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A dc transmission cable prototype using high-temperature superconductors

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Abstract. This paper gives the results from a recent collaboration between BICC Cables Ltd, its Italian subsidiary Ceat Cavi srl, and Ansaldo Ricerche srl on the design and testing of a high-temperature superconducting dc transmission cable prototype. The cable was designed to carry 10 000 A at 40 kV, operating at 40 K. Qualification testing was carried out from 4.2 K up to 40 K. At an operating temperature of 31 K the prototype cable had a current capacity of 11 067 A (the largest dc current reported in a high-temperature prototype to date), which represents a tenfold increase in current over a conventional 1000 mm^2 copper cable.

1. Introduction

The technical feasibility of producing transmission cables operating at 4 K using niobium alloys has been long demonstrated [1, 2, 3]. These prototypes proved uneconomical compared with conventional cable solutions due to the high costs associated with liquid helium refrigeration, but technical development in cables operating at 4 K is still ongoing, especially in Japan [4]. Several niobium alloy cable models have been constructed as experimental test models for high-power links [5]. The progress in this area has acted as a basis for a new project of manufacturing a similar cable using high-temperature superconductors (HTSCs), which are expected to have a large impact in the electrical engineering industry [6], and an early application in high-power underground cables is forecasted [7, 8].

Both ac and dc underground superconducting cables operating at transmission ratings of $\geq$132 kV and 350 MV A are possible. The majority of cables in the transmission network are ac cables and research in HTSC cables has reflected this fact. There are a number of HTSC ac cable demonstrator programmes in Japan [9, 10], the USA [11] and in the EC [12]. All these programmes are aiming at roughly the same technical requirements in, for example, a short ac underground link (<500 m) with a conductor critical current density (J_c) of 1×10^9 A m^{-2}, ac losses below 1 W m^{-1} and operating at or just below 77 K. The leading candidate material for the above is the ceramic $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_{10}$, thermomechanically processed in a silver tube via the powder-in-tube technique [13]. The intense effort in developing this material for ac cable applications has led to state-of-the-art tapes over 500 m long with J_c-values in self-fields of 1×10^8 A m^{-2} at 77 K [14], with J_c increasing rapidly below 60 K. The economic justification for developing such cables comes from the severe congestion in the existing underground power ducts in the Tokyo area [15], and the savings proposed from the retro-fitting of pipe-type cables in the US [16]. The situation for Europe is less clear, with neither the population density problem of Japan or the pipe-type cables common in the US. For Europe, the factors likely to be important in the future use of HTSC cables are cost savings from improved technology, environmental benefits and the effects on the national transmission grids of privatization and the integration of the EC member states.

In Europe, cables acting as ring mains around large cities or as high-power links for importing/exporting of electricity between EC member states mean that a first use of HTSCs may be as high-power dc cables. Heightened awareness of the importance of dc cables is shown from a number of international links under study in the latest EC Trans-European Energy Networks programme which, for example, is considering links of France with Italy and Belgium; Finland with Sweden; Italy with Switzerland and Austria; Germany with Norway and the UK with Norway and Ireland.

A dc cable has almost no dielectric loss and for equal power ratings can be installed at a much lower cost than an ac one [17]. However, the terminal equipment required for the ac/dc conversion has very high costs. Therefore, a dc transmission system is only economic over long distances,

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for which the cost of the terminal equipment is recouped via the savings in installation and transmission cost. A further operational advantage of using dc cables is that when back-to-back power systems are connected, they can be kept independent, preventing instabilities from arising in the two systems. A superconducting dc cable can provide lower transmission costs compared to a conventional cable solution, carrying more power at lower voltages, greatly simplifying ac–dc conversion. Other advantages include environmental benefits such as a potential reduction in the cable trench size.

2. Design and construction of the cable

The cable design is based on a proposed force-cryocooled, 100 km long, 10 000 A, 40 kV transmission line. The cooling would be maintained by two cryo-cooler plants, a pumping system at one end of the cable and a refrigerator at the other end. To maintain the cable temperature at 40 K it is calculated that the cooling system will need to initially pump flowing helium at 0.2 kg s^{-1} pressurized to 2 MPa at 15 K, with a resultant temperature rise along the cable to 65 K at the collection end [18]. The total cooling losses are calculated to be close to 150 kW. Evaporation towers would be needed at each cooling plant to release heat generated by the compressors and turbines.

3. Cable design

The cable design has a concentric structure shown in figure 1 with overall dimensions of 1.4 m length and 1275.3 mm^2 cross sectional area. An inner 67 mm flexible metallic former, calculated in the final design to contain pressurized helium gas flowing at a rate appropriate to cool a 100 km cable, is surrounded by bundles of HTSC tapes contained in specially designed copper segmental carriers acting as both a mechanical support and as a potential current shunt for fault conditions.

Thirty two of these segmental carriers are arranged on the metallic former to form the first conductor layer, which is contained within a conventional dielectric arrangement of a carbon black semiconducting screen and a 4 mm layer of oil-impregnated paper serving as the dielectric followed by a few more semiconducting screen layers. The total cross sectional area of the first layer is 583 mm^2. A second (return) conductor layer comprising 38 copper segmental carriers is wound on top of the first conductor with further semiconductor screening and dielectric layers. The total area of the second conducting layer is 692.3 mm^2. Electrical and thermal calculations mean that both HTSC layers in this design are adjacent to one another separated by a dielectric layer. In the complete cable design the conductor assembly would be enclosed within a protective sheath, an outer helium duct and super-insulation. These outer layers were omitted at this stage as only the technical feasibility of the cable was considered.

The prototype was constructed on industry-standard cable-production machines normally used in making conventional copper cables. The conductor assembly was laid using an armouring machine and the insulation using a paper-lapping machine. To provide joints, the paper insulation at both ends of the cable was stripped away and the HTSC bundles were soldered to the copper carriers using low-melting-point In:Ag alloy solder. High-current terminal joints were then clamped onto the superconducting layers. At one end of the prototype a short circuit was made between the two layers and at the other end separate current terminals were attached to each layer. In this configuration the inner layer carried the load current and the outer layer acted as the return conductor. The cable was connected in series to a secondary coil of a superconducting transformer and placed inside a closed-cycle helium cryostat. The temperature at each end of the cable was monitored and controlled so that each current joint was kept at the same required value during testing. In addition the self-field generated outside the cable was measured.

4. Qualification testing

The cable was tested in two parts, as individual HTSC tape and tape bundles and as the full conductor. Understanding the former configurations gave information on the cable design and acted as a benchmark to judge the relative performance of the cable under the test conditions.

4.1. Properties of the HTSC tape

The superconductor used was 0.25 ± 0.05 mm thick by 3.0 ± 0.5 mm wide and contained between 7 and 37 superconducting multifilaments. The feed-stock was a mixture of HTSC tapes manufactured at BICC Cables in the UK and from a commercial source†, both produced via the powder-in-tube route.

Values of the transport critical current (I_c) of the tapes ranged from 5 to 15 A along their length at 77 K in a self-field using a 100 μV m^{-1} criterion which corresponded to engineering critical current densities of the order of 2×10^7 A m^{-2}. Measurement of the I_c of short test samples in a self-field with decreasing temperature showed a fourfold increase in the I_c-value in changing the temperature from 77 K down to 32 K. The magnetic field dependence of the I_c-values showed that at 40 K an applied field of 0.1 T decreased the observed I_c-value by almost 30% of the value observed at 77 K. Similar values have been reported elsewhere [19].

In the cable, the HTSC tapes are stacked into bundles and so measurements were made beforehand to assess possible damage in winding such tape bundles. Figure 2 shows the relative I_c-drop with bend radius for a typical 7- and 37-filament tape. Metre-length bundles of tapes were constructed by stacking HTSC tapes on top of each other. After measuring the total critical current, the bundle was wound around a 55 mm diameter former with a pitch of 600 mm (equivalent to 0.1% induced strain). This value of applied strain is typical in a cabling operation and would be exerted on the tapes in the winding of the prototype. The remeasured I_c-value was found to decrease by 5% of the original unstressed value. Figure 3 shows the V–I traces for the bundle before and after winding.

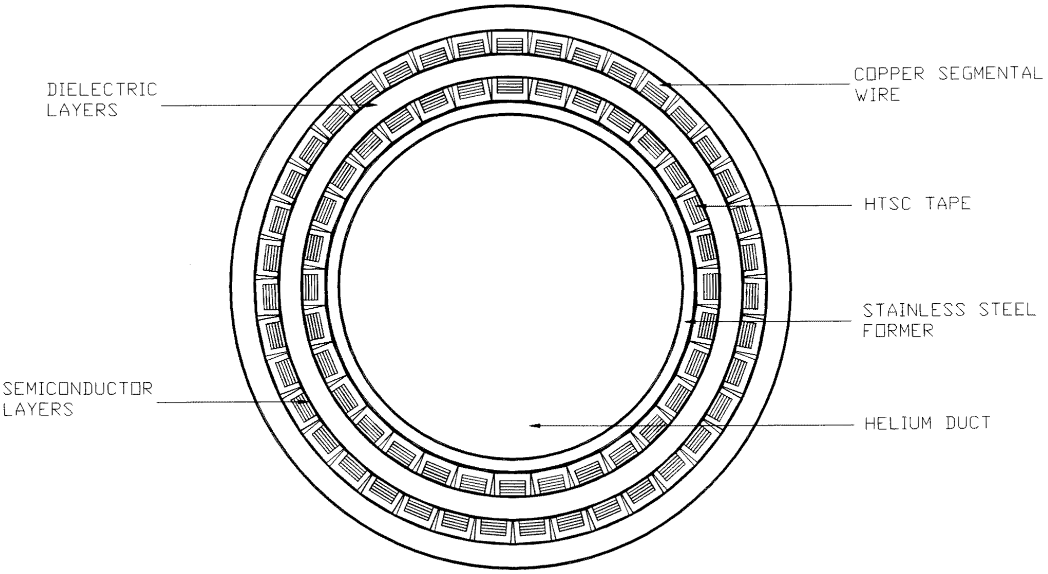

Figure 1. A cross-sectional view of the dc cable prototype.

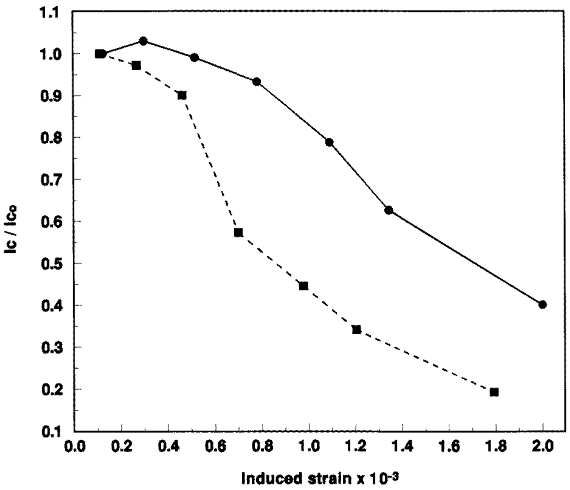

Figure 2. A graph of I_c/I_{c_0} versus induced strain for typical 7-filament (■) and 37-filament (●) tapes used in the cable.

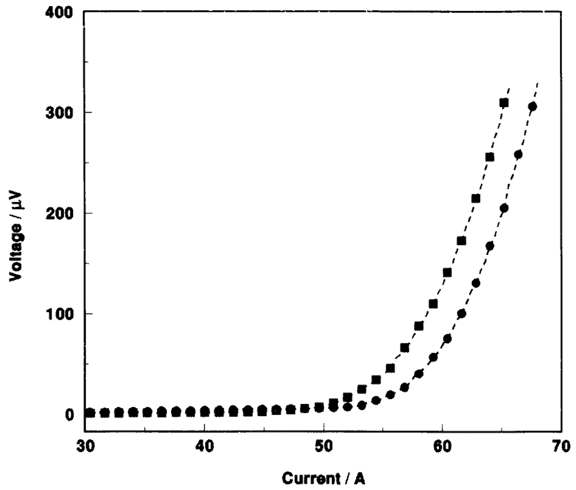

Figure 3. The V–I characteristic of a bundle of ten 1 m (Bi_{2-x}, Pb_x)$Sr_2Ca_2Cu_3O_{10-\delta}$ tapes as measured flat (●) and wound at a pitch of 600 mm on a 55 mm diameter former (■).

These tests confirmed that a conventional cabling operation would not seriously hamper the performance of the HTSC cable and the maximum self-fields expected, of 0.2 T, would also pose no performance problems at the anticipated power rating.

4.2. Properties of the cable

Once constructed, the cable model was tested inside a closed-cycle helium cryostat. Temperature control was maintained by the boil-off of a pool of liquid helium located at the bottom of the cryostat.

A current pulse of 30–35 A was supplied to the primary coil of the transformer by the discharge of a capacitance bank and the corresponding induced current in the cable measured. The current through the secondary coil was limited by the resistance in the circuit. With this system, the peak current measured in the cable was that which corresponded to a generated resistance of 48 nΩ. The measured peak cable current is equivalent to the critical current of the inner superconducting layer using an estimated criterion of 50 μV m^{-1} at 40 K and 200 μV m^{-1} at 4.2 K. Figure 4 shows the current in the primary coil and figure 5 the current in the cable against time at 31 K. The peak or critical current of the prototype is 11 067 A. The cable was also tested at 4.2 K, 35.3 K and 40 K. The results are given in table 1 along with the measured self-field. At 4.2 K, the peak current of 13 500 A was limited by a quench

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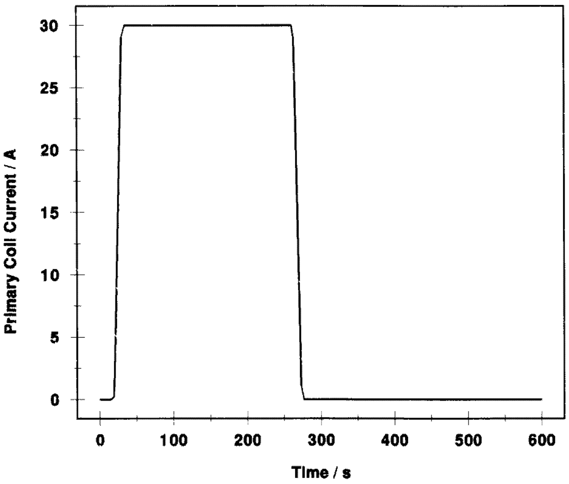

Figure 4. The transport current against time in the primary coil of the superconducting test transformer.

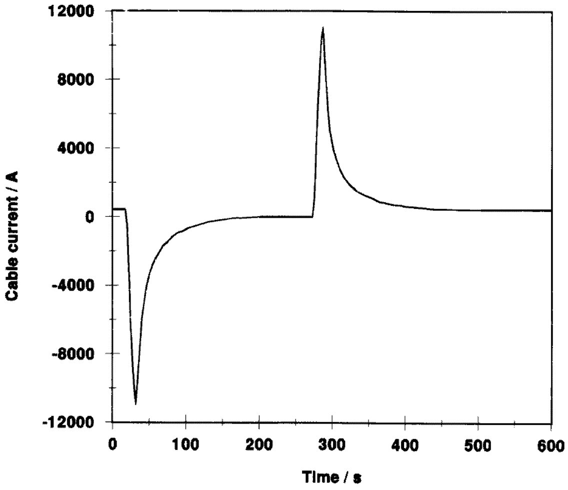

Figure 5. The transport current against time in the cable prototype.

Table 1. The results of the dc prototype qualification testing with the measured self-field at the cable surface.

Temperature (K)	Cable I_c (A)	Self-field (mT)
4.2	13 543	69
31	11 067	56
35.3	9043	46
40	4355	22

in the cable. Above 30 K the critical current was observed to fall. Such behaviour is repeatably seen in HTSC tapes in applied fields [20] and has been attributed to a phase change in the flux line lattice.

The measured I_c of the cable at 31 K is 85–90% of the calculated maximum I_c of the inner cable layer, as a multiple of the tapes and the average I_c for a single tape. This percentage is very promising and higher than that obtained previously in tests on smaller dc cable conductors [21]. From the values in table 1 and the observed field dependence of I_c, we attribute this percentage reduction to self-field effects. Other possible factors to be considered are damage to the tapes during cable construction and cooling, and local Joule heating between either end of the cable and the inhomogeneous current distribution due to the spread in contact resistances at the current joints and in the critical currents of the tapes.

5. Conclusions

A 400 MW high-temperature superconducting dc transmission cable has been designed and constructed using conventional cable-production machinery. The current capacity of the cable at 31 K was shown to be 11 067 A, representing a tenfold increase over a conventional 1000 mm^2 copper cable and the highest demonstrated value for a high-temperature superconducting prototype. This result is a promising first step towards the transmission of dc energy using force-cryocooled superconducting cables and a clear indication of the potential use of $(\mathrm{Bi}_{2-x}, \mathrm{Pb}_x)\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_{10-\delta}/\mathrm{Ag}$ tape in superconducting energy systems.

This is seen as a first stage in utilizing silver-sheathed ceramic superconductor tapes in the transmission of energy using force-cryocooled superconducting cables as a method of reducing the cost of electric power transmission. The next stage will be a large-scale working demonstrator with joints and terminations and associated cryogenic systems for a cable cooled with pressurized helium gas, operating at 40 K. The industrial application envisaged will be high-power (2 GV A and above), long-length dc underground or submarine energy-transmission cables.

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