AC loss properties of single-layer CORC cables

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Abstract. In this work, an experimental and theoretical study of the transport and magnetization AC losses of a single layer ReBCO cable is presented. Examined cable consisted of five coated conductor tapes wound in parallel helically on the round core with 40 mm pitch and six full transposition resulting in the 24 cm total cable length. Transport currents up to 600 A amplitude with frequencies 36 Hz and 72 Hz were used in the transport loss measurement. AC fields up to 50 mT were applied during the magnetization loss measurement at 36 Hz and 72 Hz, respectively. Very good agreement between the experimental results and the simulations for magnetization loss was achieved. However, the experimental results for transport loss are markedly greater than the prediction reached from simulation. Nevertheless, they are lower than the transport AC loss theoretically assumed for a straight superconducting tape with the identical critical current.

1. Introduction
Helical layout of the 2nd generation of high-temperature superconducting coated conductor (CC) tapes on a flexible round core (called CORC cables - Coated Conductors on Round Core) represents a promising option for achieving round conductor elements suitable for the winding of magnet coils. The advantage is its manufacturing by classical cabling procedures. The main drawback is rather low fill factor. However, it can be improved by increasing the number of layers. In this way also the critical current can be enhanced. For a pulse or AC magnets or power transformers the energy dissipation resulting in AC loss is of prime importance. The CORC cables [1-3] may be good alternative to Roebel cables [4-6] for this kind of applications.

2. Cable model and experiments
2.1. Cable model
In this work we present the study of AC losses of single-layer CORC cable (figure 1), consisting in five CC tapes. The summary of cable design parameters is shown in table 1.

Figure 1. The CORC cable from five CC tapes.
Table 1. Parameters of the CORC cable.

| Parameter                                      | Value                                                                 |
|------------------------------------------------|----------------------------------------------------------------------|
| CC tape                                        | *SuperPower®, SCS4050*                                               |
| Critical current of one tape (77 K, self-field) | 113 A                                                               |
| Length of one cable pitch                      | 4 cm                                                                |
| Number of transpositions                       | 6                                                                   |
| Cable length including current terminals        | 30 cm                                                                |
| Core material and dimensions                   | fiberglass former, φ 8 mm                                            |
| Current terminals                              | tapes soldered at the cable ends                                    |

2.2. Transport loss measurement

The cable transport loss was measured by the standard lock-in technique at transport current increasing with defined steps. Sinusoidal transport current with amplitude in the range 60 - 600 A and frequencies 36 Hz and 72 Hz was used. Cable was cooled by liquid nitrogen to 77K. To avoid the ambiguity of the voltage taps placing directly on some of the CC tapes, they were located on the current terminals – figure 2. In such configuration the voltage drop on resistive joints, $U_R$, adds to the cable loss voltage, $U_{SC}$, resulting in $U_{TOT} = U_{SC} + U_R$ measured in experiment. The joint resistance (about $2 \times 10^{-7} \Omega$) was estimated from $U_{TOT}$ measurement at low AC currents (from 1 to 5 A) when $U_{SC}$ is negligible. It was afterwards used to obtain $U_{SC}$ from $U_{TOT}$ by subtracting $U_R$ during the data processing.

2.3. Magnetization loss measurement

The calibration free method [7] combined with the lock-in technique was utilized for the magnetization loss measurement. Briefly, two identical Cu magnets generating AC magnetic field and each involving pick-up coils form the base of this method. If no sample is placed in one of the magnets, a voltage equilibrium exists on pick-up coils connected in series with opposite polarity. When the sample is located in one of the magnets, the voltage proportional to the sample loss will appear.

Figure 2. Experimental setup for transport measurement.

Figure 3. Experimental setup for magnetization measurement.

Figure 4. Magnetization AC losses in single CC tape, measured on short sample and long sample (with respect to magnet bore).
The cable magnetization loss was measured at AC magnetic field increasing with defined steps. The frequencies of applied magnetic field were 36 Hz and 72 Hz, respectively. The length of the cable was longer than the magnet bore to exclude any influence of the massive normal metal current terminals in which eddy currents could appear – see figure 3. In this condition the measured AC magnetization loss represents only the dissipation generated in the part of cable inside the magnet bore. This approach provides relevant data because the magnetic field outside the bore is much lower. Such conclusion was experimentally tested by the magnetization loss measurement of two samples from a straight CC tape. “Short” sample’s length corresponded to the bore dimension and the “long” sample exceeding the magnet winding on both sides in the same way as shown in figure 3. The result of this comparison is shown on figure 4 confirming that the loss is generated only in the “active” part of the tape inside the magnet bore.

3. Numerical simulations

Distributions of the current density and the magnetic field were calculated in two-dimensional approximation in the cable cross-section. The finite element technique of Comsol Multiphysics® in vector potential formulation was used [9]. For each current amplitude the AC loss was obtained by numerical integration of the calculated \( I - \Phi \) hysteresis loop formed by 40 points.

The geometry of cable used for numerical simulations is shown on the right side of the figure 5. This geometry assumes the same cross-section as the real cable and the same critical current of the tapes \( I_c \). Inclination because of lay angle is reflected by increasing the tapes width from 4 mm to 4.66 mm and reduction of the critical current density \( J_c \) by 16.5 %.

4. Results and discussion

The measured magnetization losses is shown in the figure 7a. There was no frequency dependence observed. Remarkable is the agreement between numerical simulations and experiment.

In the case of transport AC losses the measured data are about four times higher than the numerical prediction (figure 7b). This experiment was repeated several times with different configurations of the voltage taps and wiring, with the same result. Therefore we search to find the cause of such discrepancy in the assumptions implemented in the calculations. For example, the irregularity of gaps between the tapes (see figure 1), which have high influence on transport AC losses in the CORC cable [11-12] has not been considered in the calculation. Another possible reason could be a non-uniform...
current distribution in parallel superconducting tapes. Better understanding of these factors needs a separate study.

Figure 7. Measured and calculated magnetization (a) and transport (b) AC losses of CORC cable (only losses at 36 Hz are shown). For sake of comparison the transport losses calculated for the cable from uniform tapes using the Norris-Majoroš formula [12] as well as the prediction assuming a round cylinder with the same critical current [13] are shown.

In conclusion we have still some problems in the prediction of transport AC losses in our CORC cable. On the other hand, for the application of these cables in large magnets the magnetization loss is of prime concern. Here we get very good agreement between numerical simulations and experiment.

5. References

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