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SINGLE AND THREE-PHASE AC LOSSES IN HTS SUPERCONDUCTING POWER TRANSMISSION LINE PROTOTYPE CABLES

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ABSTRACT

AC losses in two, one-meter-long lengths of HTS prototype multi-strand conductors (PMC's) are measured with a temperature-difference calorimeter. Both single-phase and three-phase losses are examined with ac currents up to 1000 A rms. The calorimeter, designed specifically for these measurements, has a precision of 1 mW. PMC #1 has two helically-wound, non-insulated layers of HTS tape (19 tapes per layer), each layer wrapped with opposite pitch. PMC #2 is identical except for insulation between the layers. The measured ac losses show no significant effect of interlayer insulation and depend on about the third power of the current -- a result in agreement with the Bean-Norris model adapted to the double-helix configuration. The three-phase losses are a factor of two higher that those exhibited by a single isolated conductor, indicating a significant interaction between phases.

INTRODUCTION

Because of the increasing demand for electric power in urban areas, superconducting power transmission lines (SPTL's) fabricated from HTS conductors are the subject of study throughout the world. Their higher current carrying capacity compared to copper conductors could give HTS SPTL's an advantage in upgrading the capacity of existing underground power transmission line conduits. A detailed understanding of the ac losses in SPTL cables is essential for both the electrical and thermal engineering design of the transmission line, as well as for the design of the cable itself.

As a first step in understanding ac losses in HTS SPTL's, we measured both single-phase and three-phase ac losses in two-layer, prototype multi-strand conductors (PMC's) fabricated from BSCCO tapes. Measurements on an eight-layer multi-strand cable are now in progress. Our loss measurements are part of a US. Department of Energy Superconductivity Partnership Initiative (SPI) program involving Pirelli Cavi S.p.A., American Superconductor Corporation, Electric Power Research Institute, and the Superconductivity Technology Center (STC) of Los Alamos National Laboratory.

EXPERIMENTAL

We chose a calorimetric technique for measuring the ac losses in PMC's because electrical measurement techniques give widely varying results, which depend largely on the technique used, even for single superconducting tapes[1]. For multi-strand, helically-wound

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cables that experience ac magnetic fields from the other two phases of a three-phase transmission line, electrical measurement difficulties would be even more severe because of induced circulating currents that do not produce a coherent voltage drop along the sections of tape conductors.

Because we believe there are difficulties (cable porosity and axial conduction) in measuring electrical losses in cables by using boil-off calorimetry, we devised an alternative calorimetric technique for measuring electrical losses in meter-long lengths of cable that we call temperature-difference calorimetry. This technique allows accurate loss measurement because cable end effects do not influence it. Since developing this technique we have learned of its previous use by Wissemann, Boatner and Low[2], and others[3,4]. Because the calorimetric technique is described in detail elsewhere[5,6], we give only an abbreviated description here.

Theory of Calorimeter

The operating principle of the temperature-difference calorimeter is the parabolic temperature distribution that develops within a rod or cable with uniform internal heat generation (electrical losses), that is insulated on its periphery and cooled at each end. The solution to the steady-state heat conduction equation with internal heat generation,

$$\frac{d^2T}{dx^2} = -\frac{q_L}{kA}, \tag{1}$$

is then

$$q_L = \frac{8\ kA\ \Delta T_m}{L^2} \tag{2}$$

where T is the cable temperature at axial position x, q_L is the heat generation (loss) per unit length, k is the effective thermal conductivity of the cable, A is the cable cross-sectional area, L is the cable length, and ΔT_m is the difference between the temperature at the center of the cable and the average of the two end temperatures.

The cable and calorimeter are calibrated in situ using a heater wound around the cable midpoint to determine the effective value of the thermal conductance kA, which from the conduction equation is

$$(kA)_{effective} = -\frac{1}{2}\frac{Q_c}{(dT/dx)_c} \tag{3}$$

where $(dT/dx)_c$ is the average of the measured linear temperature gradients for each half of the cable produced by the applied heater power Q_c. The factor 1/2 occurs because the calibration heater power is split between the two halves of the cable. Combining (2) and (3) gives the governing equation for the temperature difference calorimeter:

$$q_L = -4\frac{Q_c}{(dT/dx)_c}\frac{\Delta T_m}{L^2} \tag{4}$$

with the difference between the centerline and end temperatures determined from a curve fit to the temperatures of thermometers positioned axially and azimuthally on the cable, and L being the axial distance between the thermometers placed near the ends of the cable.

Because heat flows away from the measurement section, end losses raise the overall temperature level of the cable somewhat, but they do not affect the temperature difference between the mid-point and the ends.

Calorimeter

The calorimeter, Figure 1, is designed for measurement of three-phase losses by virtue of having three conductors -- the PMC's and two "dummy" copper conductors (only one shown in side view) -- forming an isosceles triangle. Because the G-10 glass-epoxy vacuum

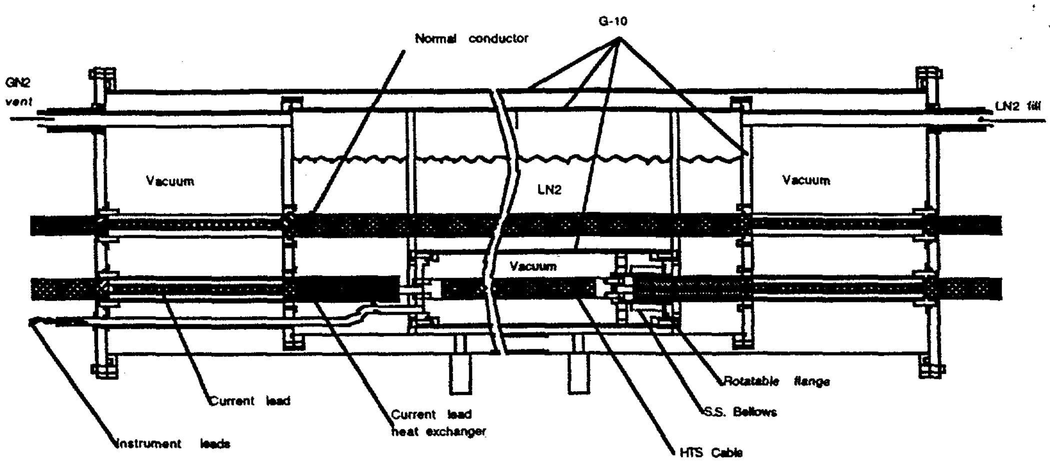

Figure 1. Calorimeter side view.

jacket surrounding the PMC is transparent to electromagnetic fields, the PMC experiences the magnetic field produced by the two co-phases of the three-phase configuration. Thus, the losses due to the co-phases are included in total loss measured.

The PMC enclosure, together with the two normal conductors, is immersed in a bath of liquid nitrogen, which can be varied in temperature from 64 K to 80 K by control of the bath pressure. The conductor spacing (10 cm nominal) between phases is established by G-10 plates bolted to each end of the PMC enclosure. This spacing is adjustable from 7 to 20 cm.

AC Power Supply

The calorimeter is powered by a variable ac, 60 Hz, three-phase current source with continuously adjustable current values from zero to 2500 A rms. To obtain continuously adjustable currents with as few harmonics as possible, a conventional design for the power supply was chosen with a series connection of a three -phase, variable voltage transformer and a step-down transformer, as shown in Figure 2. The current rating of the secondary winding is 2500 A. The circuit connection for the transformer is delta/wye, and the secondary no load voltage is 3 V. To obtain good control of the current in the superconducting cable, a high short circuit impedance of 12 to 15% was chosen for the transformer. The transformer, which has a power rating of 21.6 kVA, is custom built with a low flux density in the iron to avoid any saturation, which would result in harmonic currents with a frequency of 180 Hz.

Instrumentation and Data Acquisition

To measure the PMC temperature we selected miniature platinum resistance thermometers (1.8-mm in diameter by 5-mm long) which have a precision (random error) of 0.001 K -- equivalent to a precision of 1 mW in the ac loss. These thermometers are

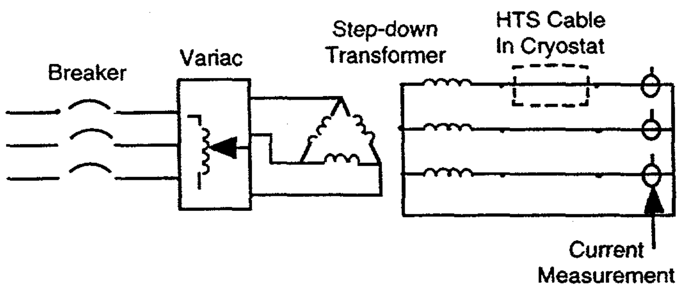

Figure 2. Electrical circuit for HTS cable loss measurement apparatus

positioned at six axial locations to characterize the longitudinal temperature profile. At each of the four innermost axial locations, three thermometers are placed symmetrically around the PMC to determine if there are any azimuthal nonuniformities.

Data are collected with a Macintosh computer using LabVIEW^{TM} software to control the interface with the instruments. The thermometers are interrogated by an HP 3794A integrating voltmeter/multiplexer which has a precision of ± 0.5 μV. All 14 thermometers are interrogated every 2 seconds.

Test Cables

The PMC's are one meter long and composed of two helically-wound layers of HTS tape (19 tapes per layer) wrapped on a 28.6-mm diameter G-10 glass-epoxy mandrel. Each layer is wrapped with an opposite pitch so that the net azimuthal component of current in the cable is zero. The tapes are soldered to copper end connectors. PMC #1 was fabricated without insulation between layers. PMC #2, which is otherwise identical in construction to PMC #1, has a film of Kapton insulation between layers. The dc critical current at 75.3 K is 1410 A for PMC #1 and 1347 A for PMC #2 using the 1 μV/cm criterion.

EXPERIMENTAL RESULTS

Figure 3 illustrates the parabolic temperature profile that develops in the cable due to the ac losses. Measurements for all 14 thermometers are plotted. The near coincidence of the measurements (three each) at the four interior positions indicates that there is little azimuthal variation in the loss -- and by inference in the current.

Comparison of loss measurements with theory requires determination of the critical current and its temperature dependence. Consequently, we measured the I-V characteristics of PMC #2 at several temperatures to establish the critical current as a function of temperature. Figure 4 illustrates a typical I-V measurement. The voltage taps (8 pairs) are 675 mm apart, giving a critical current of 2136 A dc at 65 K using the 1 μV/cm criterion. Fitting the expression $V = C_1 \cdot I^n$ to the I-V curves gives $n = 14 \pm 1$ for the cable. Figure 5 summarizes the critical current measurements for PMC #2.

For measurements on one meter long samples to be valid for application to full scale lines, the current distribution among layers should be similar. In long lines inductive coupling between layers dominates, whereas in short samples contact resistance at the end fittings is important as well. Any current imbalance between the two counter-wound layers of the PMC will generate a corresponding axial magnetic field in its core, since each layer is a low-turn solenoid -- each generating an axial field in the opposite direction. Figure 6 shows the axial magnetic field inside PMC #2 measured with an 800 turn pick-up coil wound on a 1.9-mm diameter mandrel. The conductor temperature is 64 K, so I_c = 2200 A. A field of 1 Oe corresponds to a current imbalance of 25 A. At a total current of 1000 Arms, the imbalance in current is 0.8 percent of the total current. We also observe a variation of magnetic field along the length of the PMC with the minimum occurring at the midpoint. The field near the ends of the PMC is about an order of magnitude greater than that shown in Figure 6.

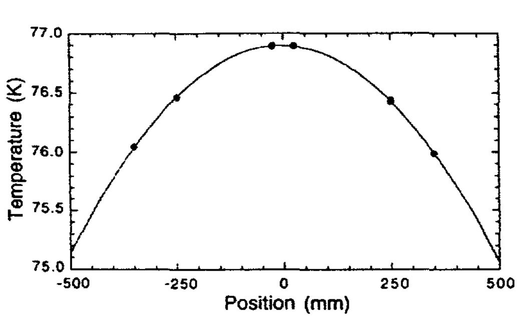

Figure 3. Typical parabolic temperature profile in the PMC. Conditions are: 800 Arms single-phase with 75 K bath.

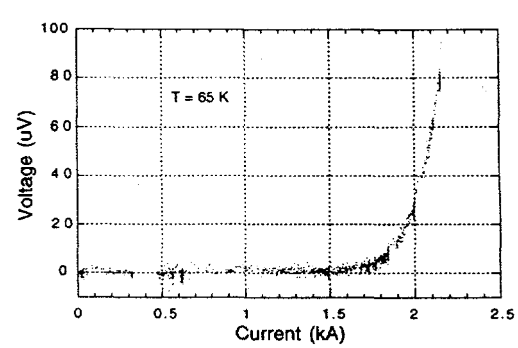

Figure 4. Measured I-V curve for PMC #2 at 65 K.

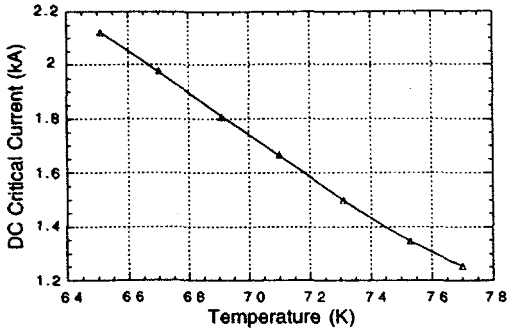

Figure 5. DC critical current of PMC #2 as a function of temperature.

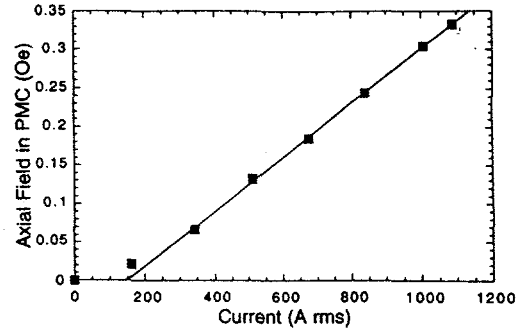

Figure 6. Measured axial magnetic field in core of PMC #2 at the axial midpoint.

Figure 7 compares the ac losses in PMC #1 for three different current configurations. The upper curve is for three-phase, balanced current operation with the conductor centers located at the corners of an equilateral triangle with 10 cm sides. The middle curve is for single-phase operation with the return current path outside the calorimeter about 1 meter away. The lowest curve, designated two-phase, is for ac current flowing in the two normal conductors, but with no current in the PMC, which is disconnected. As is evident from the figure, the balanced three-phase losses are 2-3 times greater than the single-phase losses, indicating a significant interaction between the three phases. The smaller contribution from induced currents provided by the ac magnetic fields from the other two phases does not account for this increase in the absence of ac current in the PMC.

To investigate the effect of the static component of the dc magnetic field on the coupling losses, we energized PMC #1 with ac current and the two normal conductors with dc current so as to impose a dc magnetic field on the PMC. Figure 8 shows the resulting ac loss in the PMC relative to the single-phase losses. The net dc magnetic field imposed on the PMC is 3.5 Oe/100 A current in each normal conductor. For the case where the dc current in the normal conductors is equal to the ac current in the PMC, the increase in the loss is less than 5 percent. In contrast, there is a doubling of the loss for three-phase current (10 cm spacing) relative to single-phase operation. This result indicates that the effect of the magnetic fields from the other two phases in decreasing the effective critical current of the PMC is not responsible for the most of the enhanced losses.

Most of the three-phase ac loss measurements were made with a 10 cm conductor spacing, which is that for a proposed SPTL[7]. To investigate the effect of conductor spacing on the three-phase ac losses, we measured these losses in PMC #2 with a 20 cm conductor spacing as well. Figure 9 summarizes three-phase measurements for 10 and 20 cm spacings, as well as single-phase measurements. Since the single-phase measurements were made with the return path about 100 cm from the PMC, these measurements approximate the limiting case of very large spacing. Figure 10 gives the normalized ac loss (loss/single-phase loss) as a function of $1/(R)^2$ where R is the conductor spacing. The loss is nearly linear versus $1/R^2$, whereas the magnetic field imposed by the other two conductors is proportional to 1/R.

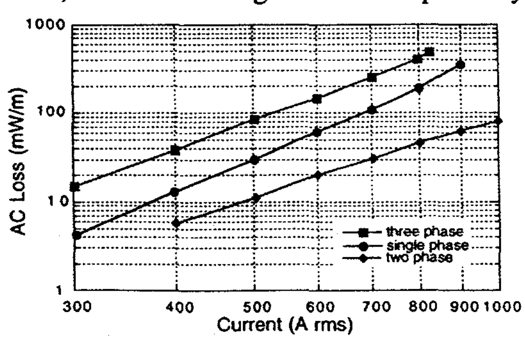

Figure 7. Measured ac loss for PMC #1. Losses are corrected to 76 K.

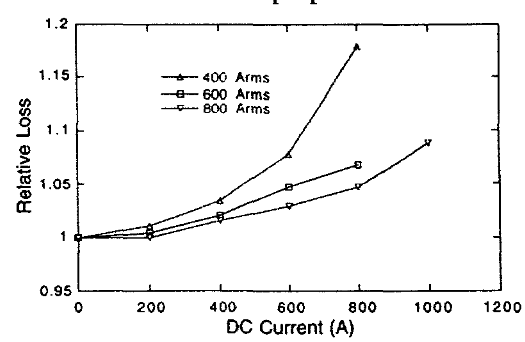

Figure 8. Relative ac loss (loss/single-phase loss) for PMC #1 as a function of dc current per normal phase. The conductor spacing is 10 cm.

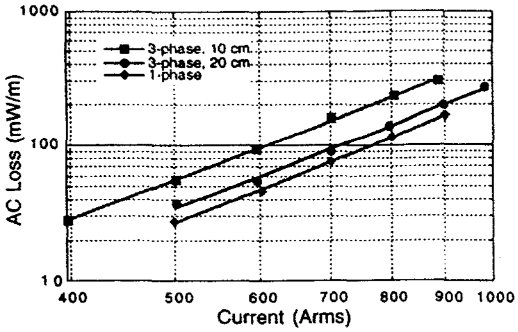

Figure 9. Effect of conductor spacing on three-phase ac losses in PMC #2. Losses are corrected to 70 K.

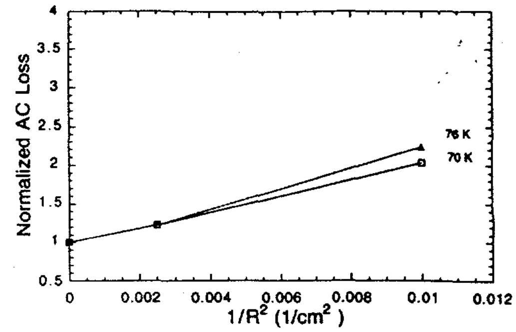

Figure 10. Normalized three-phase ac loss as a function of 1/(conductor spacing)^2 for PMC #2.

Thus the coupling loss is proportional to approximately the square of the magnetic field.

The ac loss depends on the temperature of the conductor through the temperature dependence of the critical current. Figure 11 shows the measured three-phase ac loss in PMC #2 for three different temperatures. During the measurements the liquid nitrogen bath temperature was fixed at 64, 69, or 75.2 K. Because the average cable temperature depends on the magnitude of the current -- due to heating in both the cable and its end connections -- we correct the losses to fixed values of cable temperature using measured values of loss as a function of temperature. As shown in the figure the losses at 65 K and 70 K follow closely the I_0^3 dependence predicted by the critical state models, while the power law at 76 K is 3.54. This change at the higher temperature is not understood. Figure 12 illustrates the measured temperature dependence of the ac loss for three-phase 600 Arms current (10 cm conductor spacing). This dependence of loss on temperature is consistent with the factor of two increase in critical current between 76 K and 64 K shown in Figure 5. The weak temperature dependence of the loss x I_c product shown in the figure indicates a somewhat stronger than $1/I_c$ dependence of the loss.

A previous experimental investigation of multi-strand, multi-layer cables[8] indicated that a significant reduction in ac losses could be accomplished by electrically insulating between the cable layers with a thin dielectric film. For the purpose of investigating this effect, we fabricated PMC #2 with a layer of thin Kapton® film between the two counter-wound layers of HTS tape. Figure 13 compares our measurements on PMC #1 and PMC #2 for 64 K and 75 K bath temperatures. The measurements for the two PMC's nearly coincide, indicating that at least for our two-layer cable configuration, the dielectric layer has no significant effect on the ac losses. The up-turn in the loss curves at higher currents occurs both because the measured losses have not been corrected to a constant cable temperature and because of the peak currents are near the critical current. A similar loss coincidence for the two PMC's is seen at all temperatures -- both in single and three-phase modes-- and is consistent with the nearly equal critical currents of the two cables.

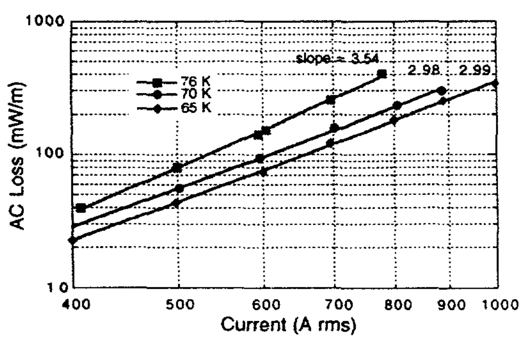

Figure 11. Measured ac loss for PMC #2 for three-phase current and 10 cm conductor spacing. Losses are corrected to fixed values of cable temperature.

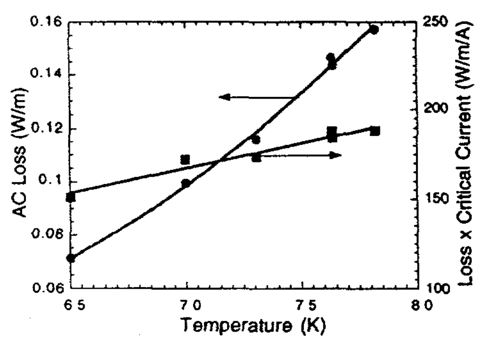

Figure 12. Measured temperature dependence of three-phase ac losses (10 cm conductor spacing) in PMC #1.

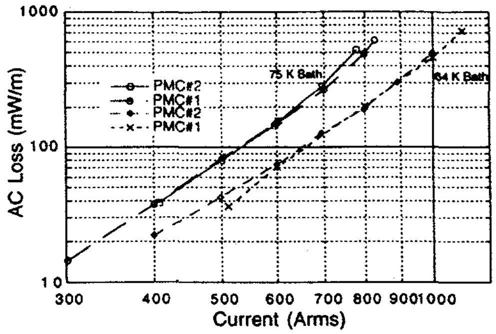

Figure 13. Comparison of three-phase ac losses for PMC #1 and PMC #2. The conductor spacing is 10 cm.

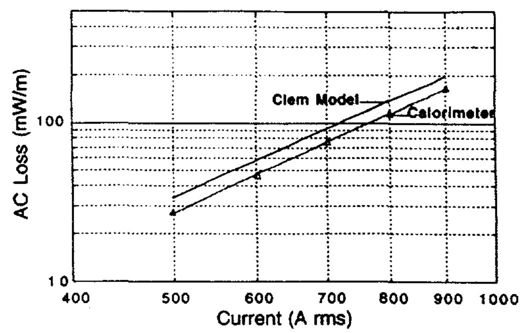

Figure 14. Comparison of measured losses to Clem model for PMC #2 at 70 K.

DISCUSSION

A concern with performing ac loss measurements on short conductor lengths is that the strand contact or termination resistances can be a significant fraction of the ac impedance. Variations in these resistances can modify the current distribution from the limit of a long length conductor for which the inductance of the layers, which scales with length, will clearly dominate the impedance. The small magnitude of the axial magnetic field indicates that current sharing between the two oppositely wound helical layers is nearly equal. The strong inductive coupling between the layers is apparently sufficient to overcome any small variations in the strand termination resistances and force balanced current into the layers. As a consequence, we believe that the current distribution and the ac loss exhibited by these short PMC's are fairly representative of longer length cables. We note that although the mutual inductance between layers within a layer pair is strong, the inductive coupling between distinct layer pairs in a conductor comprised of numerous such pairs is significantly weaker. Short conductors constructed of multiple-layer pairs are more susceptible to having the current distribution altered by inhonogeneities in the termination resistances.

The current flow patterns in the double-helix configuration are quite complex and have been extensively studied during the cable development projects of the 1970's. The mutual inductance between the counter-wound members of a pair tends to equalize their currents and cancel the axial field component in the core as described above. However, the circumferential field on the outside of the inner conductor drives a shielding current on the inside surface of the outer conductor tapes. In such cables composed of mutifilamentary HTS tapes, the filaments will be completely coupled and the losses will be determined by the overall or "engineering" critical current density of the superconducting layer. Recently Clem and Pe[9] have calculated the ac losses for the Bean-Norris model in this double-helix configuration as a function of pitch angle of the helices. They found, for the approximately 30-degree pitch angle appropriate for our cable, a loss that is 0.87 times the loss calculated for an equivalent tubular conductor with the same engineering critical current density. This results in an expression: $P_L(T)= (0.87)4\mu_o f t I_o{}^3/3D_o I_c(T)$, where f is frequency, I_o the current amplitude, $I_c(T)$ the cable critical current at temperature T, t is the superconductor thickness in a single layer and D_o the outside diameter of the cable. Figure 14 shows the comparison of data on PMC #2 at 70 K with the predictions of this model using the measured critical current at this temperature. A similar good agreement is obtained for the losses at 65K using the higher measured $I_c(65K)$. These results indicate good quantitative agreement with critical-state model predictions adapted to the double helix configuration. The temperature dependence of the losses is well accounted for by the measured values of $I_c(T)$.

The comparison of the losses between PMC's 1 and 2 shows no effect of interlayer insulation in disagreement with a previous claim[8]. The previous study found a squared dependence on current for conductors without interlayer insulation and both a dramatic reduction in losses and a cubic dependence on current when insulation was inserted between layers[8]. This behavior indicates losses dominated by ohmic currents flowing between layers. The absence of such interlayer currents in our cables is evident and may be the result of larger interface resistance between layers. On the other hand, these large interlayer currents are not predicted by current theoretical models.

The magnitude of the enhanced losses in the three-phase mode is somewhat surprising given the fact that the imposed ac fields from the other two phases is only ~ 35 Oe rms at the 1000 A rms level. The small magnitude of the effect of dc fields from the other phases rules out the depression of I_c by these fields as an explanation. It is clear that simultaneous presence of large transport currents and an imposed ac field normal to the tape surface is necessary to produce these enhanced losses. In the absence of the transport currents, ac fields of this magnitude would be largely shielded by the outer filaments of the tape. When these outer filaments are saturated by the transport current the depth of penetration of the imposed field will be greatly enhanced, and the current distribution between filaments will be altered. The results on doubling the distance between the conductors shows a quadratic dependence on field amplitude and indicates that these excess losses can be significantly reduced by modest increases in conductor spacing. This three phase effect requires further investigation.

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REFERENCES

1. S. Fleshler, L. T. Cronis, G.E. Conway, A.P. Malozemoff, J. McDonald, T. Pe, J.R, Clem, G, Vellego, and P. Metra, Measurement of the true a.c. power loss of Bi-2223 composite tape using the transparent technique, *Appl. Phys. Let.* 67:3188 (1995)
2. W.R. Wisseman, L.A. Boatner and F.J. Low, Alternating current power losses in superconducting Nb-Zr alloys, *J. Appl. Phys.* 35:2649 (1964)
3. C.H. Meyer,Jr., D.P. Snowder, and S.A. Sterling, Alternating current losses in thin film superconductors: new calorimeter measurement technique, *Rev. Sci. Insstrum.* 42:1584 (1971)
4. R.D. McConnell and P.R. Critchlow, Variable temperature apparatus using a thermal conductivity measurement technique for the determination of superconducting ac power loss, *Rev. Sci. Insstrum.* 46:511 (1975)
5. D. E. Daney, H.J. Boenig and M.P. Maley, Calorimeter for measuring ac losses in HTS cables for power transmission lines, submitted to *Cryogenics*
6. D. E. Daney, H.J. Boenig , M.P. Maley, D.E. McMurry, and B.G. DeBlanc, Ac loss calorimeter for three-phase cable, *IEEE Trans. Appl. Supercond.*, 7:310 (1997)
7. D. Von Dollen, P. Metra and M. Rahman, Design concept of a room temperature dielectric HTS cabel, *Proc. American Power Conference,* 55:1206 (1993)
8. J. Fujikami, N. Saga, K. Ohmatsu, S. Isojima, K. Sato, H. Ishii and T. Hara, Electromagnetic behavior of HTSC cable conductor in ac loading, in: "Adv. Superconductivity VIII ", 2:1319, Springer Verlag, Tokyo (1996)
9. J.R. Clem, presented at AC Loss Workshop organized by J.R. Clem and M. Suenaga, April 3-4, 1997 San Francisco, CA.