AC Loss and Contact Resistance In Copper-Stabilized Nb_3Al Rutherford Cables with and without a Stainless Steel Core

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Abstract-- **Calorimetric measurements of AC loss and hence interstrand contact resistance (ICR), were measured on three samples of Rutherford cable wound with Cu-stabilized jelly-roll type unplated Nb_3Al strand. One of the cable types was furnished with a thin core of AISI 316L stainless steel and the other two were both uncored but insulated in different ways. The cables were subjected to a room-temperature-applied uniaxial pressure of 12 MPa that was maintained during the reaction heat treatment (RHT), then vacuum impregnated with CTD 101 epoxy, and repressurized to 100 MPa during AC-loss measurement. The measurements were performed at 4.2 K in a sinusoidal field of amplitude 400 mT at frequencies of 1 to 90 mHz (no DC-bias field) that was applied both perpendicular and parallel to the face of the cable (the face-on, FO, and edge-on, EO, directions, respectively). For the cored cable the FO-measured effective ICR (FO-ICR), was 5.27 $\mu\Omega$. Those for the uncored cables were less than 0.08 $\mu\Omega$. As shown previously for NbTi- and Nb_3Sn-based Rutherford cables, the FO-ICR can be significantly increased by the insertion of a core, although in this case it is still below the range recommended for accelerator-magnet use. Post-measurement dissection of one of the cables showed that the impregnating resin had permeated between the strands and coated the core with a thin, insulating layer excepting for some sintered points of contact. In the uncored cables the strands were coated with resin except for the points of interstrand contact. It is suggested that in the latter case this tendency for partial coating leads to a processing-sensitive FO-ICR.**

I. INTRODUCTION

The "wind-and-react" method that is generally used in the construction of Nb_3Sn magnets requires the cable to be compacted under moderate pressure (some 5 MPa) and given an extensive reaction heat treatment (RHT) that finishes with a hold for several days at about 650°C. A comparable RHT, but for several tens of hours at 750°C, would be needed for Cu-stabilized Nb_3Al-wound magnets. Such treatments provide ample opportunity for Cu-stabilized strands to sinter together thereby drastically lowering the interstrand contact resistance, ICR, and increasing the coupling loss [1-6]. A low ICR of 1 or 2 $\mu\Omega$s would favor current sharing and hence cable stability. On the other hand, a high value of ICR is needed t suppress coupling currents. As a compromise betwee these conflicting requirements in the case, for example, of Rutherford-type LHC cable minimum ICR values withi the range of ~15±5 $\mu\Omega$ [7] to ~30 $\mu\Omega$ [8] have bee recommended.

To suppress interstrand sintering, prereacted strands hav been plated with Cr [9], or coated with a syntheti lubricating oil (Mobil 1) [10,11] which decomposes durin RHT to leave behind an adherent deposit of C. Today suc coated strands find use only in cable-in-conduit conductor [9,11]. The Nb_3Sn Rutherford cables used in the two mos recent high-field dipole magnets (the University o Twente's 11 T, 4.2 K, dipole [12], and Lawrence Berkele National Laboratory's 12.8 T, 4.3 K, dipole [13]) were bot wound with bare Cu-stabilized strand. The former wa ramp-rate sensitive and the latter was not. Some cabl conditions and heat-treatment variations may be responsibl fir this. But rather than let chance dictate ultimate ramp-rat sensitivity it might be prudent to introduce a pre-engineere ICR. Then with Rutherford cables, to satisfy the conflictin requirements of current sharing and low coupling loss it i desirable to exert independent control over the "side-by-side" and "crossover" ICR components. For this reason rather than coat the strand it is better to separate the "upper" and "lower" layers of the cable with an insulating o metallic core of either fixed [2-5] or variable width [14] As a contribution to the development of advanced cable for high-field-magnet applications the effectiveness of core in the controlled suppression of coupling loss i Bi:2212/Ag [15,16] and Nb_3Sn cables [17,18] has recently been studied; and for comparison with the results of th latter research, the following AC loss measurements wer undertaken on some cored and uncored cables wound with Cu-stabilized Nb_3Al strand.

II. EXPERIMENTAL

A. Cable Preparation

Rutherford cables were wound at Lawrence Berkeley National Laboratory (LBNL) from Nb_3Al-precursor strand,

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Manuscript received September 27, 1999

This research was supported by the U.S. Department of Energy, Division of High Energy Physics under SBIR Grant No. DE-FG02-97ER82460.

1051-8223/00$10.00 © 2000 IEEE

a 96-filament "jelly-roll" type manufactured by Sumitomo Electric Industries Ltd. During the cabling a stainless steel strip (AISI 316L, 9.5 mm x 25 μm) was fed along a slot in the cabling mandrel in order to furnish 6 m of the 19 m that were wound with a stainless steel (SS) core. Three cable packs were prepared for reaction-heat-treatment (RHT) and measurement. Following the LBNL procedure, samples with and without cores (**NA-C** and **NA-NC**, respectively) were insulated with S-glass braid that had been first cleaned by vacuum heat treatment and then impregnated with an easily removable sizing agent (palmitic acid, M.P. 215°C, in ethyl alcohol) to enable it to be handled. Then by way of an alternative insulation procedure, lengths of uncored cable were covered top and bottom with strips of pre-baked mica and then wrapped (no gaps) with sized S-glass ribbon -- sample **NA-NC/M**. The insulated cable segments, about 53 cm in length were mounted 6-high between the plates (about 41 x 8 cm) of an SS clamping fixture and subjected to a pressure of about 12 MPa, applied by an Instron machine and retained by two rows of 11 through-bolts. RHT of the mounted samples, which took place in flowing Ar, consisted of a slow ramp to about 750°C followed by a 50 h hold at that temperature. After RHT and cool-down the samples were vacuum-impregnated with type CTD 101 resin and air-oven cured. The impregnated samples were then trimmed to a length of 41 cm for measurement, and the 6-cm long residual pieces (part pressurized and part clamped together but unpressurized) were set aside for visual and metallographic examination.

B. AC Loss Measurement

Calorimetric measurements of AC loss were made at the University of Twente by the He-boil-off method [19]. The straight cable sample was mounted inside a single-wall liquid-He-filled calorimeter which itself was immersed in liquid He. The He boiloff rate was measured by calibrated gas flow meters. The AISI 316 SS mounting fixture, 40 cm long, consisted of two halves. Two rows of 18 bolts enabled a pressure of 100 MPa (in this case) to be applied across the broad cable faces. AC loss in the clamped sample was generated by an alternating dipolar fields of amplitude 400 mT and frequencies, *f*, of 1 to 90 mHz that were applied either perpendicular to or parallel to the broad cable faces -- the face-on (FO) and edge-on (EO) orientations, respectively. Background losses (addenda) were separately determined.

III. THEORETICAL

Based on equations listed by Sytnikov et al. [20] for power loss due to interstrand coupling per unit length of a Rutherford cable exposed to a ramping magnetic field B (amplitude B_m) in the FO (⊥) and EO (//) directions, respectively, are the following expressions for energy loss per cycle per m^3 of outside cable dimensions (width w and thickness t)

$$Q_\perp = \frac{4}{3}\left(\frac{w}{t}\right) L_p B_m \left(\frac{dB}{dt}\right)\left(\frac{N^2}{20 R_\perp} + \frac{1}{N R_{//}}\right) \qquad (1)$$

$$Q_{//} = \left(\frac{t}{w}\right) L_p B_m \left(\frac{dB}{dt}\right)\left(\frac{1}{N R_{//}}\right) \qquad (2)$$

The units of $Q_\perp$ (in general Q_e) are tesla, meter, second; N is the number of strands and L_p is 1/2 the transposition pitch of the winding. In (1) the first term describes the contributions of diamond-shaped coupling current paths (with which $R_\perp$, the resistance of each interstrand crossover contact is associated); the second term describes loss stemming from currents that utilize side-by-side contact (of edge-to-edge resistance $R_{//}$ between adjacent pairs of strands. In principle the ICRs $R_\perp$ and $R_{//}$ can be obtained from the reciprocal slopes of the Q_e versus f lines after making the dB/dt-to-f transformation as discussed in [18].

Having made the conversion, for cable-to-cable comparison it is then useful to represent the effects of both types of contact by an "effective ICR", $R_{\perp eff.}$ defined by

$$Q_\perp = \frac{4}{15}\left(\frac{w}{t}\right) L_p B_m{}^2 N^2 . \frac{f}{R_{\perp,eff.}} \qquad (3)$$

in which $R_{\perp,eff.}$ will generally be a combination of $R_\perp$ and $R_{//}$. The above equation is valid for a triangle wave, in order to apply it to the sine wave profiles used in this work we need to multiply the RHS by $\pi^2/8$.

IV. RESULTS

Fig. 1 depicts the total FO losses vs frequency for all three cables. Also shown for reference is the EO loss for **NA-C**. The uncored cables **NA-NC** and **NA-NC/M** both exhibit very high losses and hence low critical frequencies, f_c (corresponding to $Q_{tot,max}$) and low ICRs. At very low frequencies (below the range of measurement and less than 1 mHz for **NA-NC**) all three FO Q_{tot} curves should meet at $f = 0$. According to (3) the reciprocal slopes of $Q_{tot}(f)$ for $f < f_c$ (implicit for **NA-NC** and **NA-NC/M**) are proportional to the respective $R_{\perp,eff}$s which have clearly been substantially reduced by the inclusion of the SS core.

Fig. 2 depicts the total EO losses vs frequency for all three cables, with the FO response of **NA-C** included for reference. The difference between the "hysteretic" intercepts probably stems from the fact that the angle between the strands and the field direction is slightly different for the FO and EO orientations of the cable.

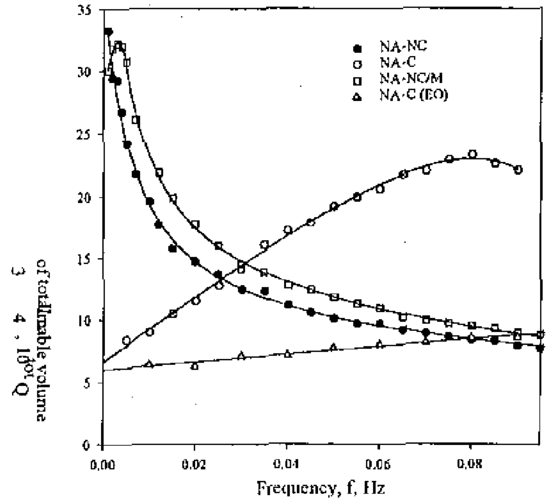

Fig. 1. Q_{tot} vs f for all cables in FO orientation with EO reference

V. DISCUSSION

Following previous studies of cored cables for which it has been possible to assume that $R_\perp = \infty$ [14,17,18], it might be concluded that the FO loss in **NA-C** is again due to side-by-side strand contact (of resistance $R_{//}$). But before proceeding to the same conclusion in this case it is necessary to estimate the magnitude of the intrastrand eddy current contribution to Q_{tot}, particularly its FO value. This we do by using Carr's expression for eddy-current loss [21], viz. $Q_e = L_p^2 B_m^2 f/2\rho_\perp$, and substituting L_p = 30 mm, B_m = 400 mT, and $\rho_\perp$ = 18 nΩcm (based on a Sumitomo quoted RRR of ≈ 175 and a λ of 0.5). Finally, after taking into account the strand-fill factor of the cable (88.2%) and renormalizing the loss in the filamentary region of the strand (78.4% of the strand) to the entire cable volume, we conclude that Q_e/f = 27 x 10^4 Js/m^3 of cable volume. This accounts for the entire Q_{tot} seen in Fig. 2, from which we conclude that EO coupling loss is immeasurably small in our experiment within the implied approximation $1/R_{//} \approx 0$. Loss slope, loss maximums, critical frequencies and resistivity values are given in Table I.

In the absence of observable EO coupling loss we must conclude that in this set of cables the FO loss is due to some form of interstrand crossover contact. This is clearly very strong in the uncored cables but much less so in the cored ones. In previous studies of Nb_3Sn cables that had received an RHT that concluded with 96 h/660°C the SS core seemed to have been fully effective in suppressing interstrand crossover contact. The fact that some kind of crossover contact is entirely responsible for the FO loss in **NA-C** suggests that is has been developed under the more aggressive RHT conditions required in Nb_3Al processing, viz. 50h/750°C. To proceed further required a detailed examination of the structures of the RHTed cables.

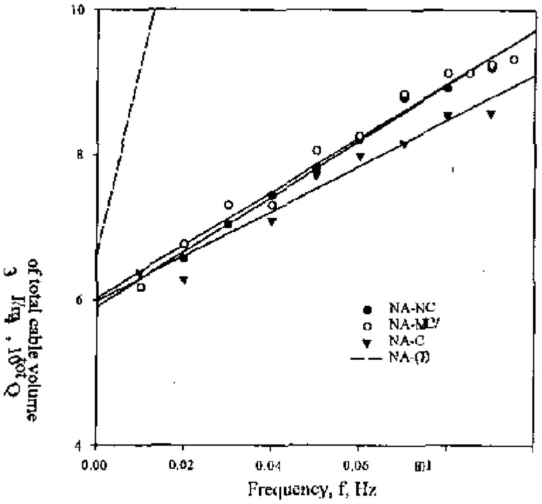

Fig 2. Q_{tot} vs f for all cables in the EO orientation with FO reference.

One of the first things that was observed was the omnipresence of epoxy (it is well known that epoxy in fully potted Nb_3Sn systems wicks up the glass sheaths and flows throughout the system [22]). In this case the epoxy was present throughout the pack, including the inside of the cable, in between the strands.

We then noticed that at the cable ends, in the uncored cables, where almost no pressure had been applied, the epoxy layer was like a uniform sheet between the upper and lower cable layers. No porosity was seen, but just inside the pressurized zone of this uncored cable, the epoxy layer had many holes, forming a kind of "sea" of epoxy surrounding "islands" of contact corresponding to the diamond current paths. A portion from the center of the pack was observed to be the same.

Disassembly of the cored cables revealed that in the unpressurized zone, the epoxy again formed a layer, this time attached to the SS strip. Within the pressurized zone, however, the islands of strand-to-strand sintered regions were of course non-existent because of the intervening core. There were, however, some regions where the Cu strand surfaces seemed to have sintered to the SS strip. These regions would seem to be the ones responsible for the FO loss.

In mounted and polished cross sections of the cored cable it was noted that the SS strip had much less metal-to-metal sintering than was the case for the uncored cables. Also, very little side-to-side contact was observed throughout the cable. Only near the cable edges, either right at the edges, or in the form of a top-to-bottom layer contact outside of the core region, was strand sintering seen (in uncored cables there was of course very much top-to-bottom sintering).

We interpret the above results as follows. Unless somehow inhibited, the epoxy tended to coat all surfaces, presumably leading to high contact values. However, in the portion of the cables reacted under pressure, crossover contacting points tended to sinter together, preventing epoxy from flowing in and coating them during subsequent low pressure impregnation. The presence of a core prevented direct strand-to-strand sintering and to that extent raised the ICR. However, as a result of the relatively high temperature of RHT (750°C), some *indirect* strand-to-strand sintering was noted; in this case via the core material. It was this contact (rather than the expected side-to-side-only contact) that was responsible for the observed coupling in cable **NA-C.**

TABLE I. CABLE PARAMETERS

CABLE	NA-NC	NA-NC/M	NA-C
f_c, mHz	< 1	3.2	80
FO Slope, 10^4 Js/m^3	27,253	23,972	361
EO Slope, 10^4 Js/m^3	38.2	36.9	31.2
$R_{\perp eff}$, μΩ	0.07	0.08	5.27
Q_{max}, FO, 10^4 Js/m^3 cable	> 33	32.35	22.9
w x t, mm	12.4 x 1.46	12.4 x 1.46	12.4 x 1.49

VI. CONCLUSIONS

Calorimetric loss measurements on Nb_3Al cables and the ICR values extracted from them show that those with SS cores had much lower levels of loss than cables without cores. $R_{\perp eff}$ values for cored cables were 5.27 μΩ, while those for uncored cables were 0.07 and 0.08 μΩ. The presence of mica seemed to have little effect on the results. In general, the impregnation epoxy tended to permeate the whole cable. The level of epoxy inside the cable was lessened in the regions of the cable which were reacted at high temperatures and under pressure because the epoxy was excluded from these already-sintered regions. Cores significantly reduced the loss, either directly by their presence in the current path, or by retarding sintering, and thus allowing more uniform epoxy layers to form. The cores increased $R_{\perp eff}$ by at least 50 times, however, the resulting value of 5.27 μΩ is somewhat below the expected target of 15-30μΩ [7,8]. In future studies we expect to be able to increase $R_{\perp eff}$ by selecting alternative core materials and/or by lowering the pressure to which the cable is exposed during RHT.

ACKNOWLEDGEMENT

The help of H. Higley (cable winding) and R. Hannaford (sample potting) both of LBNL is gratefully acknowledged.

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