BNL 28389

To be presented at the 1980 Applied Superconductivity Conference, Sept. 29 - Oct. 2, 1980, Santa Fe. NM

CONF-800980--23

AN IMPROVED 60 HZ SUPERCONDUCTING POWER TRANSMISSION CABLE*

MASTER

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Abstract

The third in a series of 10 m, Nb_3Sn cables for ac power transmission has been installed in a horizontal, refrigerated cryostat. Like the two previous ones, this coaxial cable has its ends rigidly fixed so that it cannot contract axially on cooldown, and has two layers of superconducting helices and two layers of high purity aluminum helices for stabilization in each conductor. It differs from the previous one[1] in having thicker electrical insulation (7.4 mm vs 3.6 mm), in having increased contact resistance between the superconducting layers to reduce ac loss, and in being driven by an external supply through horizontal, coaxial, vapor-cooled current leads. This is the final short cable prior to construction late this year of a 100 m cable which will be tested with high voltage and high current simultaneously. Results of current tests are presented, including ac loss at various temperatures and recovery from thermally induced quenches.

Introduction

The third in a series[1,2] of 10 meter long superconducting power cables has been assembled in the BNL cable winding facility and tested at temperatures in the 7 to 12 K range. It is the final superconducting cable of this length prior to the construction of a 100 m superconducting cable which will begin early next year. Results obtained with the second cable of the series have not been reported elsewhere and are given here.

The three 10 m cables thus far tested are designated 101, 102 and 103. Cable 102 was very similar to cable 101 and was designed to reduce the unexpectedly large ac loss observed in cable 101.[1] In a uniform magnetic field parallel to the surface of the bare niobium-tin it incurs a loss of about 0.1 W/m^2 at 500 A/cm and 4.2 K. Because of multiple surfaces in the two superconducting tape layers of each conductor, because of eddy currents in the thin copper stabilizer layers of the composite tapes, and because of field enhancement at the edges of the tapes, the loss in the cable was expected to be several times this, perhaps 0.4 W/m^2 for the same conditions and rising to 0.5 W/m at 7 K. In addition, a loss is incurred at the sheared edges of the tapes as a result of current crossing them from one face to the other.[3] This loss peaks at the transition temperature of the Nb-1%Zr substrate, 8.5 to 9.0 K depending on current density, but is negligible at 7 K. The reported loss in cable 101 at 7 K and 500 A/cm was about 2.2 W, which is equivalent to about 1.8 W/m^2 or 0.2 W/m, three or four times the expected value.

Description and Performance of Cable 102

The structure of cable 102 is given in Table 1. The layers are numbered from the center out, excluding the core. The superconducting tapes are asymmetric, having 302 stainless 0.025 mm thick soldered to one side of the superconductor and 0.05 mm copper soldered to the other. The superconductor itself has 5 to 8 μm Nb_3Sn on both surfaces of 23 μm thick (before reacting) Nb-1Zr foil. The cable length was 12.52 m.

The instrumentation of cable 102 was similar to that used in cable 101,[1] including an "AB" connection for total loss, an axial probe to measure the loss in the inner conductor and two "spiral probes" to measure the loss in individual tapes. Two heaters were installed to initiate quenches. Two new Rogowski coils for current measurement were installed, one near the superconducting transformer which drove the cable, the other near the shorted end. Unlike the earlier Rogowski coil, wound with # 36 copper wire, the new ones used # 40 to reduce eddy currents. These coils also supply the compensating voltage for the loss signal, which has a large inductive component. After compensation, the loss signal is amplified and multiplied by the integrated voltage from the Rogowski coil to give an output proportional to the loss. An out-of-phase component in the signal from the Rogowski coil can affect the measured loss and may arise from eddy currents in the coil.

In the earlier report,[1] it was hypothesized that current flow between the superconducting helices, via ohmic contact through a stainless-steel layer, was responsible for the excess loss observed. Computer studies[4] showed that the loss has a maximum at a certain value of contact resistance, and estimates of the contact resistance indicated that either substantially reducing it or increasing it could decrease the loss due to interlayer current flow. Cable 102 was constructed in a way which, it was thought, would decrease the contact resistance. The composite superconducting tapes were inverted in layers 3 and 6. This put the copper clad sides of layers 3 and 4 in contact, eliminating the stainless steel between them. By the time cable 102 was tested, however, measurements of contact resistance had been made, and it was considerably higher than estimated. The measurements also showed that the base material of the touching surfaces was not as important as the thin tinning layer on the surfaces. This tinning layer, a non-superconducting soft solder, deforms at the points of contact, increasing the actual area and decreasing the contact resistance. At the lowest pressure the tinned Cu/Cu contact resistance of a 6 x 6 mm contact area averages about 0.06 mΩ compared to 0.3 mΩ for the tinned Cu/ss contact resistance, whereas the untinned Cu/ss contact resistance averages about 5 mΩ and the untinned Cu/Cu resistance is 2 mΩ. All these numbers are higher than the original estimates. The lowest value, 0.06 mΩ, is calculated to cause additional loss in cable 102 of about 0.08 watt/meter, and the higher values would add even less loss since the loss is inversely proportional to contact resistance. There is considerable uncertainty both in the calculation and in the measured contact resistance; a factor of three or four either way in the loss is possible.

Total losses in cable 102 were measured electrically using the new Rogowski coils and "AB" probe. There was no difference in results obtained with the two coils. The lower curve in Fig. 1 shows the loss measured electrically, including the loss in the short-circuited end, as a function of surface current density

*Work Supported by the U.S. Department of Energy.

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Table 1

Cable 102 Characteristics

Layer No.	Material	Thickness (mm)	Width (mm)	No. of Tapes	Outer Dia. (cm)	Pitch Length (cm)	Angle (degrees)	Remarks
Core (2)	Bronze	1.0	12.	5	2.31			Double helix
1	Aluminum	0.2	6	9	2.34	8.74	+40.07	2500 resist. ratio
2	Aluminum	0.2	6	9	2.39	8.79	-40.5	2500 resist. ratio
3	Superconductor	0.13	6	9	2.41	8.43	+41.93	SS towards core
4	Superconductor	0.13	6	9	2.44	8.26	-42.86	SS towards dielectric
Dielectric	Polypropylene	3.6						35 layers
5	Superconductor	0.13	6	11	3.16	9.65	-45.81	SS towards dielectric
6	Superconductor	0.13	6	11	3.19	9.68	+45.99	Cu towards dielectric
7	Aluminum	0.2	6	11	3.24	9.55	-46.83	2500 resist. ratio
8	Aluminum	0.2	6	11	3.31	9.47	+47.68	2500 resist. ratio

σ in the inner conductor. At 500 rms A/cm (3830A) the loss is about 3.0 W. Excluding the end loss, this is about 0.21 W/m, which is about the same as was reported for cable 101. However, it was found that when the loss in 102 was measured using the old Rogowski coil from cable 101, it was only about half as large. The difference was attributed to an out-of-phase component in the older Rogowski coil. If such a component were a property of the coil, the reported loss in cable 101 would have been a factor of two too small.

The losses in cable 102 were also measured calorimetrically and have been presented elsewhere.[5] The carbon resistors used for temperature measurement in cable 101 were replaced by precisely - calibrated germanium resistors. Even with these more precise thermometers, the determination of electrical loss by temperature and flow measurements is difficult. The cable is cooled by pressurized counterflow helium streams, on the inside and outside of the cable. Part of the heat input is through the cryostat wall to the outer return stream. This heat leak averaged 10.5 watt compared to the electrical heat of a few watts at a cable current of 4 kA. The measurement was complicated by heat generated in the shorted end of the cable. The temperature of the return stream was not as well known as that in the cable center because of vertical stratification in the slow-moving stream. The end point temperatures were better known, but include the end losses, e.g. transformer and short-circuited end. The results of the calculation are also presented in Fig. 1. The calorimetrically measured loss is a factor of 1.52 to 1.56 higher and is 4.65 W at 500 A/cm. Measured either way, the loss varies approximately as $\sigma^{2.5}$.

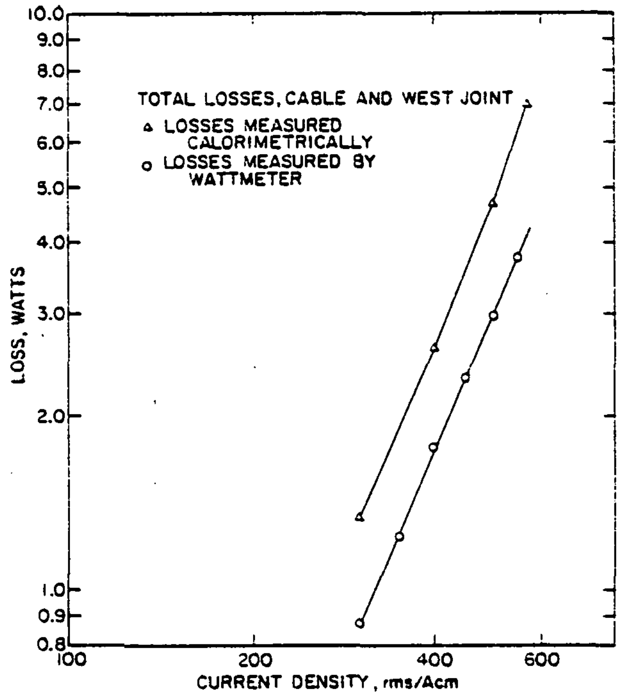

Fig. 1. Current-related losses in cable 102 at 60 Hz and T = 7.3 K.

Description of Cable 103

This cable had the tapes of layers 3 and 6 oriented the same as in cable 101. To reduce contact resistance, the solder on all surfaces was etched off. Using the measured value of contact resistance given above (5 mΩ) the added loss is calculated to be 1 mW/m at $\sigma = 500$ A/cm, too small to be detectable. The insulation between conductors was 64 layers of polypropylene, each nominally 100 um thick giving a measured radial thickness of 7.4 mm. The measured total length was 10.88 m, inner conductor o.d. 2.56 cm and outer conductor i.d. 4.05 cm, otherwise the structure was essentially the same as that of cable 102, Table 1. Unlike the first two, cable 103 was powered through coaxial, horizontal, vapor-cooled current leads by a room temperature, toroidal transformer with a single-turn secondary. Owing to the thick insulation the reactive power required for cable 103 was greater than for the earlier cables; the reactance at 60 Hz was 0.37 mΩ. The superconducting transformer used on the earlier cables would have been marginal for this cable. The maximum primary voltage of the transformer is 500 V and the turns ratio is 177:1, so the rated maximum current in the cable is about 7.6 kA.

Cable 103 Results

The current related losses obtained in cable 103 were measured both electrically ("AB" loss) and calorimetrically. Both Rogowski coils used for the electrical measurement were wound from no. 40 wire; one was taken from cable 102, the other was new. The results obtained at about 7.2 K of all measurements are given in Fig. 2 which shows total loss in W/m vs current density on the inner conductor, A/cm. The solid line is loss measured calorimetrically and the two dashed lines are loss measured electrically using the two Rogowski coils. The difference in the electrical measurements has not been resolved. One of the Rogowski coils was located in the annulus between the

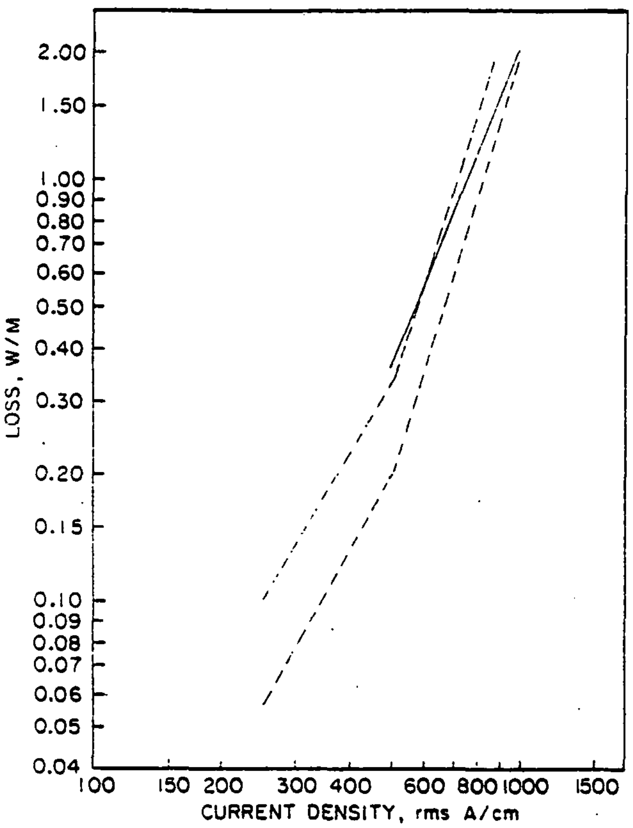

Fig. 2. AC loss in cable 103. The dashed lines were measured electrically and the solid line calorimetrically.

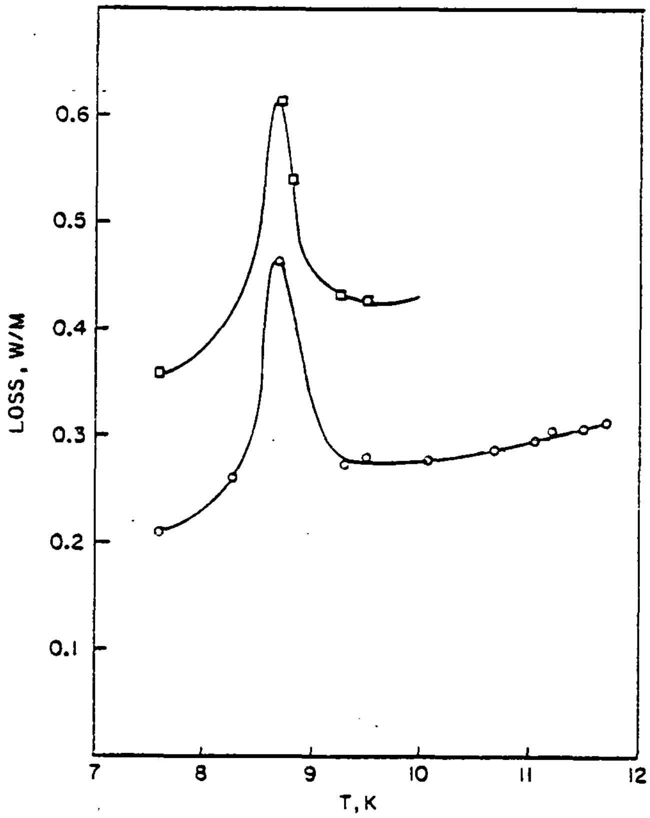

Fig. 3. Loss in cable 103 vs temperature. The two curves arise from data taken using different Rogowski coils.

helical conductors, the other at the cold end of the current leads where there are no helical conductors; the latter coil supplied the data for the upper curve of Fig. 2. The loss in the short-circuited end is included in the electrical measurements, and it and possibly the losses in the soldered current lead connections are included in the calorimetric measurements. At 500 A/cm (4014 A), the losses obtained are 0.345 measured calorimetrically and 0.331 and 0.198 W/m measured electrically with the two Rogowski coils. The loss in the short-circuited end, expressed as W/m, is about 0.02 W/m at this current density.

The current-related losses in cable 103 were also measured as a function of temperature at 4 kA, and are given in Fig. 3. The two curves were obtained using the two Rogowski coils. The peak at 8.7 K is due to losses at the edges of the tapes, as was described[1] for cable 101, in which the peak appeared to be at 9.0 K. The data shown here indicate less temperature dependence of the loss above transition. The half-width of the new peak is about 0.4 K, vs about 1.0 K in the earlier report, probably because of the improved temperature control.

Quench tests were carried out on cable 103 using a thin-film heater on the inner conductor as described for cable 101. The aluminized Kapton heater completely covered about 0.3 m of the inner conductor. Typically, with 2500 W/m^2 power density and the cable initially at 8 K, the conductor would quench in about 4 seconds. An electric circuit detected the quench when the loss voltage from a spiral probe reached a preset value and turned off the heater, whereupon the quench voltage would either continue to increase or would damp out. The highest current at which recovery was effected was 6 kA, but recovery was not consistent at this current. Recovery depends on how soon after quench initiation the heater is turned off, so these observations are essentially qualitative.

Axial flux was measured using single 40-turn coils wrapped around the inner conductor or the outer conductor at four axial locations, and by small 200-turn coils inserted at three axial locations into the cable core. Radial flux (q.v.) was measured by pairs of axial flux coils spaced 2.5 cm apart and connected differentially in series. There were three such bucked pairs, two on the inner conductor and one on the outer. The signal from a single axial flux coil is due to the net axial field generated by the helical currents in the two layers of superconducting tapes in each conductor. A difference in signal between two closely spaced coils implies a change in these currents and the existence of radial flux. A change in the currents can occur only by current crossing from one layer to another. The three coil pairs on the inner conductor were located 0.42, 0.75 and 1.74 m from the short-circuited end, and at 4 kA cable current had emfs of 1.45, 4.71 and 3.31 mV, resp. The output of the middle pair is the largest, and it implies a current transfer of about 40 A in the 2.5 cm interval. The contact resistance per crossover for this cable was 5 mΩ, so the interlayer resistance in 2.5 cm is 0.2 mΩ in both the inner and outer conductors. If the current change were the same (half of the 40 A) in both conductors, the dissipation would be 0.16 W total in both conductors, or 6.4 W/m. If the current transfer occurred entirely in one conductor the loss would be twice as high. The large loss implied for this one position suggests that the model used[4] in the calculation of contact losses may be in error.

Termination of the helical conductors may give rise to radial fields in the butt gaps between the superconducting tapes near the cable ends. Such fields may produce losses. The radial field is given by

$$B_r = \varepsilon \, (w + b)/(Nb \, \omega\pi \, D \, S) \qquad (1)$$

where ε is the emf of a differential coil pair spaced a distance S, having N turns each, wrapped around the conductor of diameter D, with tapes of width w having an average butt gap between them b. The stated emf of the middle coil pair gives an average radial field B_r of 30.9 G rms in the butt gaps. This field implies the existence of a current density gradient across the tape, but it is probably very small; a simple model putting this differential current at the tape edges would give a current increment ΔI at opposing edges given by $\Delta I \simeq \pi B_r b/2 \mu_o$. For B_r obtained above $\Delta I = 1.2$ A. Neither B_r nor ΔI are sufficiently large to add substantial loss.

Summary

A total of three, 10 meter Nb_3Sn superconducting cables have been built and tested. All three ran in steady-state above the design current of 4 kA rms and design current density of 500 A/cm. The latest one ran at twice the rated current for more than one-half hour while being powered through vapor-cooled current leads by a room temperature transformer. It recovered from a heater-induced quench while running at 6 kA.

A great deal of effort has gone into measuring current-related losses. Calorimetric measurements of total cable loss in the latter two cables are about the same. The electrical measurements of total loss are more scattered. Table 2 gives loss (excluding loss in the short-circuited end) on a W/m basis with estimated short-circuited end loss subtracted from the calorimetric loss. The data for cable 103 have been reduced about 4% to adjust to the lower current of the other cables, at 500 A/cm current density. The temperature is 7.2 K.

Table 2

	Loss in W/m	
Cable	Electrical	calorimetric
101	0.20	
102	0.21 (2 coils)	0.35
103	0.30, 0.17	0.31

Eddy currents in the Rogowski coil, or axial field pick-up by imperfectly wound Rogowski coils located between helical conductors have been suggested as explanations for the variation in the electrical measurements. A narrow peak in loss occurs at about 8.7 K due to current crossing the superconducting substrate, which becomes normal at this temperature.

Measurements were made of contact resistance between superconducting tapes pressed lightly together, and a theory of loss due to resistive contact between the layers of superconductor was developed. The theory predicts that the loss should vary inversely with contact resistance in the range observed. The three cables cover a range of contact resistance of about 80:1, yet the observed loss is about the same in all three.

Another possible loss mechanism is due to hypothetical radial magnetic fields; presumedly these could exist only near cable ends. Measurements were made of the radial field in several locations and it was found to be too small to have much effect on losses. The radial field is measured by two closely-spaced coils which measure axial flux. A change in axial flux can occur only by current crossing from one layer to the other; in the largest of three cases observed, such resistive crossing implies a local loss at 4 kA of at least 6 W/m.

Acknowledgements

The authors gratefully acknowledge the technical abilities of Stanley Pollack, who installed the instrumentation and did the tedious work of connecting the cable ends. T. Muller, R. Kowalski, H. Noehren and K. Stevenson constructed the cable. W. Kristiansen, N. Houvener, D. Farrenkopf and K. Rogers installed the cable and assisted in testing it. J. Jensen reduced the thermodynamic data and calculated the losses from it.

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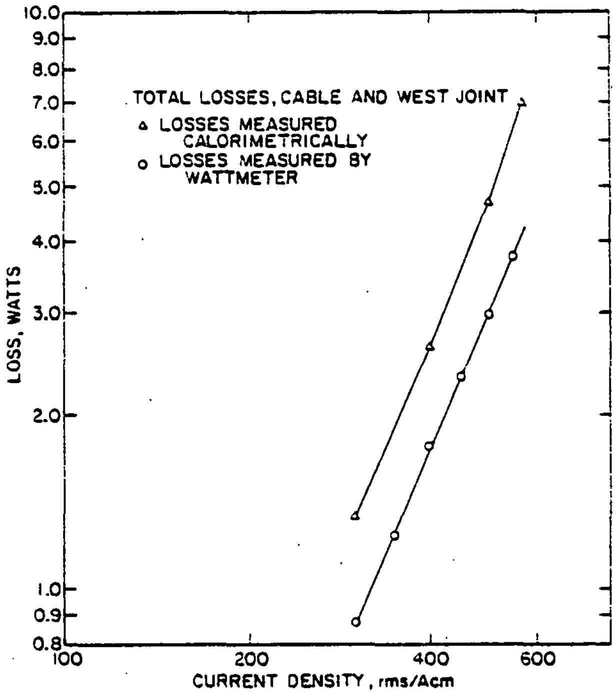

Fig. 1. Current-related losses in cable 102 at 60 Hz and T = 7.3 K.

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