 1.06 μΩ, 0.65 μΩ, and 0.73 μΩ, respectively. Each termination resistance was about 0.33 μΩ. It was noted that the upper termination resistance of Tape #2 was 0.73 μΩ. The high resistance resulted in the slow charge of the current of Tape #2 seen in Fig. 6 (b).

The 24% degradation of the tightly stacked cable has been explained by the self-field effect on the critical current. According to SuperPower data for a similar YBCO tape, the normalized critical current reduces to 35% at the perpendicular field of 200 mT [7]. From simple interpolation one can calculate the critical current would be reduced up to 84% of the maximum value at the estimated maximum perpendicular self-field of 50 mT at the cable critical current of 253 A as seen in Fig. 5. The overall actual perpendicular self-field distribution over the tapes is smaller than 50 mT as seen in Fig. 5, but the estimated degradation from the interpolation is optimistic since the critical current degrades much more sharply than that estimated from the 200 mT data. Therefore the 24% degradation observed experimentally is likely to be due to the perpendicular self-field of the tightly stacked-tape cable.

Fig. 7 shows the sample voltage of each tape of the same 4-tape cable, but the tapes were separated from each other by 4 mm spacers (thick Teflon TEF tape). During charging the tape voltages showed instabilities near the 100 μV/m criteria voltage as seen in Fig. 7, which were not seen in the tightly stacked cable. The transition behaviors of the V-I curves of the separated tape cable are quite different from that of the tightly stacked cable shown in Fig. 6. Further details of tape current behaviors during charging of a multi tape cable will be discussed elsewhere.

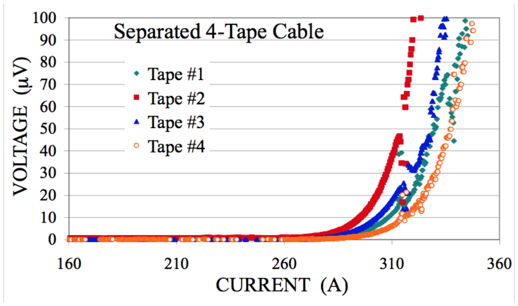


Fig. 7. Tape voltages of 4-tape cable separated with 4 mm spacer between tapes as a function of the total current.

The cable critical currents evaluated from these tape voltages of Tape #1, #2, #3 and #4 were 324 A, 308 A, 319 A and 331 A, respectively. These values are about 28% higher than that obtained for the tightly stacked cable, and much closer to the expected value of 331 A. The perpendicular self-field of the 4-tape cable with the 4 mm spacers calculated from (5) was about 13 mT at the outer edge of the center plane. It results in about 4% degradation from the simple interpolation method of the perpendicular field. It agrees with the experimental result of the degradation of 3% (the critical current 331 A estimated from single tape values and the averaged critical current of 321 A obtained for the separated tape cable).

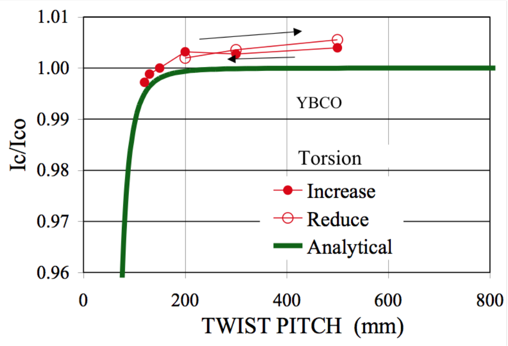


Fig. 8. Normalized critical currents of YBCO 4-tape cable obtained under various torsional twists with an analytically obtained curve.

Various torsion twists were applied to the 4-tape tightly (no spacer) stacked-cable of 340 mm in liquid nitrogen. The twist pitches were decreased to 120 mm, and then return to the untwisted condition. During one full-cycle process the critical currents of individual tapes were measured, as shown earlier. The averaged values of 4 tapes are plotted as a function of the twist pitch length in Fig. 8. The critical currents were normalized by the initial value of the untwisted cable. Fig. 8 also shows the analytical curve obtained with (2) in the same way as discussed in [4]. The 4-tape stacked cable showed very similar behavior as that of the single tape [4]. No permanent degradation by twisting was observed.

V. CONCLUSIONS

A small-scale test of a twisted stacked-tape conductor made of coated YBCO tapes was performed. The critical current degradation and current distribution among tapes composed of the cable were investigated while taking account self-field and termination resistance. Current distributions among the tapes were investigated by measuring each tape with a Hall current sensor. Four-tape stacked cable showed about 24% degradation due to the self-field.

It was determined that the operation current degradation resulted from the self-field effect and not due to strains by the twisting action. A 40-tape, 3.2 kA cable of the cross-section 4 mm x 4 mm would produce the maximum perpendicular self-field of 275 mT to the tapes. The self-field degradation is a serious concern for the compact cabling method of a twisted stacked-tape cable, especially for superconducting tapes having highly anisotropic behaviors to the magnetic field. Field anisotropy of YBCO tapes has recently been dramatically improved and such YBCO coating tapes are commercially available [9]. For high field applications of the twisted stacked-tape conductor it is desirable to make further improvements to the field anisotropy, especially at low temperatures, i.e., much below 77 K.

The critical currents of the twisted stacked-tape conductor with four tapes have been confirmed not to degrade for twist pitches as short as 120 mm in length.

Uniformity of the termination resistances is one of the important requirements especially for a short sample test of a multiple superconductor cable. Furthermore, the tape cabling needs special attentions to cable joints because of the asymmetric conductivity of YBCO tapes.

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