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ULTRA HIGH-CURRENT SUPERCONDUCTING CABLES FOR A 2.2-TESLA, 300-KILOJOULE ENERGY STORAGE MAGNET††

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ABSTRACT

We have built and tested two types of superconducting cables to be used in pulsed energy storage magnets for the LASL Magnetic Energy Transfer and Storage (METS) program. These 2.2-T, 300-kJ magnets are to operate at 10 to 12 kA with a safety factor in critical current of about 50% at 10 kA. The conductor must exhibit low losses in addition to being stable. Magnetic Corporation of America (MCA) designed a flat conductor using 1224 copper-matrix, monofilament wires combined in two stages of cabling followed by two stages of flat braiding. Two of these conductors were constructed, one with wire already on hand and the second using wire made specifically for this application. Intermagnetics General Corporation (IGC) designed two rectangular conductors using 315 and 319 mixed-matrix multifilament wires combined in three stages of cabling followed by compaction in a Turk's head. The maximum transport current capabilities (I_T) of these cables were measured in hairpin shaped samples with the straight section under test in perpendicularly applied fields. The measured results at 2.5 T for the two MCA cables were 11.7 kA and 15.4 kA, and for the IGC cables were 18.2 kA and 19.3 kA (extrapolated). In addition, samples of the compacted and uncompacted major strands from the IGC cables were tested. The results of these measurements are compared with values of I_T calculated from the single-wire critical currents taking into account the adjacent conductor fields and the cable self-fields. Several causes of degradation of I_T in the compacted cable are discussed including those due to experimental factors.

I. INTRODUCTION

The Los Alamos Scientific Laboratory is conducting a program to develop pulsed discharge, magnetic energy transfer and storage (METS) systems for fusion reactors. One type of storage magnet was to operate at 2.2 Tesla with a stored energy of 300 kJ. The operating current was to be 10 to 12 kA with a critical current safety factor of about 50% at 10 kA. The magnet is to be charged in 10 s and discharged in 2 ms. The conductor must exhibit low losses in addition to being stable. The cables discussed here were designed by Magnetic Corporation of America (MCA) and by Intermagnetics General Corporation (IGC).

MCA designed a flat braid using copper-matrix monofilament wires, and IGC built two rectangular, compacted cables with 315 and 319 strands of mixed matrix, multifilamentary wire.

The maximum transport current capabilities (I_T) of these cables were measured in transverse magnetic fields to 4 T. In addition, samples of the major strands from the compacted and uncompacted IGC cables were tested. Single-wire short sample critical currents were measured for the MCA and IGC production wires. These data are used to calculate I_T for the production cables and the

results are compared with the experimental data.

II. CONDUCTOR DESIGN

The conductors for the 300-kJ METS magnet are required to carry a transport current of 10 kA at 2.2 T with a safety factor in transport current of 50%. In addition to being stable, the conductors must exhibit low losses when the magnet is discharged in millisecond times. Two approaches were considered for the design of a conductor to meet the requirements.

MCA Braid

The design by MCA is similar to one described previously.¹ The conductor is a flat braid using 1224 insulated monofilament copper-matrix wires combined in two stages of cabling followed by two stages of flat braiding. The first stage of cabling yielded a 3-wire cable, and the second stage combined three of the first stage cables into larger cables. Eight of the second stage cables were flat braided and seventeen of these braids were then combined into a final flat braid. Two of these 1224-wire braids were made. The first was made with wire already available (Cu:NbTi::1.4:1, 0.114 mm diam) and was used to check assembly procedures. The second was made with wire manufactured specifically for this application (Cu:NbTi::1.58:1, 0.127 mm diam). The final conductor was a $3 \times 3 \times 8 \times 17$ braid with a 35.5 cm transposition length and was 25-mm wide by 3.2-mm thick.

IGC Cable

The IGC conductors were rectangular cables with 315 and 319 strands of insulated, mixed-matrix, multifilamentary wire with matrix ratios CuNi:Cu:NbTi::1.5:2:1 and diameters of 0.419 mm and 0.389 mm respectively. The wire was twisted with a pitch of 3.4 ± 0.2 mm. The wire for both cables was first combined into a seven-wire primary strand. For the prototype cable, five of these primary strands were cabled together to form the main strands, of which, nine were combined together to form the final $7 \times 5 \times 9$ cable which was then compacted in a Turk's head. The cable pitch of the final conductor was 23 cm and the cross section was 5.5 mm by 15.2 mm. The production cable consisted of eleven main strands. Each main strand was formed by cabling four primary strands around a single central wire. The final conductor was then a $(1 + 7 \times 4) \times 11$ cable, which was compacted in a Turk's head and had a cable pitch of 10.6 cm and dimensions of 5.5 mm by 17.5 mm.

III. EXPERIMENTAL DETAILS

The maximum transport current capabilities (I_T) of the superconducting cables were measured in fields to 4 T. The two MCA braids and both of the IGC cables were tested. In addition, main strands from the IGC compacted and uncompacted prototype cable and an uncompacted main strand from the material used for the production cable were tested.

The samples were hairpin shaped and were wrapped with fiberglass cloth and vacuum impregnated with epoxy in a reusable mold clamping fixture. This potting procedure still allowed for some mechanical motion of the individual wires in most cases. The distances between the voltage taps and the solder connections to the flux pump were 6 cm for the MCA braids and were 10 cm and 21 cm for the IGC prototype and production cables respectively. The corresponding lengths of the sample in the test field were 59 cm for the MCA conductor and 51 cm

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and 60 cm respectively for the IGC conductors.

The apparatus used for these measurements is similar to that described elsewhere^{2,3} and consists of a one-shot flux pump and a dipole magnet. Measurements were taken by recording the voltage across the sample as a function of the current through the sample. We chose I_c to be that current at which the electric field along the sample increases to 4 to 5 $\mu\text{V}/\text{m}$. This electric field value is set mainly by experimental considerations and corresponds to a potential of 2.5 μV across the sample. For the range of currents measured here, these conditions correspond to superconductor resistivities of approximately 1 $\text{p}\Omega\text{-cm}$.

Current sharing was not observed in the MCA braid and none should be expected to be seen easily. There are several reasons for this: (1) monofilament wires have a V-I characteristic curve which rises very steeply as the current approaches I_c , (2) the low copper ratios of 1.4:1 and 1.58:1 would cause the voltage rise to be very steep, and (3) the strands are all insulated from each other except at joints and voltage taps and current cannot easily transfer from one strand to another. Because of this rapid increase in voltage and the consequent heating, all runs terminated in a quench of the samples, and the data are the highest currents at which the sample quenched. The currents thus obtained may not be true critical currents but do represent a lower limit for I_c .

IV. EXPERIMENTAL RESULTS

Transport current data for the large superconducting cables are shown in Fig. 1. The MCA braids were

Fig. 1. Transport current data for the large superconducting cables. The measurements on the 1224-wire MCA braids are the maximum quenching currents. The data on the IGC 315 wire prototype and 319 wire production cables are the currents at which the electric field developed along the length of the cable increased to 4 to 5 $\mu\text{V}/\text{m}$. For the range of currents measured, this corresponds to cable resistivities of approximately 1 pico-ohm-centimeter. All cables exhibited mechanical motion and training.

oriented such that the applied magnetic field was perpendicular to the narrow edge of the cable. Other measurements on these braids show a negligible anisotropy with respect to the orientation of the field. With the hairpin shaped sample in this orientation, the field generated at one leg of the braid by the current in the other leg of the braid will be either parallel or antiparallel to the external field. This adjacent conductor field (ACF) will cause the I_c -B curve to be split into two separate curves, one for each direction of transport current.³ The true I_c curve falls between the two sets of data points for each braid sample. The tests indicate that there were small amplitude mechanical motions within the braid strands, some of which resulted in a quench of the sample. The data points thus represent a lower limit on the true I_c -B curves which could have somewhat different slopes from those indicated by the data.

The IGC cables were oriented so that the ACF was primarily perpendicular to the external field. In this configuration the external field is also perpendicular to the broad face of the cable. The measurements on the production cable show a much steeper slope than those on the prototype cable. This is probably due to experimental considerations which cause the data at higher currents to appear degraded. This will be discussed further in the next section.

Figure 2 shows data taken on the major strands from the IGC cables. Five of the 35-wire major strands from the compacted prototype cable were tested and of these only one appeared to be degraded with respect to the uncompacted major strands. This strand had several broken wires and many other wires which showed severe damage due to the compaction process. The remaining main strands from the compacted prototype cable contained very few damaged or broken wires. Most of the I_c values from the prototype main strands are within $\pm 6.8\%$ of each other.

Data are also shown for a section of 29-wire major strand used for the production cable.

Fig. 2. Transport current data for the major strands from the IGC cables. The prototype strands contained 35 wires and the production strand contained 29 wires. All nine strands from the uncompacted prototype cable and five of the strands from the compacted prototype cable were tested. The data for all but one of these strands lie in the region indicated. One strand from the compacted prototype showed some degradation and had several severely damaged or broken wires.

Critical current data taken on a section of production wire for the IGC cable are shown in Fig. 3. These data are based on an increase of the resistivity of the whole wire to a value of 1 pΩ-cm.

Fig. 3. Critical current data for the IGC production wire. These data are based on a whole-wire resistivity of 1 pico-ohm-centimeter.

Figure 4 contains I_c data for the MCA monofilament production wire. This wire would quench at very low values of whole-wire resistivity and therefore the I_c values are based on a resistivity of 0.1 pΩ-cm instead of the usual 1 pΩ-cm. At 2.0 T the wire quenched just before the resistivity actually reached the critical value and that data point was obtained by extending the voltage-current curve. The error introduced in this way is a fraction of a percent. At lower fields the wire quenched at progressively lower resistivities.

Fig. 4. Critical current data for one of the MCA monofilament production wires. These data are based on a whole-wire resistivity of 0.1 pico-ohm-centimeters. Below 2.0 Tesla the wire sample quenches before the resistivity increases to 0.1 pΩ-cm. This sample of the wire appears to have an unusually high critical current density. For example at 3.0 T, $j_c = 2.9 \times 10^5$ A/cm², whereas a fairly good wire is approximately 2.5×10^5 A/cm² or 15% lower.

The sample of wire appears to be exceptional with an unusually high critical current density. A good wire normally would have $j_c = 2.5 \times 10^5$ A/cm² at 3 T which is 15% lower than the value for the present sample. It is known that the matrix ratio of this type of wire can vary by as much as 33% which gives a 20% variation in the cross section area of the NbTi filament. This is probably responsible for the very high values for I_c of the sample tested. In the discussions to follow we shall use a value of 85% of this sample's I_c for the production wire I_c .

V. DISCUSSION

If a long straight cable is isolated from all external fields (B), each strand will still experience an applied field due to the transport current in all the other strands in the cable. This field is the self field of the cable (SF) and causes a decrease of the cable transport current from the value obtained by simply multiplying the single wire I_c at B by the number of strands in the cable. The magnitude of the vector sum of B, SF, and ACF must be calculated to relate the single wire I_c to the cable I_c .

In the cables studied here the wires are almost completely transposed and each wire experiences all local values of the magnetic field within the cable. Under these conditions, all strands will carry approximately equal currents and it is only necessary to calculate the maximum field in the cable to determine I_c . Since the SF is larger than the ACF, the strongest field will be near the cable surface. When the applied field B is stronger than the ACF, the maximum field occurs near to the point on the cable surface at which B and SF are parallel. In this situation, the highest field point need not be located exactly, but instead the total field at certain selected points may be calculated to approximate the actual field. The resulting error will usually be insignificant when the critical currents are determined.

Fig. 5. Arrangement of the IGC superconducting cables for the transport current measurements showing the adjacent conductor field (ACF) and the cable self-field (SF) near the location of the highest field during a test. Shown are dimensions for the IGC production cable. The experimental arrangement for the MCA braids differed only in that B is oriented in the horizontal direction. The maximum field point is near a line passing through the centers of the cables and is between the cables when the ACF aids B and on the outer side of the cable when the ACF opposes B. The symbols at the conductor centers indicate the direction of current flow.

The total field can be calculated with reference to Fig. 5 which shows, in cross section, the arrangement of the rectangular IGC samples in the applied field. The round major strands are arranged in the same manner. In the MCA sample tests the field would be drawn horizontally instead of vertically.

One could solve the simultaneous equations for the total field and the single wire critical current to obtain the cable transport current. The solution is relatively simple for the MCA sample field orientation, however, in the case of the IGC arrangement this procedure leads to a quartic equation, which is difficult to solve analytically but can be solved numerically. An alternate approximation which is used here, is to use the measured I_c to calculate the ACF and the SF and thence the single wire I_c .

The values of I_c at 2.5 Tesla calculated for the MCA and IGC production cables are 15.5 kA and 22.1 kA respectively. The value calculated for the major strand of the IGC production cable is 2.10 kA. The corresponding experimental values for I_c at 2.5 T are, from Figs. 1 and 2, 15.4 kA, 19.3 kA, and 2.45 kA respectively.

The agreement between calculated and measured values is quite good for the MCA braid. The IGC cable measurement is 13% lower than expected and the measurement on the major strand appears to show a value 17% higher than the calculated value.

Critical current densities as high as those apparently exhibited by the MCA monofilament wire and the wires in the IGC production major strand are rather unusual and we are making further tests to determine whether or not these j_c 's are real.

One of the reasons that the measured I_c of the IGC cable is lower than the calculated value is the possibility that some of the wires were broken or otherwise degraded during compaction in the Turk's head. Inspection of the individual wires in the production cable during the insulation-stripping operation showed that none of the wires were broken in either of two 1-1/2 foot sections of the cable. Some of the wires had rather sharp bends in them, but our experience with NbTi is that these would not cause any significant degradation in a good quality wire. The prototype cable showed a 14% degradation from its calculated I_c , but it contained a large number of broken wires. These wires were rather brittle and of poor mechanical quality to begin with and many of them had nearly cut through by the compaction process.

Given a situation in which wire breaks occur at random throughout the length of a cable, one would find, through the Poisson distribution, that the number of undamaged wires in that cable and thus I_c would decrease exponentially with the length of the sample measured. The obvious inference here is that a cable of this type of any reasonable length wound into a magnet will fail to exhibit superconducting behavior and may even exhibit open circuit characteristics.

Fortunately, it is possible to manufacture cables which do not contain these randomly distributed wire-breaks, as shown by the above-mentioned inspection of the IGC production cable.

There are two main sources of experimental error in the measurements on the IGC cables. The high resistivity of the wire matrix makes it necessary to use a longer solder joint between the cable and the flux pump than would be needed for copper-matrix wire. The lengths of the connections to the prototype and production cables were 10 cm and 15 cm respectively. Even though the cable ends were each wrapped with copper matrix superconductor to spread the joint to all sides of the cable, it is possible that there was still enough heating to cause a 5% or 10% reduction in the measured current.

The inclusion of the "commutation" voltage from the solder joints in the voltage tap signal could cause an apparent reduction of 2% to 10% in the measured critical

current. The tap-to-joint distances were 10 cm and 21 cm for the IGC prototype and production cables respectively. Furthermore, the section of prototype cable between the tap and the joint was tinned whereas in the production cable these sections were left untinned. Tinning this portion of a conductor with a high resistivity matrix has the effect of spreading the commutation region to the voltage taps. It is not possible, with our present apparatus, to increase this spacing beyond 25 cm.

VI. CONCLUSION

We have designed, built and tested two types of high current superconducting cables for a 2.2-T, 300-kJ magnetic energy transfer and storage (METS) coil. Maximum transport currents (I_c) of the cables were measured in perpendicularly applied magnetic field. These experimental values were compared to the values calculated from the short sample critical current (I_c) data for single wires. The measured I_c for the copper-matrix MCA braid was found to agree with the calculated value. The mixed matrix IGC cable appears to be degraded when I_c is compared to the calculated values. The probable causes for this degradation are: heating of the sample due to inadequate solder joints between the cable and the flux pump, inclusion of the "commutation" voltage from the solder joints into the signal from the voltage taps, and broken or damaged wires caused by the compaction of the cable. Inspection of the IGC production cable shows that the wires are basically sound and that there is no gross wire damage. The most difficult problems expected to be encountered in the application of these cables is in providing adequate solder joints to CuNi matrix or mixed matrix cables, the thorough stripping the insulation from all wires within the cable, and the prevention of mechanical motion of the strands or wires within the cable.

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