AC loss of the short coaxial superconducting cable model made from ReBCO coated tapes

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Abstract. Coaxial cable model with both the core as well as the shield conductor made from high-temperature superconducting tapes of the 2nd generation was constructed. AC current was fed to the model of 0.5 m length using a cold core transformer system. The core consists of 14 EHTS YBCO tapes of 4 mm width, and its properties have been published already. Now the system was completed by the shield conductor using 16 ReBCO tapes of 10 mm width produced by Nexans. In this contribution, the properties of the shield conductor are reported in detail. The experimental data on ac transport loss are presented and compared with ac transport loss of the superconducting core. The currents in individual tapes and the total cable current was monitored using Rogowski coils. Significant non-uniformity of the current distribution was found, which is a common issue in short cable models. Therefore, the AC transport loss of the shield conductor was measured by 16 lifted loops placed along the cable, using the averaging method to extract the true loss voltage.

1. Introduction
Transmission power superconducting cable lines are considered to use in one of the three configuration: as three independent phases with three cryogenic cryostats, as three phases in one cryogenic envelop or as configuration with three concentric phases (triaxial) placed in one cryostat. Every solution has its advantage. In the case of coaxial phases no outer magnetic field exist, low ac loss is generated and very low cable inductance is achieved. Latterly a lot of effort is devoted to the characterization of the cable models constructed from YBCO coated conductor which are supposed to replace BSCCO superconducting tapes [1-5].

In this work we present experiments with short ReBCO model of such kind of cable, in particular the test in AC regime.

2. Experimental
Superconducting coaxial cable model consisted from two parts: superconducting core and superconducting shield conductor. The core was constructed of 14 YBCO tapes of 75 A critical

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current [6]. Tapes were placed in single layer on the surface of the epoxy-fiberglass mandrel of diameter 2 cm and length of 50 cm, with the lay angle of 15°. The electrical connection between each tape and the cable termination was created by soldering of 4 flexible braids consisting of $\phi 80$ µm Cu/Ag wires as is shown in lower part of Fig. 1. Such unusual technology was utilized because only 2 µm metallic protection layer of the YBCO tapes was used. Total transport capacity of the superconducting tapes in the core was 900 A. Complete DC and AC characterization of this cable part has been already performed in our previous work [7] and in the following text only AC properties of the shield conductor will be presented.

The shield conductor was constructed from 16 ReBCO coated tapes of 10 mm width [8] and critical current 32 A. They were placed in parallel configuration on the surface of the epoxy-fiberglass mandrel of diameter 10 cm and length of 50 cm in one layer, with the lay angle of 15° – upper part of the figure 1. Connection to the Cu terminals was performed by soldering. Critical current of the shield conductor was 485 A (details of the DC study of this cable part were presented in previous work [9]). The core was inserted into the shield conductor and both conductors were connected in series by Cu plate on one cable side. To the other cable side Cu strands for current supplying were attached. As a source for supplying of the cable model an audio amplifier and cold toroidal transformer (immersed into LN$_2$ together with cable model) were utilized. In the path of each tape the calibrated Rogowski coil was placed allowing to measure the AC current $I_m$ of individual tapes – figure 2 (m=1-16). In such way the distribution of the total cable current $I_{tot}$ to the individual tapes was possible to monitor. On each tape the voltage taps were placed to measure the loss voltage on individual tapes $U_m$. The length...
between taps was \( l = 50 \) cm. The measurement wiring formed 16 loops of length 40 cm along the cable. To ensure to feel the whole relevant voltage signal there were lifted 1 cm above the cable surface. The block scheme of the shield conductor is illustrated in figure 3.

The principal scheme of the ac shield conductor loss measurement using lock-in technique is shown in figure 4. The measurement was performed at \( f = 36 \) Hz, 72 Hz and 144 Hz and at temperature of LN\(_2\). Total ac current of the cable was measured by Rogowski coil in channel A of the lock-in amplifier. In channel B the voltage \( U_m \) from everyone of 16 loops was measured subsequently in dependence on \( I_{tot} \). From measured \( I_m \) and \( \text{Re}(U_m) \) (part of \( U_m \) in phase with total current \( I_{tot} \)) the shield conductor loss was calculated as \( P = I_m \times \text{Re}(U_m) \). More, the dependence of the individual tape currents and their phases with respect to the total current were measured as well. In this case the channel B was utilized for measurement of the Rogowski coil signal proportional to the ac current in individual tapes and in channel A the signal from Rogowski coil measuring the total current \( I_{tot} \).

3. Results and discussion

Before ac cable shield loss measurement the loss of the short 10 cm Nexans sample was checked using lock-in technique and the same apparatus as was described in previous section. In figure 5 ac loss per cycle \( Q \) of the short sample measured at frequencies 36 Hz, 72 Hz and 144 Hz are shown. No dependences on frequencies was found confirming pure hysteretic loss behaviour of the sample. The deviation from the Norris theoretical prediction can be ascribed to the ferromagnetic substrate loss contribution on which the superconducting layer was deposited. Different ac loss behaviour was found for EHTS short tape which fulfilled Norris prediction for ellipse [10].

![Figure 5](image1.png)

**Figure 5.** AC loss per cycle of short sample measured at different frequencies.

![Figure 6](image2.png)

**Figure 6.** Dependences of the currents in individual tapes on total current. \( f = 72 \) Hz

Due to the spread in soldered contact resistances, we expected the tape currents that vary both in amplitude and phase, with severe consequences on the determination of AC losses by an electrical method. In figure 6 the dependences of the individual tape currents on total transport current \( I_{tot} \) measured at \( f = 72 \) Hz are shown. This non homogenous distribution of \( I_{tot} \) also below critical current of the shield conductor \( I_c \) is due to different values of the contact resistances. This relative low currents spread can slightly influence measured loss voltage signal. The same dependences were measured also for \( f = 36 \) Hz and 144 Hz. In figure 7 phases of the currents in individual tapes with respect to the total current phase in dependence on \( I_{tot} \) measured at \( f = 72 \) Hz are shown. They differ up to several degree and as a consequence different loss voltage signals \( \text{Re}(U_m) \) taken from various measuring loops were monitored. These voltages contain except relevant loss signal also false signal because \( \text{Re}(U_m) \) is part of measured voltage in phase with total transport current and measuring loops, depending on their...
positions, register signals induced from tapes. After calculation of the loss per cycle $Q$ even negative “loss” values can be acquired. This is shown in figure 8 where losses measured by individual loops are depicted in dependence on total ac current $I_{tot}$.

*Figure 7.* Phases of the currents in individual tapes with respect to the total current phase in dependence on $I_{tot rms}$, $f=72$ Hz.

*Figure 8* AC “loss” measured by individual loops lifted 1 cm above the cable surface measured at $f=72$ Hz.

We have found in previous investigations on Bi-2223 cable [11] that the correct loss voltage could be obtained from the average of voltage signals taken on all the tapes and led by straight signal wires lifted in certain distance above the cable surface. Ac loss of the shield conductor derived by this procedure is shown in figure 9. Measurement was performed at three different frequencies $f = 36$ Hz, 72 Hz and 144 Hz. Again, like for short sample, no dependence of the loss per cycle of the shield conductor was found. In the same picture the loss of the short sample recalculated with respect to the cable shield conductor and shield conductor itself are compared. Lower loss in shield conductor at higher total transport current can be explained by partial saturation of the ferromagnetic substrate due to external magnetic field generated by currents flowing in neighbouring superconducting tapes.

*Figure 9.* AC loss of the shield conductor acquired by averaging of the “loss” measured by individual loops.

*Figure 10.* Comparison of the AC loss per cycle of the core and shield conductor normalized by Norris formula pre-factor in dependence on normalized total transport current.
Higher ac loss measured on short Nexans sample caused by additional ac loss mechanism in ferromagnetic substrate are visible also in loss measurement in shield conductor. This is presented in figure 10 where the comparison of the AC loss per cycle of the core and shield conductor normalized by Norris formula pre-factor in dependence on normalized total transport current is displayed.

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