Critical Current Properties of HTS Twisted Stacked-Tape Cable in Subcooled- and Pressurized-Liquid Nitrogen

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Abstract. A 2 m length Twisted Stacked-Tape Cable (TSTC) conductor which was fabricated by 32-YBCO-tapes (4 mm width) with a 200 mm twist pitch was investigated at various temperatures near 77 K in subcooled- and pressurized-liquid nitrogen. The critical current of the TSTC cable which was 1.45 kA at 77 K measured from 64 K to 85 K by controlling the equilibrium vapor pressure of nitrogen bath and were varied from 3.65 kA at 64 K to 0.42 kA at 85 K. The temperature dependence of cables’ critical current agrees with that of the 4 mm width YBCO tape. These results are encouraging for applications of a compact Twisted Stacked-Tape Cable application in railway systems.

1. Introduction
Railway Technical Research Institute (RTRI) in Japan has developed superconducting cable applications for railway systems. The aim of this development has been to investigate a new system to feed electric power to electric trains by using high temperature superconducting (HTS) cables to replace copper cables. Introduction of superconducting cables in railways could significantly reduce the voltage drop in feeder. Therefore, DC HTS electrification has various advantages, such as the reduction of transmission loss, the increase of regeneration efficiency, and fewer substations. More specifically, the HTS feeder cable could result in significant energy savings, while improving the power handling capacities of feeder cables and railway substations [1].

At present, we are developing a power testing system using a conventional superconducting power transmission type cable with helically wound HTS tapes on a cylindrical former, operated at 77 K in liquid nitrogen [1]. However the current density and cooling of the power cable are not sufficient especially for the catenary lines above ground as a feeder. From a practical application perspective in railway systems, we have investigated a compact superconducting cable system based on a TSTC conductor of REBCO HTS tapes [2].

2. Experimental details
The TSTC cable is typically made from twisting freestanding flat tapes torsionally along the axis of stack. A 2 m long, 32-YBCO-tape (4 mm width) TSTC cable with a 200 mm twist pitch was tested at
various temperatures from 64 K to 85 K in subcooled- and pressurized-liquid nitrogen using a variable temperature power cable test system.

2.1. TSTC conductor
To investigate of a TSTC conductor performance for electric railway applications, an existing 32-tape YBCO cable of about 2 m length was used. The cable is composed of 32-YBCO tapes made by SuperPower Inc. The YBCO HTS tapes were 4 mm width and 0.1 mm thick (SCS4050-AP, 2010), and the average critical current was 85 A at 77 K in self-field. The tapes were stacked between copper strips 0.82 mm thick and 4.8 mm width, and twisted together with a twist pitch 200 mm. This TSTC conductor shown in Figure 1 was originally fabricated and used for a bending [2], [3].

2.2. Cable Termination
The YBCO layer of a HTS tape is deposited on a base substrate, therefore it has an asymmetric conductivity and the electrical conductivity of the YBCO layer side (conductive side) with the silver layer is better than that of substrate side. Given this asymmetry in electrical conductivity, to fabricate a termination of YBCO tapes, the conductive side must be properly soldered or connected to an electric conductor of copper. The YBCO-BSCCO termination method developed earlier was used [2]. To assemble the YBCO-BSCCO terminator, 32 YBCO tapes were sandwiched between the BSCCO tapes after cleaning all contact surfaces, and then they were clamped with 6.4 mm thick, 70 mm length stainless steel plate without soldering. The contact pressure of about 110 MPa between YBCO and BSCCO tapes was applied by fourteen 6–32 screws with a known torque measured with a torquemeter. The copper tube of the terminator was clamped into a copper block to be connected to a current lead of the cryostat. The total length of the cable which was encapsulated with a glass sleeve for electrical insulation was 2335 mm including the terminations (about 222 mm each end) which could fit in the test cryostat.

2.3. Test cryostat system
Figure 2 shows a cryostat used for a TSTC conductor test [4]. A 2 m cable can be mounted in the horizontal corrugated pipe between the current lead towers. Test sample current-terminations were connected to copper terminators with mechanical clamping at the bottom of the current leads. Side flange on each current lead tower can be opened to mount a sample and to make connections of current leads. The temperature of operation during the test whose values were determined using platinum resistance temperature sensors mounted at the center of the conductor as shown in Figure 1 and installed near the bottom of each current lead was controlled with nitrogen vapour pressure (0.0146-0.2290 MPa) by adjusting the inner cryostat pressure using a vacuum pump or nitrogen gas cylinder with pressure controlled valves shown in Figure 2. The TSTC conductor was inserted horizontally into the cryostat from the side flange windows. An overall view of the cryostat is shown in Figure 2.
Figure 1. 32-tape YBCO TSTC conductor encapsulated with a glass sleeve for insulation before mounting in the cryostat with instrumentation wires: four voltage tap wires on Tapes #4, #16, #17 and #29, and two termination resistance measurements at each termination, and two platinum resistance temperature sensors on the conductor.

Figure 2. Test cryostat.
3. Results and discussion

3.1. Test Results of 32-Tape TSTC conductor

DC current of the maximum capacity of 7200 A was supplied. For the critical current measurement, four pairs of voltage tapes mounted on four tapes selected in the 32-tape stack (#4, #16, #17 and #29), as shown in Figure 1. To measure the termination resistance, two pairs of voltage taps were provided at each termination: one to measure the YBCO-BSCCO joint resistance between YBCO cable and BSCCO tapes ($V_{jYBCO-BSCCO}$), and other to measure the contact resistance between the copper tube of YBCO-BSCCO terminator and the copper terminator ($V_{jCu-BSCCO}$). The termination resistances were measured: $R_{jYBCO-BSCCO}$ (Positive side) 13 nΩ, $R_{jYBCO-BSCCO}$ (Negative side) 10-18 nΩ, $R_{jCu-BSCCO}$ (Positive side) 5.0 μΩ, and $R_{jCu-BSCCO}$ (Negative side) 1.2 μΩ. These joint resistances between YBCO cable and BSCCO tapes for both sides were as low as expected, however the contact resistance between the copper tube of YBCO-BSCCO terminator and the copper terminator were very high. The high resistances were resulted from the diameter mismatch between the copper tube diameter and the copper terminator. These resistances can be reduced by one order of magnitude using properly fitted adapters.

A 32-tape TSTC conductor was evaluated under various temperatures between 64 K and 85 K. During the test, the temperature was decreased first from 77 K to 64 K, and then next day it was raised from 77 K to 85 K by 1 K step. During the experiment the $V-I$ curves were plotted and critical currents and $n$-values were analyzed. All the $V-I$ curves, critical currents and $n$-values measured between 85 K and 64 K are plotted in figures 3 and 4. The critical current was 1421 A at 77 K in self-field, and varied between 421 A at 85 K and 3620 A at 64 K, ($I_c$ at 85 K is roughly 8.6 times the $I_c$ at 85 K).

We have evaluated the performance of a HTS tape power conductor taking into account of the self field effect on the degradation. It was based on the analytical averaged self-field of a TSTC conductor and the “minimum” critical currents of a single tape as a function of the angle between the tape and the magnet field applied at low magnetic fields [5]. To evaluate the critical current temperature dependence of a 32-tape TSTC conductor, we need the field orientation dependence of the critical current at low fields and at various temperatures. Figure 5 shows estimated the “minimum” critical current of a single tape at various temperatures. Minimum critical current has been defined in reference [8] as the minimum critical current obtained from a field angle dependence between 0 degrees ($B_{//a-axis}$) and 90 degrees ($B_{//c-axis}$). In figure 5 the $I-B$ curve at 77 K was measured [2], while the other curves were calculated from the field dependence at various temperature [6].

A load line given with 47.8 A at 100.2 mT in figure 5 was obtained by a self-field analysis of 32-tape TSTC conductor [2]. From the intersection points of this load line and the critical current curves the operation critical current can be obtained for a single tape. The cable critical current for the 32-tape cable in self-field can be calculated by multiplying by 32. Calculated cable critical currents of a 32-tape TSTC conductor are plotted with the measured results in figure 6. The calculated critical currents agree quite well with the experimental results. The maximum differences between them were about 15%. It is desired to measure critical current temperature dependences of the same tape as that of the cable under various fields up to 0.3 T in order to evaluate cable performance more accurately.
Figure 3. V-I curves measured for four voltage taps at 85 K to 64 K.

Figure 4. Test results of the critical currents and n-values for four voltage taps of Tapes #4, #16, #17 and #29 at 64 K to 85 K. The upper figure shows the critical current with both criteria of 100 \( \mu \text{V/m} \) (solid symbols) and 1000 \( \mu \text{V/m} \) (open symbols).
Figure 5. Estimated the minimum critical-current vs. field of a single tape at various temperatures with a load line of self-field for a 32-tape TSTC conductor. The intersection between the load line and the critical current curve gives the critical current of one tape in a cable.

Figure 6. Calculated temperature dependence of the critical current for 32-tape TSTC conductor with the measured results.
4. Conclusions
A 32 tape YBCO TSTC cable has been successfully tested at various temperatures near 77 K. By decreasing operation equilibrium vapor pressure of liquid nitrogen the cable critical current was improved significantly (1.4 kA at 77 K and 3.6 kA at 64 K). The cable capacity can be increased roughly 2.6 times by decreasing the nitrogen vapor pressure.

The test results of critical currents in the TSTC cable were evaluated with our power cable design method developed for a TSTC conductor. The comparison between the measured and calculated results agrees in an error of less than 15% in the temperature range between 66 K and 84K, although the YBCO tape used for temperature test was not exactly same type.

In an electric railway application the power load fluctuates during the day, therefore it is really beneficial that the power cable capacity can be increased when the load increases by subcooling system. Compactness of a TSTC cable will be very beneficial in this application.

Optimization of a TSTC conductor design and termination methods should be investigated. We have developed various types of TSTC cables other than one used for this test [2]. Other options, such as (1) Stack first, then twist, then clad. (2) Stack and then embed in helical open grooves on a structured conduit, could be considered for future investigations.

By using helium or hydrogen gas with cryo-cooling system without liquid nitrogen it will be possible to operate at lower temperature such as 50 K to 20 K. In this way the cable capacity can be dramatically increased. Such gas-cooling power-cable system operated below 77 K should be evaluated for specific railway applications. To take subway into account, for example, nitrogen cooling is not preferable since nitrogen gas is heavier than air and could cause suffocation in case of a leak. In the subway application helium gas system should be considered. We will continue to develop and promote superconducting cables, all with the aim of realizing a cable applicable for railway use.

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