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Investigation of REBCO Twisted Stacked-Tape Cable Conductor Performance[1]

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Abstract. Performances of Twisted Stacked-Tape Cables (TSTC) made of YBCO tapes were discussed for self-field and high-field operations. Power transmission cables of a single stack cable and a 3-channel conductor were evaluated by self-field distributions. A new concept of a double coaxial cable was discussed to obtain a high performance, high current density power cable. High field test results of 50-tape and 40-tape TSTC conductors were summarized, and their degradations were evaluated with single-tape data measured.

1. Introduction

The second generation high temperature superconductor (HTS) REBCO tapes such as coated YBCO tapes are very attractive to various low field and high field applications. For high current applications of power transmission cables and various large magnets, a few cabling methods of REBCO tapes such as Roebel, CORC and TSTC have been developed [1]-[3]. We have been developing one of the cabling method; TSTC (Twisted Stacked-Tape Cable) [3]. The TSTC method consists of stacking flat tapes and twisting them along the stack axis. Compact cabling technique of a TSTC for REBCO coated tapes is very useful for both power transmission and magnet conductors. For a power cable, the presence of a self-field significantly affects and degrades performance especially at around 77 K [3]. In order to obtain a high performance from the conductor, it is important to improve the magnetic self-field effect.

Studies of field orientation effects for NbTi and Nb_3Sn wires were investigated [4], [5]. The critical currents of Nb_3Sn increased by a factor of two with the longitudinal field at high magnetic fields [6]. Similarly the longitudinal field enhancement of critical current performances for HTS tapes has been investigated, and Matsushita, et al. has developed an advanced power cable structure of a traditional HTS power cable to improve its performance using the longitudinal magnetic field effect [7]. We are developing a double coaxial cable of a new compact high performance HTS cable composed of two types of cables: an inner cable of TSTC and an outer wrapping-wire cable like a CORC conductor. In this paper we will first present magnetic field orientation dependences measured for a single YBCO tape, and discuss performances of a single stack and 3-channel TSTC conductors including a newly developed double coaxial cable taking into account self-field effects. We will then discuss the degradations of TSTC conductors tested at 20 T in liquid helium.

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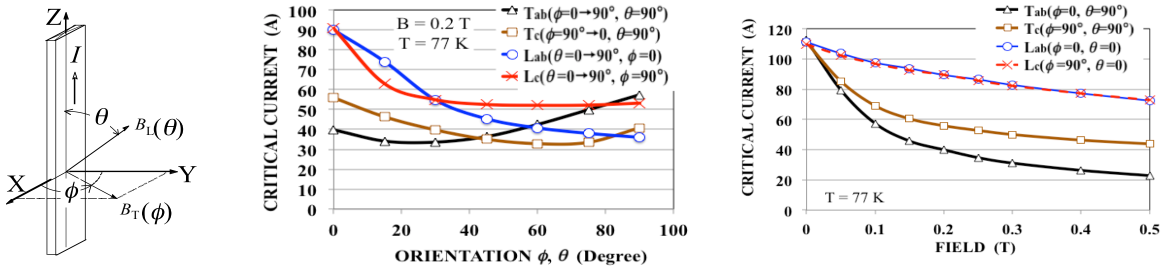
2. Low Field Performance

2.1. Field orientation effect on critical current of a single tape

Critical currents of single tapes (4 mm width, 0.1 mm thick YBCO (SuperPower SCS4050-AP) were measured at low magnetic fields at 77 K in two different configurations: transverse and longitudinal field orientations. Four samples were mounted 90° apart on a sample holder, so that all samples were tested at once in the different orientations. In the transverse orientation, the transverse field B_T was rotated from the x-axis and the y-axis for Samples T_{ab} and from the y-axis and the x-axis for Sample T_c in the xy plane shown in Figure 1(a), while in the longitudinal orientation, the longitudinal field B_L was rotated for Samples L_{ab} and L_c from the z-axis (the tape axis) to the x-axis and the y-axis, respectively. The applied fields were varied between 0 and 0.5 T.



(a) (b) (c)

Figure 1. (a) Geometric illustration of a single tape test, and Field orientation effects on critical current I_c measured: (b) I_c vs. field orientation, and (c) I_c vs. magnetic field.

Measured critical currents are shown in Figures 1(b) and (c). In Figure (b) field orientation dependences of critical currents measure at 0.2 T are shown as a function of the field orientation given by the angles ϕ and θ. The angle dependences of critical currents for Samples T_{ab} and T_c are approximately mirror symmetry of each other as expected from the geometrical symmetry of the sample orientation. Note that the critical current of Sample L_c decreased more sharply than that of L_{ab}. The similar behaviors were confirmed at the applied field of 0.1 T and 0.5 T. Figure 1(c) shows the critical currents vs. the field intensity in transverse fields parallel to the ab plane (Sample T_{ab}) and parallel to the c-axis (T_c), and in longitudinal fields (L_{ab} and L_c). Longitudinal field affects the critical current much less than transverse fields. These data are used in the following analyses. The critical current of the tested YBCO-AP tape in the c-axis field was larger than that in the in-plane field.

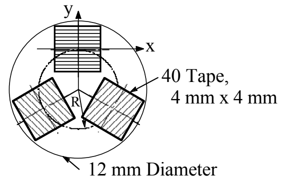


Figure 2. 3-channel conductor of three 40-tape, 4 mm x 4 mm, placed 120° apart shown in the inset (R=3.5 mm).

2.2 Self-field analysis of various TSTC conductors

Performance of a 32-tape single-stack TSTC conductor of YBCO tapes at 77 K has been characterized by the self-field effect [8]. Self-field of an untwisted stacked-tape conductor was analytically calculated for an infinitively long conductor with a uniform current density over the cross-section [3]. Using a similar method self-fields of a 3-channel conductor have been analytically calculated by superimposing vector fields of three conductors. Self-field distributions over the cross-sections of a single stack and 3-stack-in-a-round-rod (3- channel) conductor were calculated with a tape current of 44.5 A. Each stack (4 mm width, 4 mm height) was composed of 40 YBCO tapes (0.1 mm thick, 4 mm width). The 3-channel conductor was comprised of three stacks 120° apart which locate circumferentially as shown in Figure 2. The distance between the stack center and the conductor axis, R, was 3.5 mm. The self-field distributes more uniformly in a single stack conductor than in the 3-channel conductor where the field distributions of each stack affect other stacks while the in-plane field components are enhanced. The average self-field over the cross-section for the 3-channel

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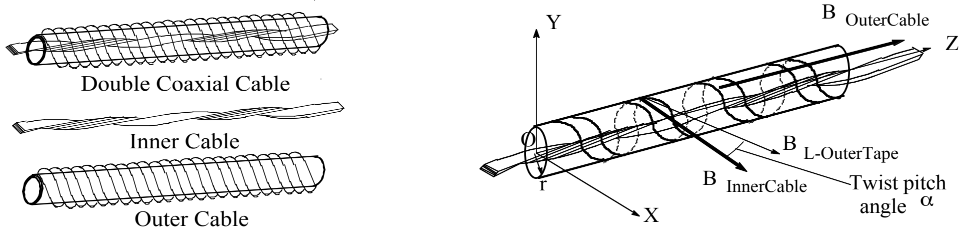
conductor is B_{ave}= 137 mT and the average orientation ϕ_{ave}=38°, while for a single stack conductor B_{ave}= 108 mT and the average orientation ϕ_{ave}=45°.

Critical currents of a TSTC conductor can be dominated by the overall minimum tape critical current $I_{\text{c-min}}$ [A]. It has less orientation dependences for a transverse field angle $\phi \approx 20°$ as seen in Figure 1(b). From the experimental data for fields between 0.1 T and 0.5 T, the overall minimum tape current $I_{\text{c-min}}$ was found to be given by $I_{c-\min} = 13.08 B^{-0.562}$ (B in unit of T) in a limited field range between 0.08 T and 0.55 T for the tested YBCO tape. From this equation and the average field B_{ave} the cable critical currents of a single stack cable and 3-channel conductors were evaluated at 77 K in Table 1. In the 3rd column the estimated overall cable diameters are also given. Measured critical current of a 40-tape single stack conductor was 1.8 kA which agreed well with the calculated value of 1.78 kA.

Table 1. Calculated critical currents of various TSTC conductor in self-field at 77 K.

Conductor	Tapes	R (mm)	Cable OD (mm)	B_{ave} (mT)	Tape $_{\text{Ic-min}}$ (A)	Cable I_c (kA)
A. Single stack	40 x 1	3.5	6.0	108	44.5	1.78
B. 3-channel	40 x 3	3.5	12	128	41.7	5.00
C. 3-channel	20 x 3	3.5	10	94	50.0	3.00
D. 3-channel	20 x 3	2.5	8.2	102	48.0	2.88



(a) (b)

Figure 3 (a) An illustration of a double coaxial cable concept, composed of an inner cable of a twisted stacked-tape cable (TSTC) and an outer cable of a helical winding wire cable on a round surface over the inner cable. (b) Magnetic filed arrangement along a double coaxial cable.

2.3 Double coaxial cable

Double coaxial cable is composed of an inner cable and an outer cable which have two different type cables mounted co-axially, as shown in Figure 3(a). For example, the inner cable is made of a twisted stacked-tape cable (TSTC) and the outer is a helical winding tape type cable like a CORC conductor on the round surface of the inner cable. The magnetic field produced by the inner cable current creates the circumferential field $B_{InnerCable}$ longitudinal to the tapes of the outer cable, and the magnetic field by the outer cable currents creates the axial field $B_{OuterCable}$ longitudinal to the tapes of the inner cable, as shown in Figure 3(b). The longitudinal magnetic fields of these inner and outer cables enhance each other performances. It is confirmed from the experimental data in Figure 1 that the longitudinal fields do not degrade the cable performance if the cable is designed properly.

For example, the minimum tape current $I_{\text{c-min}}$=41.7 A of Conductor B in Table 1 (40-tape, 3-channel TSTC conductor) creates the average transverse field B_{ave}= 128 mT. The inner cable can reach the total field of 200 mT with the longitudinal angle θ=33° if the outer cable applies a longitudinal field of 154 mT. From L_c in Figure 1(b) the longitudinal field increases the tape critical current to 55 A. If the inner cable current increases the transverse self-field also increases, therefore a precise analysis requires iteration. By iteration the inner cable current was obtained to be 6.2 kA with the inner tape current of 52 A under the total field of 200 mT with the longitudinal angle θ=52° if the outer cable applies a longitudinal field of 121 mT, which is produced by an outer cable carrying 4 kA, (10-helically wound cable, each subcable carrying 400 A). The inner cable current can be increased to more than 6 kA (from to 5.0 kA) through the longitudinal field of the outer cable. The inner cable can be enhanced by 20%. This double coaxial cable will carry total 10 kA at 77 K, composing the inner cable current of 6 kA and the cable outer current of 4 kA. The diameter of this double coaxial cable will be less than 15 mm. If the outer cable is made of a 6 kA cable of 5-helically windings (each

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subcable of 1.2 kA), this outer cable generates the longitudinal field of 370 mT, which will allows the inner cable current 6 kA by the longitudinal field of 400 mT with the longitudinal angle θ=23°. This double coaxial cable would carry a total of 12 kA or ±6 kA in a cable diameter of 18 mm at 77 K.

3. High Field Performance

For testing a TSTC cable in a high field magnet, we have been developing a new magnet winding method called the Stacked-Tape Twist-Wind (STTW) technique, suitable for the fabrication of complicated 3D windings of 2G HTS tape cables [9]. Two samples of YBCO tapes were fabricated and tested at 4.2 K using a 20 T, 195 mm warm bore Bitter magnet at NHMFL, Florida State University [9]. Both tested cables were 2.3 m length composed of 50-stacked tapes (SuperPower, 0.1 mm thick and 4 mm width). They were wound on a 165 mm diameter pentagonal cylinder by the STTW method. The test result of the first sample showed that the critical current at the criterion of 100 μV/m was 4.0 kA [9]. The cable quenched at 4.7 kA. It was degraded. The cable itself was soldered between the stacked tapes but it was not well supported in the round groove. The sample could be degraded by the Lorentz force. The second sample was not soldered but the conductor was supported with Stycast epoxy in the groove. The critical current of the second sample was measured at various fields from 4 T to 20 T. The sample carried 10 kA at 4 T without developing any voltage at the start of the test. However the sample gradually degraded showing noticeable resistive component as the tests progressed. After the whole test, it was noticed that a high current spike (few times of the critical current) was produced at the end of each shot when the sample current was dumped. This over-current could be degrading the sample performance.

A 40-tape TSTC conductor soldered in a copper tube of 9.5 mm OD was tested at the KIT FBI facility [10]. A cycle test was performed between 6 T and 12 T. The test results showed degradations between the first measurements and the second measurements of about 11% at 6 T and 4% at 12 T. After the first test no further degradation was confirmed [10].

From these three sample tests it was found that in high magnetic field that TSTC cables showed about 50% degradation compared with the strand data obtained in perpendicular field (parallel to the c-axis). Transverse load tests of YBCO single tapes and TSTC conductors have not shown such large critical-current degradations observed in the cable samples [11]. In order to understand the high field degradations further electrical and mechanical work is required.

4. Conclusions

Performances of TSTC conductors for power cable applications have been evaluated based on self-field and field orientation data measured at low fields up to 0.5 T. It will be possible to obtain a 3-channel YBCO TSTC conductor of 5 kA at 77 K. A double coaxial cable composed of a TSTC inner cable and a wrapped wire type outer-cable can provides conductors of 12 kA or ±6 kA. Longitudinal field of a double coaxial cable can enhance inner cable performance by more than 20%. A double coaxial cable can provide a high current compact power cable with a low heat loss. High-field performance of TSTC conductors tested at up to 20 T have revealed significant degradations. Its origin has not yet been understood. Further electrical and mechanical investigations will be required for a twisted stacked coated-tape conductor.

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