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AC loss of a model 5m 2G HTS power cable using wires with NiW substrates

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Abstract. A model 5 m cable prototype was constructed using American Superconductor second generation (2G) high temperature superconductor (HTS) wires - 344 superconductors, produced with the MOD/RABiTS™ process. The model cable consists of two helically counterwound layers of brass-laminated tapes. Twist pitches were calculated to provide uniform current distribution between the two cable layers. The NiW substrates of the tapes were oriented to face radially inward and radially outward for the inner and outer layers of the cable, respectively, to minimize the spacing between the HTS layers and any effects of the weak substrate magnetism. To verify the calculations and design principles, the model cable was instrumented with potential taps and sensors, including Rogowski coils and Hall probes, to measure the current distribution among layers, voltage – current characteristics and other parameters. AC losses in this cable model have been measured and analyzed by use of digital measurements of current and voltage. At low to intermediate currents, they are in the range of a few tenths of a watt per meter, consistent with the ferromagnetic loss of the substrate. Analysis of the individual contributions of the Ni-W substrate and the superconductor hysteresis loss is given.

1. Introduction

Second generation HTS wires – coated conductors - are considered as most promising for future applications. These wires are non symmetrical, with the superconducting layer located on one side of conductor's tape. Thus, different orientation of tapes is possible when making, say, two layer helically wound conductors for power cables. Choosing the proper orientation could be particularly important to optimize properties such as ac loss when the substrate used for the wires is weakly ferromagnetic.

We designed, produced and tested a model 5 m cable prototype made of American Superconductor second generation (2G) high temperature superconductor (HTS) wires - 344 superconductors, produced with the MOD/RABiTS™ process. The model cable consists of two helically counterwound layers of brass-laminated tapes. The NiW substrates of the tapes were oriented to face radially inward and radially outward for the inner and outer layers of the cable, respectively. To verify the calculations and design principles, the model cable was instrumented with potential taps and sensors, including

Rogowski coils and Hall probes, to measure the current distribution among layers, voltage – current characteristics and other parameters.

In this paper we present a model cable design and its test results, particularly AC loss measurements. We analyze AC loss in terms of the contribution of the Ni-W substrate and the superconductor hysteresis loss.

2. Cable design and instrumentation.

As a former for the 5 m cable, we used a 25 mm diameter stainless steel tube. The tube was insulated by Kapton™ tape. Two counterwound layers of tapes of 344B superconductors from American Superconductor have average twist pitch ~20.9 degree with superconducting layers facing each other. Kapton tape was placed between layers to insulate them. Outer insulation was made by Kapton as well. Each cable layer has 17 344B tapes with 34 tapes in total.

Instrumentation of the model cable is similar to our previous work [1,2] (see Figure 1). Two pairs of Rogowski coils on inner and outer layers were installed to measure current in each layer. Each layer has two pairs of voltage taps with about 4-4.5 m between them. Voltage taps on the inner layer were located exactly under the voltage taps on the outer layer. Extra voltage taps were installed at joints with terminations. Hall sensors measured the magnetic field distribution inside and outside the cable.

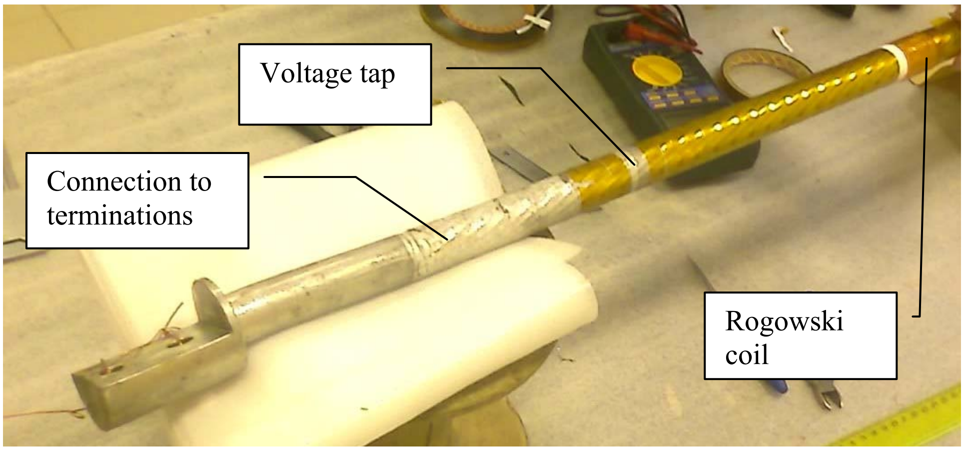

Figure 1. Photograph of instrumentation installed in the 5 m model cable, and a termination.

3. Test facility and DC tests

The 5m cable model was tested in atmospheric liquid nitrogen (77 K) at a low voltage high current test facility at VNIIKP [1]. The facility includes a 6.8m flexible cryostat produced by Nexans Co. with inner diameter 100 mm, power supplies capable of DC currents up to 2000 A and 6.3 kA and AC currents up to 3.6 kA_{rms}, and a variety of measuring devices including a multichannel Yokogawa digital data acquisition system.

A DC cable test was conducted to determine the cable critical current. We also measured the DC current distribution among layers and joint resistances. Due to the asymmetry of HTS tapes and the chosen different orientations for the two layers, joint resistances were rather different: $\sim 2\cdot 10^{-7}$ Ohm between outer layer and termination and $\sim 8\cdot 10^{-7}$ Ohm between inner layer and termination. Because the DC current distribution among layers is determined by joint resistances, the DC current distribution was highly non-uniform as shown in Figure 2. One can see that the outer layer current exceeds the inner layer current until critical current is reached. Near the critical current value, the layer currents become almost the same, within ±4%. This permitted us to determine critical current by measuring the V-I characteristics of layers as shown in Figure 3. One can see that all layers have very similar V-I characteristics near the critical current. A best fit to the standard power law expression returned a total cable critical current of I_c~2750A with n~27 at 1 μV/cm. This critical current coincides with that expected from the sum of all tape critical currents. The rather high *n*-value demonstrates the good quality of the starting HTS wires and their integrity after cable production.

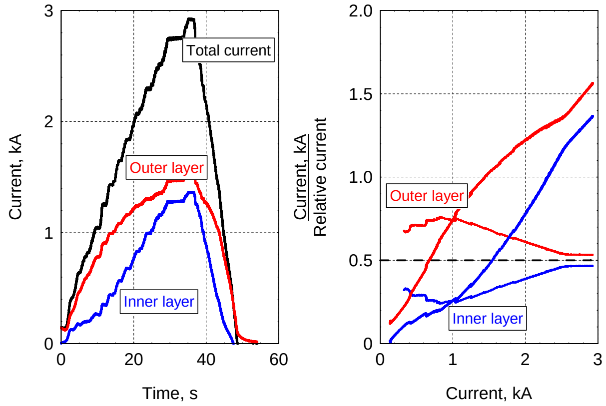

Figure 2. Example of DC current run to 3 kA (left) and current distribution among layers (right). Right: rising curves – total layer current; flatter curves – fractional current.

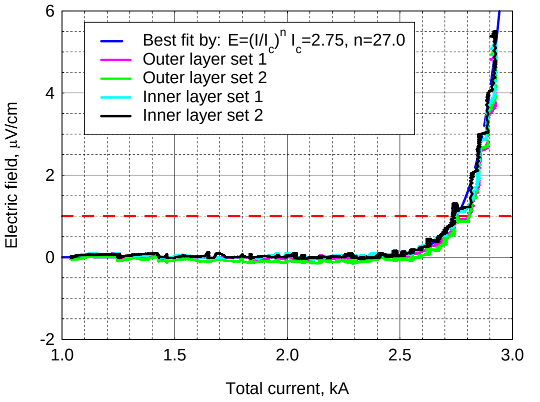

Figure 3. Example of voltage-current curves (VCC) from all voltage taps. Best fit of all VCC by standard expression returns a total cable critical current value ~2750 A.

4. AC tests

Next we measured the current distribution among the layers in AC mode and the AC losses in the model cable. We used four return cables located symmetrically around the cryostat, and the model cable has been placed in the centre of the cryostat, so that all four return cables were at equal distances from the centre of the cable. This was essential to minimize the influence of the return cables' magnetic field on the AC loss measurements.

The current distribution among layers is shown in Figure 4. One can see that in AC mode, the current distribution among layers is much more uniform than in DC mode. In AC mode the current distribution is primarily determined by layers' inductive impedance, which is much higher at 50 Hz in a 5 m cable than the joint resistances. It is interesting to note, that in AC mode below I_c~1950 A$_{\mathrm{rms}}$, the higher current is in the inner layer, not in the outer one like it was in DC mode.

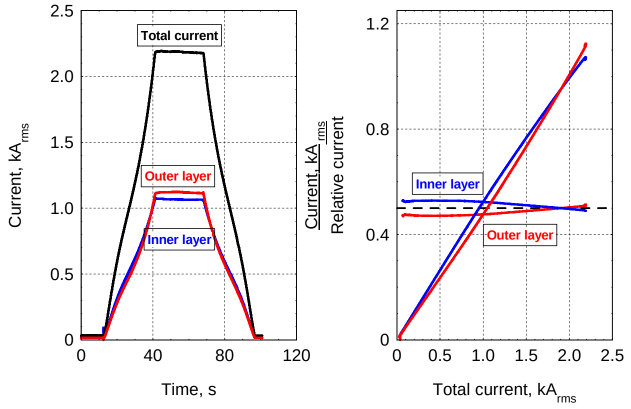

Figure 4. Example of AC current run to 2.2 kA$_{\mathrm{rms}}$ (left) and current distribution among layers (right). Right: rising curves – total layer current; flatter curves – fractional current.

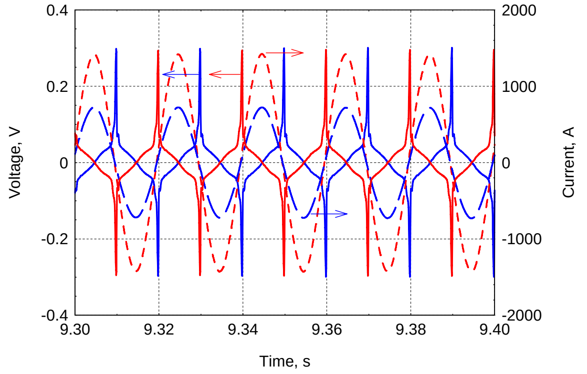

Figure 5. Typical current and voltage signals during measurements in AC mode. Voltage of inner layer is reversed to be seen well. Higher current is the total cable current, lower current is the current in the inner layer.

Voltage and current in the individual layers, along with total current, were measured in all AC current runs. An example of voltage and current data is shown in Figure 5, where voltage on the inner layer is shown reversed in sign to be seen well. In reality voltages at the inner and outer layers were exactly the same. These graphs are quite typical. They were basic for all following data reduction procedures, especially for AC loss analysis.

Spikes seen in the voltage signals shown in Figure 5 are connected with re-magnetization of the substrate. These spikes made it difficult to use the phase shift method for AC loss evaluation, described in [1]. Therefore, we used for AC loss evaluation a standard integration of the V·I product [3].

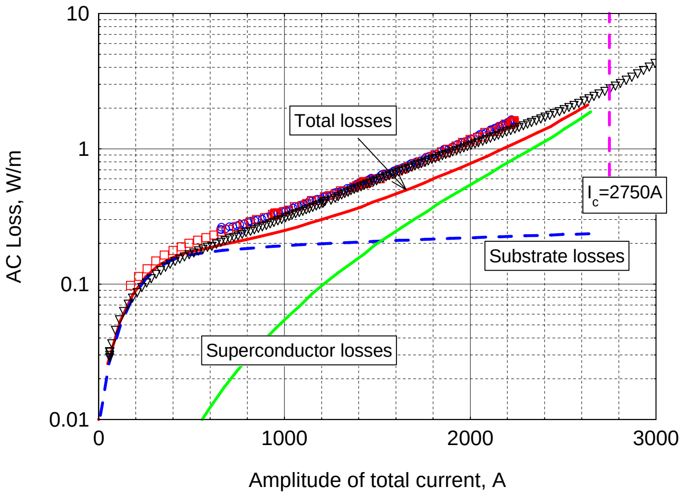

Figure 6. AC loss evaluation data, log Y scale at different runs. At dashed vertical line, peak current reaches I_c. Symbols – experimental data, solid lines – calculations.

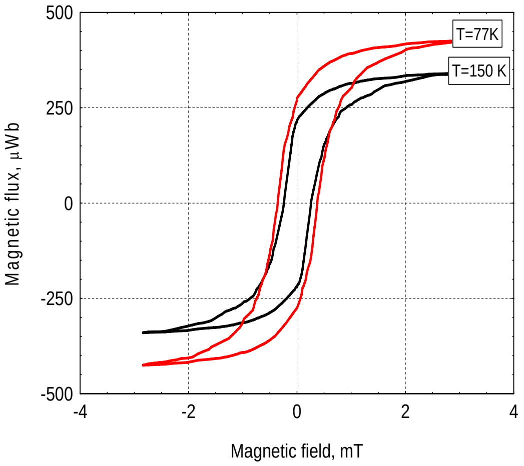

Figure 7. Magnetization measurement of 344B wire at low magnetic field and two temperatures.

One can see that at low to intermediate currents, AC losses are in the range of a few tenths of a watt per meter. We measured magnetization curves of single tape at temperatures 77K and 150 K. They are shown in Figure 7. Calculation of substrate contribution to AC losses made from this measurement by multiplying the individual wire loss by the number of tapes in the cable is shown in Figure 6 by dashed line. Calculations of AC loss in a 2G superconductor layer should be different from those in 1G superconductor. Following [4] one should take into account surface superconductor losses [4] and gap losses [5,6] altogether. We estimated losses from Norris model for elliptical conductor [6]. If to use the Norris model for strip conductor or Majoros model for gap losses we would obtain noticeable less AC loss estimations, than for elliptical conductor. Corresponding calculated hysteretic superconductor and ferromagnetic losses along with the sum of all AC losses are shown in figure 6. Total losses are slightly less than the measured ones. One possible additional loss is polygonal loss [7]. We also assume that flux transfer losses arising from imbalanced currents in the two layers are small in our case due to the close balance of the measured layer currents.

5. Conclusion

We produced and tested a 5 m model HTS cable made of AMSC 344B superconductor. The NiW substrates of the tapes were oriented to face radially inward and radially outward for the inner and outer layers of the cable, respectively. The model cable demonstrated expected the DC critical current and quite uniform current distribution among the two layers in AC mode. AC loss measurements demonstrated magnitudes of few tenths of W/m at currents ~0.5I_c. The choice of wire orientation ("in-out") for the two layers is believed to be important to achieve these low AC losses. Ferromagnetic losses contribute most at low current but are relatively small. At higher current different mechanisms of AC losses should be taken into account [4]. AC loss analysis in 2G superconductors with magnetic substrates needs further work to be understood. In the future more experimental work will be needed to test more cable models with other substrate orientations to check the influence of magnetic substrate orientation on AC losses.

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