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A 10 m Nb_3Sn CABLE FOR 60 Hz POWER TRANSMISSION*

M. Garber†

ABSTRACT

A 10 m Nb_3Sn cable for 60 Hz power transmission has been constructed. The coaxial cable is of flexible, multiple helix, tape wound form. It has been designed and instrumented for short circuit current tests. The inner and outer conductor diameters are approximately 24 and 30 mm respectively. The cable is installed in a horizontal cryostat with its ends fixed to room temperature supports. Measurements have been made of ac losses, fault currents, current sharing, and recovery from local quenches.

INTRODUCTION

In a recent review[1] plans have been described for the completion of a 100 m outdoor test facility and for tests on 138 kV, 4 kA single and three phase cables. The ratings correspond, on a three phase basis, to a circuit capacity of 1000 MVA. In order to determine the final design of this cable, a number of shorter 10 m cables of similar rating are being made and tested. The first major test of one of these is described in this paper. It is concerned with the current carrying components of the cable.

The design of this type of cable has been discussed in several publications.[2,3,4] The conductor configuration is illustrated in Fig. 1. Flexibility and the ability to take up longitudinal contraction are provided by helical tape construction, but double layers of opposite helicity are required in order to minimize the effects of axial magnetic flux. Layers of high purity aluminum back up the Nb_3Sn in order to share current during transient overloads or quenches. Starting with the commercially fabricated flexible bronze core‡, the conductors and dielectric were wound using a modified cable winding machine. The resulting 10.6 m long cable is installed in a horizontal dewar with its ends fixed to room temperature supports. The flow of supercritical helium refrigerant is through the core. The cable is short circuited at one end as it is intended for current tests only.

The test period lasted two months. During the first few weeks minor refrigerator problems necessitated cycling to room temperature three times. This produced no adverse effects. During the final run the cable was cooled continuously for a period of two weeks.

EXPERIMENTAL DESCRIPTION

Materials. The superconducting tape was obtained from IGC.[5] The Nb_3Sn tape is clad with 25 μm thick stainless steel on one surface and 50 μm thick copper on the other. The stainless steel is a variety of type 302 verified to have low magnetic loss at helium temperatures. The copper has a residual resistance ratio, rrr, of 150. The cladding bond is a tin alloy solder which is non-superconducting above 5K. The cable is wound with the stainless steel surfaces of the tapes facing the high field side. The tapes are 6 mm wide. As they were slit from a wider starting tape, the edges are stripped of Nb_3Sn. This leads to a type of ac loss which is discussed below.

The aluminum tapes are 200 μm thick and 6 mm wide. The measured rrr (prior to winding) was 2500, so the tapes are approximately one skin depth thick. The tapes are coated with a thin flash of copper to facilitate end connections.

Polypropylene tape, 90 μm thick by 22 mm wide is used for the insulation. The expansion coefficient is such that the radial contraction of the wrapped insulation matches that of the metal layers.

The bronze core is of double helix form in order to be mechanically stable. It is constructed of 1 mm thick by 11 mm wide tapes.

The cable is held together radially by nylon lacing rather than by the compression layer shown in Fig. 1.

Dimensions. The principal dimensions are summarized in the following table.

TABLE I

10.6 m Cable Parameters

Conductors: Double Helix Nb_3Sn & Al

	Diameter	Lay Angle	No. of 6 mm Tapes in Each Helix
Inner	24.5 mm	43°	9
Outer	30.4 mm	44°	11

X_L (60 Hz): 1.6×10^{-5} Ω/m ($L = 4.3 \times 10^{-8}$ H/m)

Insulation: 3 mm, Polypropylene

Core: Bronze, Double Helix

The lay angles of the superconductor and aluminum layers were chosen as close to ± 45° as feasible as this angle leads to nearly complete cancellation of axial flux and, therefore, to small electromagnetic interaction with dewar walls or other external structures. The butt spaces between tapes are 0.2 mm wide. This

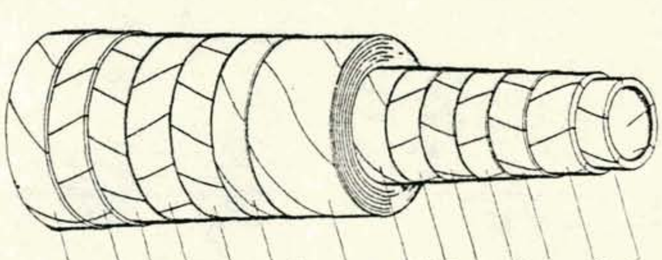

Fig. 1. Schematic of cable construction. c, flexible bronze core; a, aluminum stabilizer layers; s, superconductor layers; d, plastic tape insulation; d', dielectric screen - not included in current test cable; k, compression layer - replaced by nylon lacing in this work.

‡Note: in contrast with European terminology we use the term "core" for the inner support structure and "cable" for the coaxial cable exclusive of its dewar enclosure.

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†Brookhaven National Laboratory, Upton, N.Y. 11973

DISCLAIMER

would permit a 50 mm dia cable to be reeled on a 2 m drum without edgewise overlap of tapes.

Connections. A detailed description of the manner in which terminations were made is not possible here. Briefly, at the input end, 10 mm wide superconducting tapes are indium soldered to each superconducting layer of the cable. These links, lying parallel to the cable axis, are soldered to the leads of a low temperature transformer. Copper strips are used to link the aluminum layers to the input transformer. At the short circuit end similar links are used for the superconducting layers. These are connected to a thin copper ring. The aluminum layers are extended and joined beyond the superconducting ones. The space between these separate joints was made in order to locate there a current monitor for the inner aluminum layers.

Instrumentation. Ac losses are measured by an electronic wattmeter technique. The total cable loss is determined by means of a voltage probe across the input. From this is subtracted the loss read by a probe across the short circuit joint. This correction is about 16% at 4000 A. In order to monitor the superconductive material loss, as opposed to the cable loss, voltage pick-ups running along the surface of individual tapes of the inner conductor are installed. Total cable current and inner aluminum layer current are measured by means of Rogowski coils. The voltage waveforms which are illustrated below are compensated, i.e., the inductive component has been subtracted. The derivative signal from the Rogowski coil is used to do this. Care was taken to ensure that the phase of this signal is correct to better than 10^{-4} rad.

In order to study the response of the cable to thermal quenches a surface heater is wrapped over the inner conductor surface, under the dielectric wrap. It is made of aluminized mylar, low temperature resistivity 0.3 ohm/square (rrr = 3.). The heater length is 285 mm. It is located approximately 3 m from the shorted end. Usually, 70 W pulses were used to produce the local quenches.

Current to the cable is supplied through a transformer located in the cold box at one end of the dewar. This transformer has an iron core and Nb_3Sn tape windings. The step down ratio is 82:1. Cw excitation was available to 7000 A. Higher currents are obtained by resonant discharge of a 2000 μF capacitor bank. Q is about 50 up to 15 kA and falls thereafter due to transformer losses.

Temperatures are measured by means of calibrated carbon thermometers located every 2 m both in the core and outside the cable.

Refrigeration. The supercritical helium pressure was generally 12 atm. While the inside and outside of the cable are in pressure equilibrium, the flow of refrigerant is forced to take place through the core, entering at the short circuited end and leaving at the current input (transformer) end.

The available refrigeration was about 0.4 gm/sec corresponding to a flow velocity of about 1 cm/sec at 7.5K. This was much lower than expected and provided an unplanned worst-case test, in effect.

RESULTS

Ac losses. In Fig. 2 the sum of the inner and outer conductor losses per meter is shown as a function of temperature for I = 3850 A (500 A/cm) rms, f = 60 Hz. The peak near 9K has been discussed previously[3,6]. It is due to components of the current which circulate around the individual tapes and pass through the niobium substrate. As present plans call for line operation at approximately 6 to 8K, the effect of this peak will be small. The loss at 7K is approximately 0.2 W/m. This is about three times greater than expected from previous short cable experiments and is a matter of some concern. The observed current dependence up to 6000 A is $I^{2.2}$. Eddy current losses in normal metal parts of the cable and dewar appear to be ruled out by the frequency dependence, $f^{0.7}$, up to 110 Hz. In addition, the axial flux, measured by a coil wound around the cable, is too small to produce appreciable loss in surrounding pipes. Current flow in the aluminum layers is too small to account for the loss. The spiral surface probes show that losses in the Nb_3Sn tapes are about the same as for the as-received material. Thus, the tapes were not degraded by the cabling process - at least not those monitored (5 m length of tape). The observed loss voltage waveform has a large sinusoidal component which together with the preceding facts indicates an ohmic loss mechanism. G. Morgan has suggested that current flow between the superconducting helices, passing through a layer of stainless steel may be the source of the observed dissipation. Preliminary computer modeling supports this possibility and indicates that replacing the stainless by copper would greatly reduce the loss. Previous 1 m model test results[4] using copper clad tapes are consistent with this conclusion. Some stainless, however, is needed for strength.

Fault currents. At high currents the superconductive hysteretic loss waveform becomes much larger than that due to the previously discussed effect. The onset of the resistive transition can then be readily defected by deviations in the voltage waveforms. Figure 3 is an example of this behavior. Inspection of

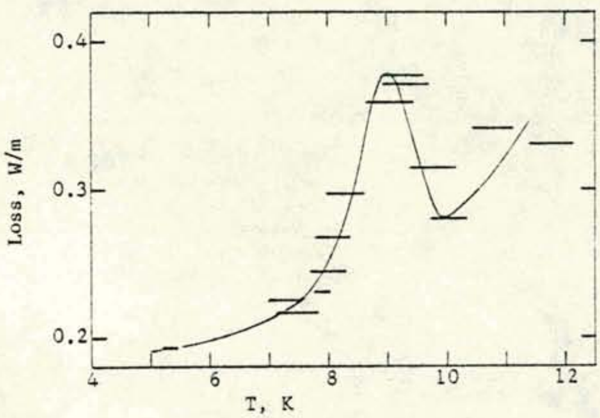

Fig. 2. Ac loss, inner and outer conductors. I = 3850 A (500 A/cm) rms, f = 60 Hz. Horizontal bars represent temperature extremes along the cable.

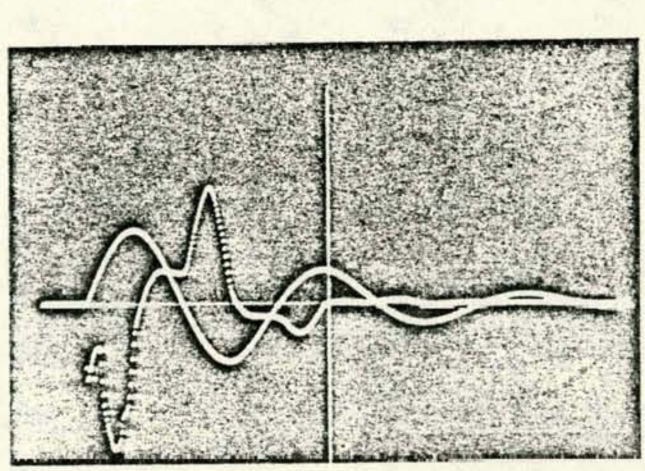

Fig. 3. Pulsed fault current and cable loss voltage. Rms values of the first three ½-cycles of current are 21.9 kA (2840 A/cm), 17.1 kA (2230 A/cm) and 10.0 kA (1300 A/cm). T = 6.7K

the spiral surface probes shows that not all parts of the cables are resistive at this point. It can be seen that for this single cycle of overload, the superconducting waveform is fully recovered after one cycle. Values of the resistive onset at T = 5.3, 6.7, and 8.3K were 22 kA (2850 A/cm) rms, 20.8 (2700) and 19.3 (2500) respectively. These values are in line with previous data for lab samples.[7] As was expected, placing the copper cladding entirely on the low field side of the tapes provides adequate flux jump stability.

The cable was pulsed to greater currents than the above. The maximum ½ cycle current applied was 27.7 kA (3600 A/cm) rms. Recovery again occurred in one cycle, when the current had fallen to 8.4 kA.

Current in stabilizer layers. The normal state resistance of the Nb_3Sn tapes when quenched by a sufficiently large current is much larger than that of the aluminum - 40 times at 8K. In this state current flow is mostly through the aluminum. This is observed in measurements at elevated temperatures (~ 25K) and serves to show that the coil sensing the aluminum current works properly. In the superconducting region, current distribution among the various layers can be calculated by means of the model equations described in references 2 and 3. It is necessary to assume an effective ohmic resistance for the superconductive loss, and to use a computer to solve for the eight complex currents. The results of the calculation can be summarized as follows:

1. At low currents the fraction carried by the aluminum is small, about 1% of the total, and shifted by ~180° - i.e., there is a return flow.

2. As the superconductive loss increases, current transfers to the aluminum, amounting to approximately 25% of the total when the layer resistances are equal.

3. The phase of the aluminum current shifts from ~180° to 0° as it increases in magnitude. These predictions are in reasonable accord with experiment, the main disagreement being that at low cable current the fraction carried by the aluminum is less than calculated by a factor of 2 to 3. Figure 4 shows cable and aluminum current waveforms for an initial current pulse of 21.2 kA rms. The first aluminum peak is 196 A rms. The phase angle behavior described above is apparent. A plot of the aluminum current magnitude and phase vs cable current is shown in Fig. 5. The high current points are derived from transient data such as Fig. 4, while the lower points are from cw measurements.

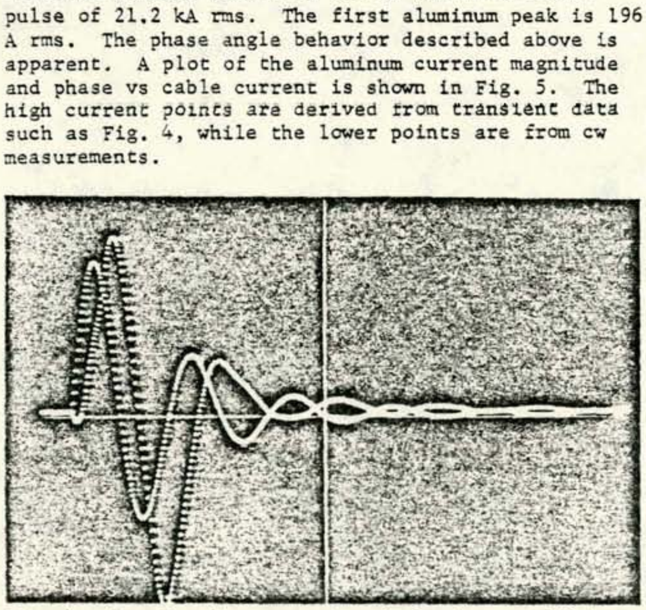

Fig. 4. Total cable current and aluminum stabilizer current. Current pulse (first to peak) is approximately same as   Aluminum current values are given in text. Note phase shift to 180° at low currents. T = 8.5K.

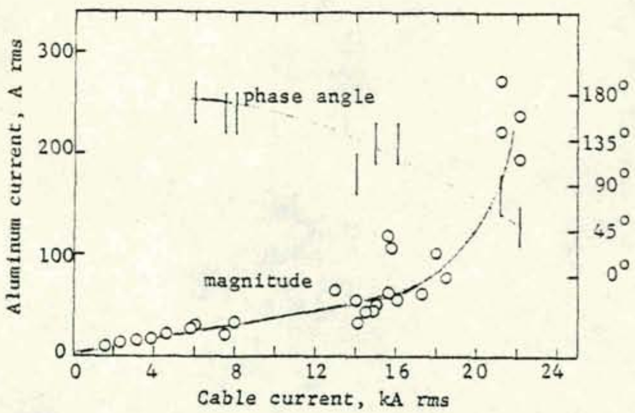

Fig. 5. Magnitude (O) and phase (|) of current in aluminum stabilizer layers vs total cable current. Vertical bars represent uncertainty in phase angle determination. T = 8K.

Recovery from local quenches. Cryogenic stability of the cable was touched on in early work.[8] This refers to the property by which a local normal region of the cable does not grow in extent while current is being carried. A similar though not exactly the same property is the response of a region which is thermally quenched while the cable is carrying current. A complete investigation of this phenomenon has not been carried out but rather we have demonstrated that the cable will perform adequately in this respect. The method is described by reference to Fig. 6. The upper trace shows the loss voltage from a 1 m long surface probe located in the heated region, while the lower trace shows the current detected in the aluminum monitor. Destruction of superconductivity and transfer of current to the underlying aluminum occurred 1.31 sec after the heater was turned on. With cable current left on, the heater was turned off at 1.61 sec and the normal zone collapsed within 0.07 sec. The maximum current transferred to the aluminum was 200 A rms, indicating that the normal region remained small in extent throughout. The effect is dependent on the length of time the 70 W heater remains on after quench begins. At 2300 A, recovery occurred for the longest such time tried, 2 sec, but for the highest cable cur-

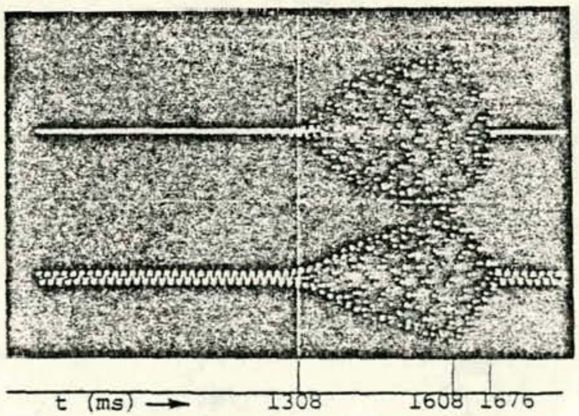

Fig. 6. Quench initiation and recovery experiment. I = 2.3 kA (300 A/cm) rms. T = 8K. Upper curve: superconductor loss voltage for heated region; the cursor indicates the point at which this region of the cable goes normal. Lower curve: current in aluminum stabilizer. The sinusoidally varying signals in the normal region have a patterned appearance due to the choice of sampling rate and scale.

rent tried, 3850 A (500 A/cm) rms, recovery occurred for heater on-times up to about 0.14 sec. It should be noted that in view of the low helium flow velocity in these experiments, heat transfer between the inner conductor and the refrigerant was an order of magnitude less than it would be in a properly refrigerated system.

SUMMARY

Tests have been described on a realistically constructed flexible cable installed in a horizontal dewar with ends fixed to room temperature supports. Performance as regards fault current and quench recovery is very good. The cable remains entirely superconducting for single cycle pulses of current up to 19 kA (2500 A/cm) rms. It has been run continuously for periods up to an hour at 3850 A (500 A/cm), behaving quite stably. At this current, when it is thermally quenched it recovers to the superconducting state without disconnecting the current. The cable has been pulsed or quenched in the above ways more than 100 times without ill effect. The ac loss is less satisfactory, being two or three times larger than expected. The extra loss is resistive in nature and does not seem to be due to the superconductor which appears to perform well. The effect was not observed in previous 1 m models and can, we believe, be eliminated.

The 10.6 m cable has revealed no obstacles for the design of the future 100 m prototype and is an encouraging precursor to it.

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