IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 6, October 2008
(ASC Preprint 1LPF01 conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)
The published version of this manuscript appeared in *IEEE Transactions on Applied Superconductivity*
19, No. 3, Part 2, 1706 - 1709 (2009)

The AC Loss Analysis in the 5m HTS Power Cables

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***Abstract* — In the framework of the Russian R&D Program for superconducting power devices, the 30 m HTS power cable has been developed made of 1G Bi-2223 tapes. Before the full length cable production, as the first prototype the short 5 m cable model was produced and tested. After 30 m cable production the 5 m witness sample has been cut from the long piece and tested as well. To verify the calculations and designing principles both 5m cables were heavily instrumented by potential taps and sensors to measure current distribution among layers, voltage – current characteristics and other parameters. AC losses in these short cable pieces have been analyzed by use of digital measurements of current and voltages along the cable. The witness sample has been provided by thermocouples to evaluate AC losses by calorimetric method. The details of AC losses measurements are discussed. Their analysis and comparison with calculations by standard theoretical models are presented.**

***Index Terms*— HTS power cables, AC losses, Bi-2223 tapes, Digital measurements.**

I. INTRODUCTION

THE Russian R&D Program for HTS power cables is underway, supported both by government and electric power companies. The first step is to produce and test 30 m three phase cable. The 5m piece of the full scale power cable has been tested before as the first prototype [1]. The 30 m cable has been delivered to the test facility this February and its test is about to start [2]. The proposed parameters of this power cable should be 2000 A and 20 kV. The 5 m witness sample has been cut from the longer piece of the cable to verify the parameters of the 30 m cable after the full technological route has been passed. Therefore, we had two 5 m cables' samples with the full size cross-sections to test. Both 5 m samples were made of Bi-2223 tapes.

Both 5 m cables were heavily instrumented by potential taps and different sensors to measure current distribution among layers, voltage – current characteristics, temperature and other parameters. Details about instrumentation and test results of the 5 m prototype are presented in [1]. Details of the witness sample test are presented in [2].

The goal of this paper is to analyze AC losses in these two 5 m cables. AC losses are the important operational parameter of HTS power cables. The knowledge about AC losses permits to evaluate the cryogenic load for cooling systems and to estimate the effectiveness of HTS power cables. The data about AC losses in full size cross-sections HTS power cables presented in the literature are rather ambiguous. The data about measured AC losses at currents above 2000 A_{rms} are practically absent.

We made the attempt to use digital measurements of voltage and current to evaluate the magnitude of AC losses during 50 Hz AC current operation. To verify the digital measurements two calorimetric methods were used.

In this paper, the details about AC loss measurements, data reduction and AC loss results are presented for two 5 m cables mentioned.

II. EXPERIMENTAL DETAILS

The parameters of 5 m cables are presented in the Table I. More details about cables' design can be found in [1], [2].

TABLE I PARAMETERS OF THE CABLES TESTED

Sample #	Cable	Former	HTS wire used	Cable I_c, measured, A
1	5 m test prototype. 2 layers, 48 tapes in total. No insulation, no shield.	Composite Al-Cu central spiral covered by two layers of the copper tape, o.d 35 mm	American Superconductor (AMSC) Hermetic™, Avg. I_c,~105A, brass laminated	5000
2	5 m witness sample from 30 m cable. 2 layers, 42 tapes in total. 7 mm paper insulation, copper shield.	Central SS spiral, bunch of copper wires, o.d. 30 mm	Sumitomo Electric Industry (SEI) CT-OP™ wire, Avg. I_c,~100A, , no lamination	4200

Both samples were provided by the potential taps attached directly to the layers with the thin copper ring [1]. Two copper – constantan thermocouples (TC) were attached to the sample #2 in the middle of the cable directly to the layers via the little hole in the insulation. After the TC installation the hole was hermetized by the Stycast™ epoxy. The reference end of the TC has been put to the copper tube exposed directly to the liquid nitrogen.

Manuscript received 19 August 2008.
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The samples were tested at the VNIIKP low voltage test facility [1] in the 5 m flexible cryostat filled by the liquid nitrogen. During AC tests the cables were provided by AC current then current and voltages were measured by multichannel digital data acquisition devices, ether by PC card or by Yokogawa SL1400 digital oscilloscope. The number of the data points measured per AC cycle was from 100 to 400, accuracy in the amplitude measurements (both for current and voltages) was 0.25-1%. The typical view of the voltage and current records is shown in Figure 1 for the part of the 3500 A_{rms} run. Such "cuts" of records we used to evaluate AC losses, because during 10-20 cycles the amplitudes of voltages and current changed negligibly and were easy to analyze.

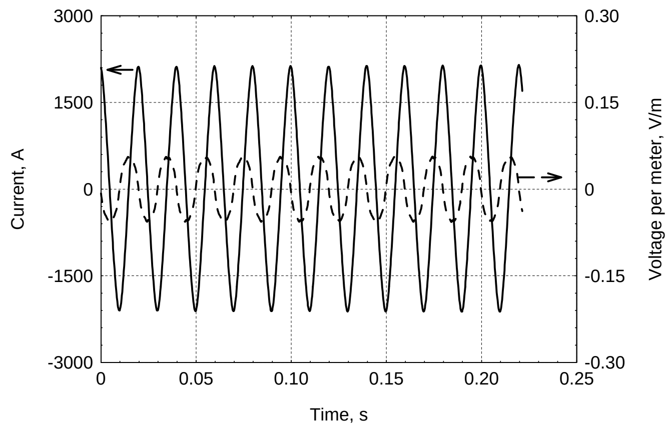

Figure 1. The typical view of the part of the recorded AC current run (solid line) and voltage (dashed line) of the sample #2. Amplitude current is ~2100 A. Similar "cuts" of records were used for the data reduction to evaluate AC losses.

For calorimetric measurements, the sample #2 was provided by DC current first with the magnitude well above the critical one and signals from TC have been measured along with DC currents and voltages. These measurements provide us by the calibration curve between power released in the cable (the product of Dc current and voltage) and TC signals. Then, by measuring TC signals at AC current we could find the corresponding power released due to AC losses. This method was offered in [3] and employed in [4].

The dependencies of the heat release at DC conditions (per meter of the cable length) on TC voltage signals and the AC cable currents (rms) on TC signals are shown in Figure 2. The data in Figure 2 permitted us to find the AC losses at AC mode by the calorimetric method for the sample #2. They are shown in Figures 4 by closed circles.

During tests of the sample #1 we tried to evaluate losses by use of the gas flow meter. We measured the evaporation rise at AC conditions in comparison with the evaporation at DC conditions [1]. The accuracy of these measurements is rather low, as we try to find a little addition due of AC losses against large background evaporation due to current leads. Nevertheless we present these data in Figure 3 with the closed boxes for the sample #1.

III. Data Reduction Methods and AC Losses Determined

The basic data we obtained during measurements were sinusoidal curves of cable's current and voltage vs. time. In accordance with the classical definitions the AC losses are the product of the active part of the voltage by current. To find out the active part of the voltage in the case of superconductors is not easy task due to the low magnitude of the AC losses. Classical analog methods were offered by use either phase converters or electrical voltage signal compensation along with multiplier and analog integration [5].

Modern measuring devices permit to obtain digital data with high resolution and large number of measuring points per AC cycle as we mentioned above. That is why we tried to employ similar methods to find out the active part of the voltage by use the digital data and the mathematical data reductions. Eventually, three methods were used as below, verified by the calorimetric methods described above.

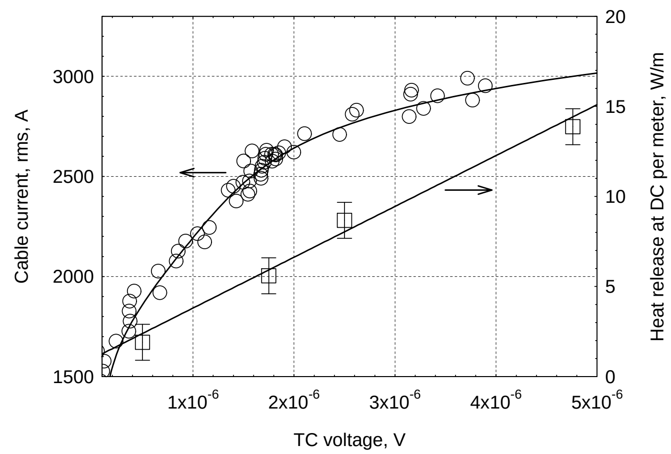

Fig.2 Heat release at DC mode (right Y-axis) and total current at AC mode (left Y-axis) versus signals from thermocouple.

A. *Integration*

By the definition the losses at the single phase AC conductor with the current *I(t)* and voltage *V(t)* are described as:

$$P_{\mathrm{int}}(t) = 1/t\int_0^t V(t)\cdot I(t)dt \qquad (1)$$

In our case of sinusoidal signals, the reactive part of the voltage – current product is subtracted during integration and proper AC loss data may be obtained. We performed such digital integration of the products of voltages by currents for several "cuts" from full measurement run similar to shown in Figure 1 at different total currents. It returned us the energy released due to AC losses versus time. The AC losses could be found by dividing the integral mentioned by the time as in Eq.(1). This returned us the power vs. time for current amplitude. Estimation of calculations errors for this method was about ±15-20%.

The results of the measured data reduction by use the integration are shown in Figures 3 and 4 by open circles.

B. *Phase shift*

Another classical expression to calculate active power (losses) is:

$$P_{shift} = \frac{I_0\cdot V_0}{2}\cos\varphi, \qquad (2)$$

were I_0 and V_0 are amplitudes of the current and voltage correspondingly, and φ - is the phase shift angle between sinusoidal current and voltage. To find out the phase shift between current and voltage we made the best fit approximation of the voltage and current for data "cuts" similar to shown in Figure 1 by the sinusoidal functions like $V(t)=V_0 sin(\omega t+\varphi_V)$ and $I(t)=I_0\ sin(\omega t+\varphi_I)$. The difference of $\varphi=\varphi_V-\varphi_I$ returns us the phase shift to evaluate AC losses by Eq.(2).

The use of data "cuts" for determination of the phase shift is necessary not to have deal with the changing amplitudes of current and voltage during entire current run. The use of several cycles for the approximation increased the accuracy of the data reduction. Anyway, our estimations of calculation errors gave us the value about ±25% for the AC loss determination via digital phase shift measurements.

The results of the AC loss determinations from measurements by the phase shift are shown in figures 3 and 4 by open boxes.

C. *Inductive voltage extraction*

Considering sinusoidal $I(t)$ and $V(t)$ curves like shown in Figure 1, it is correct to suggest that the amplitude of the inductive (or reactive) part of the voltage is exactly those when the current is going through zero. Then one can plot the sinusoidal curve for the inductive part of the voltage with amplitude found when $I(t)=0$ and with the phase shift equal to $\pi/2$ in relation to the $I(t)$.

The difference between measured voltage and calculated reactive voltage return us the active part of the voltage. The product of the active part of voltage and the measured current should be integrated and then divided by the time. This gives us the average losses per cycle P_{ext} again.

The data for AC losses derived by this method are shown in figures 3 and 4 by the open triangles.

IV. Discussion

In figures 3 and 4 the data about our AC losses measurements are shown for two 5 m cables determined by four different methods. The data reductions were done for several different AC runs for each cable. One can see that different methods of the data reduction by use of digital measurements and digital mathematics data processing returned quite coinciding results. It is not surprising, because all data reduction methods realize the same ideas about finding of the active part of voltages.

The calorimetric measurements used gave us coinciding data as well. That means that digital measurements and data reduction methods proposed are fair and can be used for AC losses evaluations.

We have to note that AC losses for two 5 m cables tested are rather close in spite they have quite different central formers. It is illustrated in Figure 5, where AC losses in both cables are shown versus relation of transport current to the critical current of corresponded cable. The sample #1 has low cross – section of the former made of Al-Cu composite spiral with rather high inductance. The sample #2 has former made with the bunch of copper wires with total cross-section about 220 mm^2. Coinciding of AC losses means that in both our cables AC losses in formers are low like it was also noticed in [6]. This is because during design of cable the twist directions and pitches of both HTS layers were carefully optimized to provide uniform current distribution among layers and lowest possible magnetic field in the center of a cable. This fact has been confirmed by measurements. For example central field in the sample #2 was ~1.5 mT/kA that is quite low value [2]. In our cables dominated AC losses are in Bi-2223 tapes and their Ag matrices.

AC losses in the sample #1 are slightly more at currents close to the critical one. It may be explained by the fact that a bit more HTS tapes are used in this sample in comparison with the sample #2 (see Table I).

We also made the evaluation of AC losses in our cables by use well known theoretical models: monoblock model [7], incomplete – penetration model from L.Dresner [8,9] and Norris model [10].

The theoretical curves for models [7] and [8] are shown in figures 3 and 4 by solid lines. Theoretical curves for model [10] are shown in figures 3 and 4 by dashed lines. One can see that theoretical models [7] and [8] rather closely coincide with our measurements at currents above 2000 A_{rms}, at that Dresner's

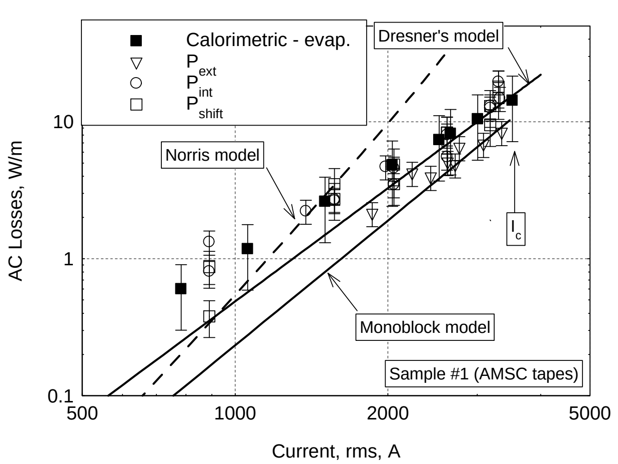

Fig.3 AC losses versus current in the 5 m cable prototype made of AMSC tapes

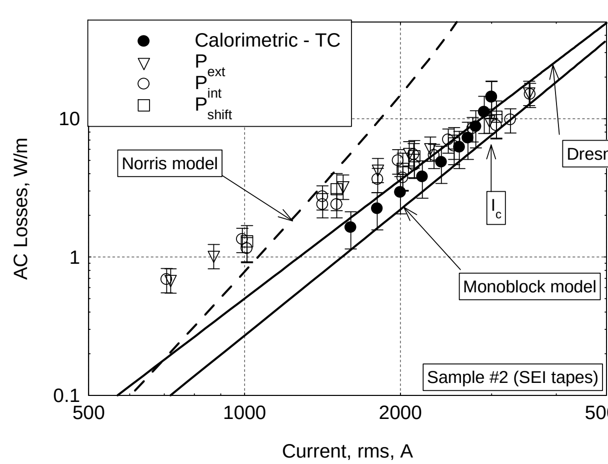

Fig.4 AC losses versus current in the 5 m witness sample cable made of SEI tapes

model better coincides with experimental data. It means that models mentioned could be used for estimations of AC losses in HTS power cables as lower limits. Similar relations between monoblock model and experimental data were observed in [11], [12], [13]. In [14] estimations made by the monoblock model were more than experimental data measured.

The Norris model [10] provides higher estimations of AC losses than experimental ones and it may be used as the upper limit for AC loss evaluation.

Discrepancies between models [7] and [8] at low currents could be due to both: the models proximity and not so precise measurements at low AC losses.

In general we could state that at currents ~1000A_{rms} AC losses in both cables are about 1W/m and rise to 3-5 W/m at 2000 A rms. The later value could be considered as rather high. Some efforts should be done to reduce this value in future to make real HTS power cables more effective for practical use. Proposed methods are to use the reduced width of 1-G of basic HTS tapes, or to use twisted filaments in 1-G HTS tapes. Or maybe the use of 2-G HTS conductors will reduce AC losses. We plan to study 5 m cable model from 2-G conductors in close future.

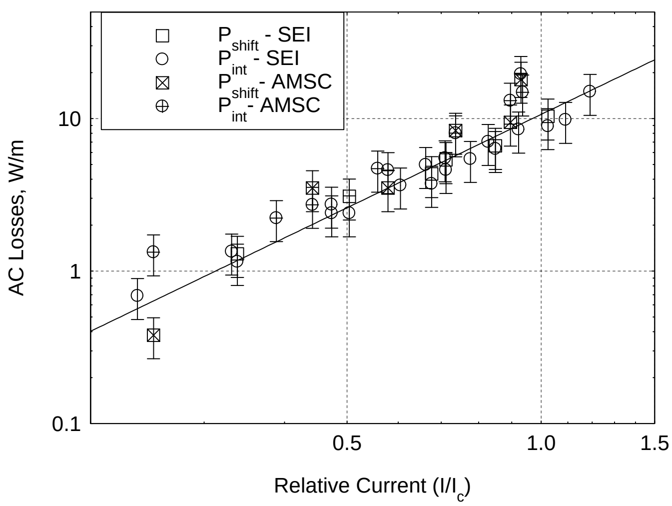

Fig.5 AC losses versus relative current for both 5 m cables tested.

V. Conclusion

Two 5m HTS power cables with full cross-sections made of 1-G Bi-2223 HTS tapes were tested and their AC losses were studied. The AC losses were determined from digital measurements of currents and voltages of cables with the followed mathematical data processing. Three methods were used for data processing that provided coinciding results. These results coincide with two types of calorimetric loss measurements as well. That means the AC losses digital measuring methods discussed can be employed for experimental AC losses determination.

The data about AC losses at currents from 800 to 3600 A_{rms} are presented.

The known theoretical models were compared with experimental data and it was shown that they could be used for AC losses estimation in HTS power cables made of Bi-2223 basic tapes. For future HTS cables based on YBCO 2G tapes new approaches should be developed.

Acknowledgment

VSV would like to thank Prof. N. Amemiya and Dr. F. Gomory for fruitful discussions and clues provided for AC losses measurements and analysis.

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