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STUDIES OF HELICAL CONDUCTOR MODELS FOR SUPERCONDUCTING AC POWER TRANSMISSION†

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ABSTRACT

In the BNL concept of a superconducting ac power transmission cable the conductors are made of Nb_3Sn tapes wound helically on cylinders. Recently, it was decided to make each conductor in the form of a double layer winding in which the layers are of opposite helicity. This reduces undesirable consequences of axial flux generation. After reviewing the considerations which lead to the double helix conductor, experiments with short models (0.8 m long) are described. Results are given for ac loss and quench current measurements. Quench currents in excess of 3400 A/cm rms have been obtained. Ac losses are higher than those of short samples of the tapes used but are acceptable. Loss calculations for the double helix configuration are discussed.

I. INTRODUCTION

Nb_3Sn cable designs for superconductive power transmission generally involve a flexible, tape wound type of construction.[1] This readily allows for thermal contraction, enables lengths $\sim$ 1000 m to be made in a factory and installed in the field, and facilitates the use of Nb_3Sn which is generally made in tape form. For these reasons it is the basis of the Brookhaven superconductive ac power cable design. Recently, the flexible tape wound type of cable has been adopted in a dc Nb_3Sn cable design[2] and in an ac Nb cable design.[3]

Measurements of ac losses and quench currents on superconductive materials have for the most part been made on small lab samples (typically 1 to 10 cm^2) in idealized geometries.[4] Losses and quench currents of tape wound solenoids made of Nb-Cu and Nb-NbZr-Cu laminated tape have been reported recently.[5] Among other results it was found that the losses were enhanced by a factor $\sim$ 1.8 due to edge effects.

In the present paper we report results for two Nb_3Sn model cables of the type to be used for ac power transmission. These are coaxial cables in which both inner and outer conductors are double layer tape windings. The double layers are of opposite helicity in order to reduce inductive effects and are referred to as "double helices" for short. The cables were short circuited at one end and driven by a transformer with superconducting windings at the other. Losses were measured on the central portion of the inner conductor. The measurements were made at 4.2 K.

II. DOUBLE HELIX DESIGN

The double helix design originated when it was realized that the axial flux which is generated by a simple helical winding can produce a number of undesirable consequences. These are: eddy current losses in metallic cryogenic enclosures[6] and in supportive metal cores[7], and large voltage drops over the length of the outer conductor.[7] The axial flux which causes these problems is greatly reduced in the double helix design. In the simplest type of construction the layers of opposite helicity are laid one on top of the other with no insulation between them other than that of the normal metal claddings of the superconductive tapes. The layers are soldered together only at the ends, or at the joints of a long cable. Fig. 1 shows the fabrication of a double helix on a commercial tape winding machine. Magnetic field measurements on such cables have been reported recently and are in good agreement with model calculations.[8] Axial magnetic fields (except those in the thin annulus between the layers of each double helix) are reduced to a few percent of single helix values over a wide range of winding pitch angles. More complicated constructions, such as interleaving of the tapes, are not necessary.

III. SAMPLE DESCRIPTION

MASTER

The double helix conductors were wound on thin plastic tubes. The superconductive tapes were tied down with nylon lacing and copper end rings were soldered on. In addition to holding the tapes in place during assembly the nylon lacing also served to eliminate mechanical vibrations. The copper end rings served as current lead-ins at one end and as a short circuit at the other.

The starting materials were commercial tin-diffused tapes obtained from Kawecki-Berylco Corp. The tapes have a solder bonded copper cladding 30 μm thick for stabilization. The tapes were 1.27 cm wide as received and were slit commercially to produce the narrower tapes used to make the helical conductors. The first of the cables, which will be referred to as A, was made with tape, so-called KB-15, which has been a subject of several previous studies[9-11] and has, therefore, been described in some detail. The inner conductor of the second cable, B, was a double Nb_3Sn tape laminate (called KB-30) plus 30 μm copper cladding. This material (called KB-30) had a greater current carrying capacity but also had rougher, lossier Nb_3Sn surfaces.

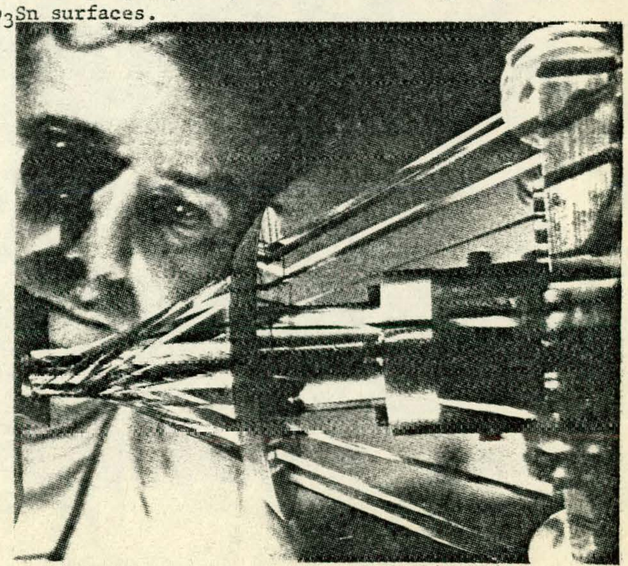

Fig. 1. Cable machine winding of double helix conductor

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Both cables were about 80 cm long, outer conductor diameter 2.85 cm, inner conductor diameter 1.95 cm. The minimum bending radii of the tapes (0.4 cm for A and 0.9 cm for B) were less than the inner conductor radius. The inner conductor of cable A was hand-wound with a pitch length 23 cm (lay angle 15°). There were 15 tapes in each layer, each 0.38 cm wide. The average butt space between tapes was about 0.01 cm, but due to variations in pitch and unevenness of lay the range of butt spaces was 0 to 0.05 cm. Cable B was machine wound (see Fig. 1). There were 16 tapes per layer, 0.32 cm wide each. The pitch length was 11.2 cm. The lay angle of this cable, 28°, is a realistic one in that it is about right for matching the radial thermal contraction of the conductor and that of high voltage plastic insulation. The same outer conductor was used for both cables. It was made with 21 tapes per layer, of KB-15 tapes, 0.38 cm wide, pitch length 24.2 cm (lay angle 20°). The inner and outer cable conductors were stabilized against mechanical vibration by means of annular fiberglass spacers which were inserted during assembly.

IV. EXPERIMENTAL

Ac losses were measured by means of an electronic wattmeter. A block diagram of this apparatus has been published.[12] Signals proportional to the voltage and to the derivative of the current in the inner conductor (Rogowski loop) are fed to a wide band amplifier and amplifier-integrator, respectively, and thence to a multiplier of the pulse-width modulation type. At the input pre-amps, a fraction of the dI/dt signal is used to buck out the inductive or out-of-phase component of the voltage signal. This inductive component is typically 100 to 1000 times greater than the loss signal; inductive compensation increases the useful gain by this amount, therefore. The compensation adjustment is made by observing the amplified current and voltage signals prior to multiplication. The common practice of making in-phase as well as out-of-phase adjustments is strenuously avoided, since if this is done it becomes difficult if not impossible to observe loss components other than those with hysteretic waveforms. The relative phase shift of the amplifiers in our circuit is $\lesssim 5 \times 10^{-4}$ rad for frequencies between 40 and 200 Hz. The sensitivity is such that loss voltage signals must be $\gtrsim 5$ µV at the amplifier input.

Voltage signals were obtained with two different pick-ups on the inner conductor. These are shown schematically in Fig. 2. The loop I is an inductive pick-up, while S is formed by solder contacts. The sensitivity of I can be increased by winding with many turns. In practice this is tedious for many more than ~ 10 turns, which was the number used. The S and I pick-ups should give the same results if the electric field in the inner core region of the conductor is zero, as it should be. Losses determined by the S pick-up were ~ 40% higher than for the I coil in the cable A experiment, and ~ 60% lower in the cable B runs. Observation of superimposed S and I signals showed the hysteretic parts of these waveforms to be virtually identical. The differences appeared to be due to common mode error signal in S and to the comparatively low sensitivity of this single turn pick-up.

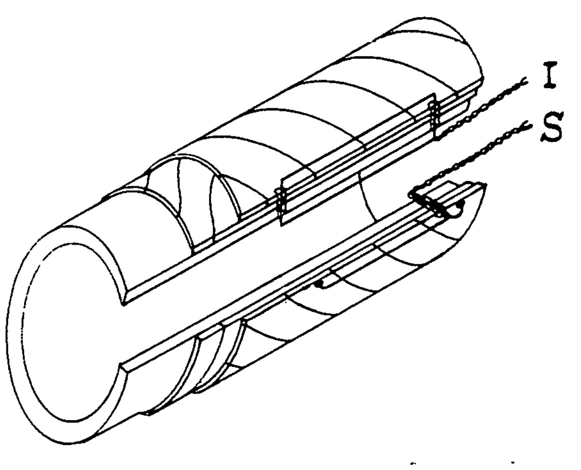

Fig. 2. Inner cable conductor schematic showing placement of voltage pick-ups

The pick-up loops were ~ 45 cm long so that all of the region of measurement was at least 8 diameters away from the end; end effects were probably of no importance, therefore.[5]

The comparatively large currents required in these tests were supplied through a 100:1 step-down transformer operating in liquid helium, with superconducting windings. A toroidal geometry was used to facilitate connection of the secondary to the cable. The dimensions of the core, which was made of transformer steel, were 12.7 cm OD, 8.4 cm ID, and 11.7 cm long. The primary and secondary were single layer windings. The inner, primary winding consisted of 100 turns of 2.3 mm wide RCA Nb_3Sn tape, insulated with fiberglass braid. The secondary consisted of 20 GE Nb_3Sn tapes, 1.27 cm wide, uninsulated, with all the tapes connected in parallel. The windings were mechanically secured by nylon lacing. The transformer was tested to 15 kA rms CW, and was estimated to be capable of carrying pulses in excess of 40 kA rms without quenching. These values are well above the corresponding ones for the cables tested. CW measurements to 9000 A were made with the aid of a 2.5 kVA amplifier. Measurements on cable A were limited to this value. For the later tests on cable B a pulse current supply was assembled. The method consisted of discharging a 1500 µF capacitor bank through the transformer - cable inductance. By varying the capacitance the frequency was conveniently varied between 60 and 200 Hz. Quench currents are determined by observation of the onset of a resistive component in the loss voltage waveform. As quench currents are not dependent on frequency in this range, this measurement was generally made at a frequency ~ 170 Hz since the higher $Q (\approx 15)$ at this frequency provided a more gradual pulse decay.

Losses at the higher, pulsed currents were determined by means of a digital storage oscilloscope and computer link. Single cycles of the pulsed current and loss voltage were digitally stored, then multiplied and averaged to give the loss.

V. RESULTS

In presenting the data which follow, the measured losses and currents are referred to an ideal cylindrical surface of diameter D, equal to the OD of the double helix conductor. If the measured loss of a length ℓ is P then the loss per unit area (plotted in Figs. 3 and 4) is $P/A = P/\pi D \ell$. Likewise the abscissa in these figures, the surface current density σ, is defined as $\sigma = I/\pi D$, where I is the cable current.

Fig. 3 gives the loss data for cable A together with short sample data for the tapes of which it was made.[9] For current densities above ~ 500 A/cm rms the losses are approximately twice the short sample values. The losses are due largely to the Nb_3Sn in this region and vary as $\sigma^{\sim 3}$. Cable data taken between 40 and 200 Hz were nearly linear in frequency, the largest deviation of ~ 15% occurring at the lowest current density, $\sigma \approx 300$ A/cm rms. The losses are mainly hysteretic, therefore, over the entire range of currents measured. The low σ hysteretic losses are evidently associated with the cladding solder. This is seen in the loss waveforms. In the cable, the solder loss at low σ is greatly enhanced relative to the small eddy current contribution ($\sim$ 5 $\mu W/cm^2$ at 300 A/cm rms). This is in contrast to the short tape behavior where the two contributions are closer in importance. The solder loss increases slowly as a function of σ above $\sim$ 100 A/cm rms;[9] hence, the solder contribution from the inner two surfaces of the double helix is disproportionately larger than that of either the Nb_3Sn or the copper cladding at low σ in the cable.

There was little or no evidence of vibrational, resistive, or other non-hysteretic loss contributions.

The losses of cable B are shown in Fig. 4. The tape used for this cable was of necessity different because our supply of KB-15 tape, which is no longer in production, was depleted. The tape used, KB-30, is much lossier, and photomicrographs show a rough Nb_3Sn layer and a coarse solder layer. The losses in the cable varied as σ^3 from 500 to 1500 A/cm and as $\sigma^{4.2}$ at higher current densities up to the quench point. The losses were mainly hysteretic and, again, roughly double those of the short samples of the tapes.

The quench current density for this cable was 3380 $\pm$ 20 A/cm rms, calculated from the amplitude of the initial pulse. At this value of the current density, the onset of a resistive component is observed in the voltage waveform of the initial pulse. For larger current densities up to 3600 A/cm rms it was observed that the resistance disappeared within a cycle of the decaying current, indicating a prompt recovery of the superconducting state. For initial current densities above 3600 A/cm rms the superconducting state recovered only after several cycles, at which time the current density had fallen to low values of a few hundred A/cm rms. The quench current density of the KB-30 tapes as measured in a short sample transformer[12] is 2390 A/cm rms. The surface quench field is therefore, 1.4 X greater in the double helix cable.

Losses of cable B after quenches of the type last described are shown in Fig. 4. In general there was a slight decrease in loss after quench. This was most noticeable at the lowest current densities, i.e., in the region where the solder contribution is important. Above 500 A/cm the change is very small.

VI. DISCUSSION

Comparison of the loss per unit area in the cables with that of short samples of the tapes is made in Fig. 5, which shows that losses are increased by a factor of about 2 in the cables. The increase is greater at current densities below $\sim$ 500 A/cm rms. Part of the increase, due to the multiple surfaces in the double helix, is predictable because the magnetic fields are reasonably well known.[8] An expression for this effect, assuming the loss varies as σ^n, is

$$\alpha = 1 + 2\,(1/2 \sec \theta)^n \qquad (1)$$

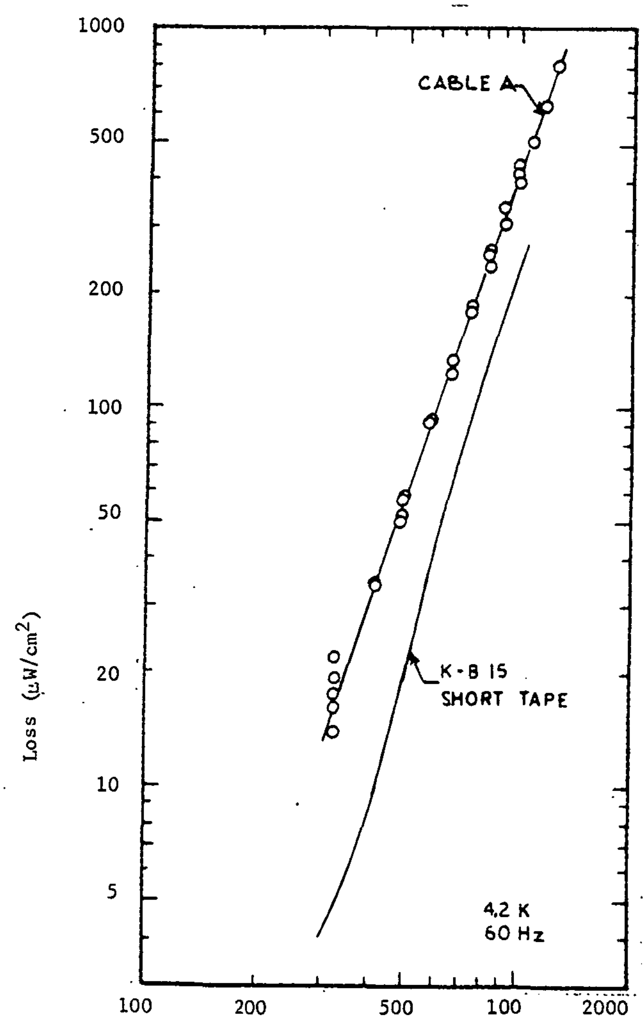

Fig. 3. Loss Data for Cable A

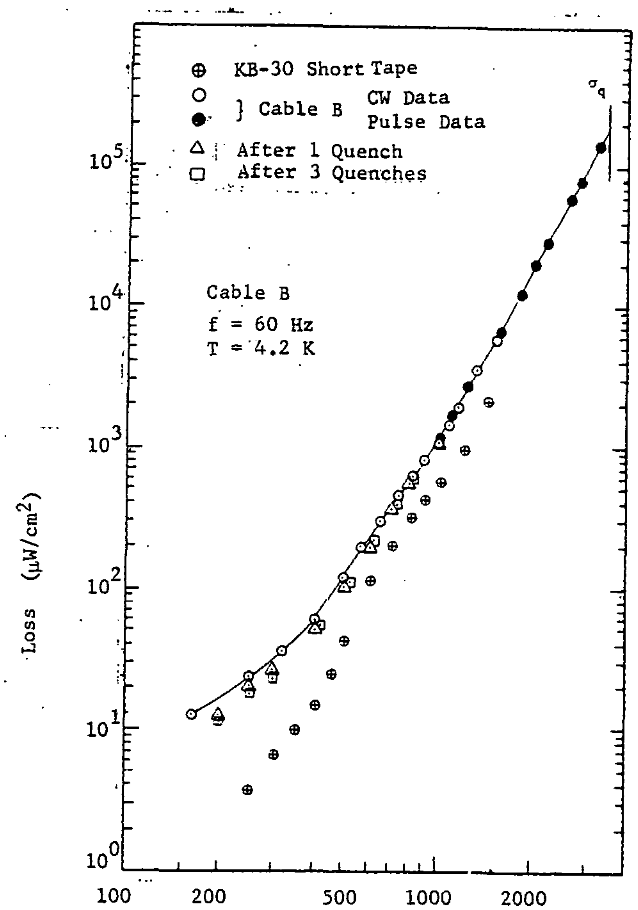

Fig. 4. Loss Data for Cable B

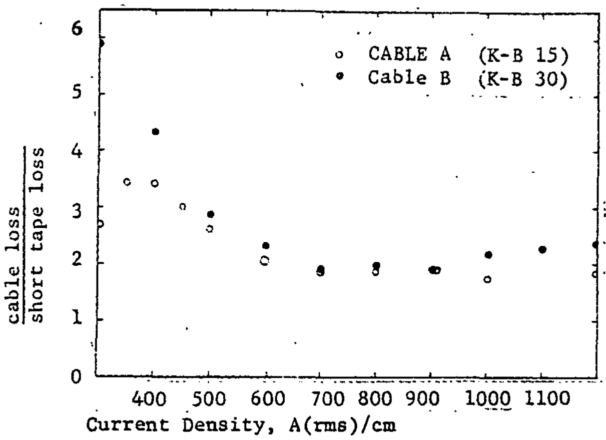

Fig. 5. Ratio of Cable to Tape Losses

where α is the ratio of cable loss to tape loss due to multiple surfaces and the fields to which they are exposed, and θ is the lay angle. The actual loss increase is greater than the value given by this factor, which is 1.3 and 1.4 for cables A and B, respectively. In general the cable loss can be expressed in the form:

$$P_{cable} = \sum_i \alpha_i \beta_i P_i + \alpha_e (2/w) P_e \qquad (2)$$

The sum refers to the various components of the tape composite, e.g., Nb_3Sn, solder, copper etc.; β_i is a factor which takes into account possible increases due to misalignment, slitting, etc., other than edges, which are given by the last term. The P_i vary as σ^{n_i} where the exponents are different for each of the layers, e.g., 3 to 7 for Nb_3Sn, 2 for copper, and 1 for solder at $\sigma \gtrsim 100$ A/cm rms.[3] The various P_i can either be calculated or deduced from short tape data. The loss of a given component will depend on its location in the composite, e.g., the eddy current loss in the copper is increased by the presence of an underlying solder layer.[4] The last term of Eq. 2 contains the factors P_e, the edge loss per unit length, which is not known, w, the tape width (2/w is the edge length per unit area) and α_e, which is given by Eq. 1. P_e is due to field enhancement effects and does not include edge losses due to circulating currents through the Nb substrate, which may be significant near the substrate transition temperature ($\sim$ 9 K). Equation 2 states that the loss in the various components is additive, which is true in the sense that the loss in the Nb_3Sn layer is essentially unaffected by the superficial layers.

For cable A, the known factors in Eq. 2 are given in Table I for σ = 300 and 450 A/cm rms.

TABLE I

LOSS ANALYSIS OF CABLE A

	Nb_3Sn	Solder	Cu	$2\alpha_e/w$
		σ = 300 A/cm rms		
α:	1.0	2.0	1.5	6.5
P:	~0.2	1.5	2.3	?
		σ = 450 A/cm rms		
α:	1.0	2.0	1.5	6.5
P:	4.2	4.3	5.2	?

Assuming that the β_i in Eq. 2 are ≈ 1, i.e., that the loss increase in cables is entirely due to the edges, one obtains values for P_e of 0.86 and 3.4 μW/cm at 300 and 450 A/cm rms, respectively (approximate cubic dependence).

This formulation is speculative at present; however, it is useful for comparing the contributions of the solder, copper and unknown causes. The last named, which appears to be especially important at low σ, to the extent that it is due to edges will be reduced by the use of wider tapes. The formulation can also be used to extrapolate known loss data to other conductor configurations and temperatures.

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