Dependence of AC Transport Current Losses of HTS Wires on Their Structures and Synthesizing Processes

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Abstract — HTS wires of various structures and synthesizing processes are being developed for power apparatus applications in Super-GM project. AC transport current losses of four of those wires were measured by an electric method using a lock-in amplifier. Measured wires are a Bi2212 rod fabricated by the laser pedestal growth method, a Y123 tape fabricated by the pulsed laser deposition and multilayered Bi2223/Ag sheathed wires of square and tape shapes. In this paper, based on measured data, dependence of AC transport current losses of HTS wires on their structures and synthesizing processes is discussed.

I. INTRODUCTION

High Temperature Superconductors (HTS) are more promising for AC power apparatuses such as power transmission cables, transformers, current limiters and motors than Low Temperature Superconductors (LTS) because efficiency of cooling AC losses is higher for HTS operating in 20 K~77 K range than for LTS operating in 4.2 K range. The knowledge of AC losses and understanding of loss mechanism in HTS wires are important to apply HTS to the AC power apparatuses and develop low AC loss HTS wires and windings. The AC loss characteristics are influenced by many factors including configurations, structures, materials, synthesizing processes and critical currents of wires.

The R&D on HTS wires of various structures and synthesizing processes for application to power apparatuses has been conducted in the Super-GM project [1]. We measured the AC transport current loss characteristics of four kinds of wires of different structures and synthesizing processes which were developed in the Super-GM project.

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The losses were also measured in background DC magnetic field. The AC transport current losses were measured by measuring the voltage across the potential taps attached on the wire using a lock-in amplifier. The tested wires had various shapes, round, square and tape, therefore, proper care was taken for the potential leads arrangement. We used the spiral potential leads arrangement where the potential leads are spirally wound on the cylindrical surface surrounding the wire. It has already been verified both theoretically and experimentally that the correct AC transport current losses can be measured using this arrangement regardless the shapes of the wires [2].

Measured AC losses were compared with theoretical values calculated from the Norris' formula based on the Bean model [3]. In this paper measured AC transport current losses are presented and the dependence of the AC loss characteristics on the wire structures and synthesizing processes are discussed by investigating the discrepancies between the experiment and theory.

II. EXPERIMENTAL SET-UP AND

The arrangement of the sample HTS wire is illustrated in Fig. 1. The sample shown in Fig. 1 was placed in a gap of a laminated iron core electromagnet. I is the transport current of the sample. The background field was parallel to the tape surface. The leads from the potential taps on the tape were spirally wound around the wire. This arrangement was also useful to measure the AC transport current losses in the tight space of the magnet gap by avoiding problems caused by the limited space between the potential leads and the tape. The return current from the tape was adjusted to flow in the two divided current leads evenly and the leads were placed in the magnet gap to avoid the power flow between the power supplies of the sample and magnet by electromagnetic coupling. The AC transport current losses were measured by measuring the transport current and the resistive component of the voltage signal using a lock-in amplifier.

Specifications of the tested 4 wires, samples A, B, C and D

are listed in Table I. The samples A and B are multilayered Bi2223/Ag sheathed wires made by the multi-pipe method and shaped into tape and square forms respectively from round form wires [4]. The sample C is a Bi2212 rod fabricated by laser pedestal growth method [5]. The sample D is YBCO film deposited on textured Ag tape [6]. In the experiment AC transport current losses of the samples wires were measured for different frequency with and without the DC background field.

III. RESULTS AND DISCUSSIONS

A. Sample A (Multilayered Bi2223 tape)

Dependence of the critical current I_c and n value on the background field is shown in Fig. 2 (assuming the electric field along the wire is proportional to the n -th power of the wire current density). Fig. 3 shows the AC transport current losses at 60 Hz dependent on the background field plotted against the peak value of the transport current I_p . In the figure I_p is normalized by I_c at the applied background field. The loss is expressed by the normalized value (J/m/cycle/A²: Joule per meter and cycle divided by I_c^2 at the applied background field). In Fig. 3, the curve calculated from Norris' elliptical model is also plotted. Fig. 4 shows the dependence of the losses on the AC transport current frequency for various value of $i = I_p / I_c$ at 0 T.

As seen in Fig. 3, the loss data deviate from the Norris' curve as the background field increases. Similar loss characteristics were observed in a multi filament Bi2223 / Ag sheathed tape [7][8]. Presently reasons for the discrepancy are not clear. It is considered partially because the n value decreases as the background field increases (see Fig. 2) [8]. From Fig. 4, the losses slightly decrease as the frequency

Fig. 1. Arrangement of sample wire.

TABLE I
SPECIFICATIONS OF SAMPLE WIRES

Sample	A	B	C	D
Material	Bi2223 (Ag sheathed)	Bi2223 (Ag sheathed)	Bi2212	YBCO (dep. Ag tape)
Shape	Tape	Square	Rod	Tape
Dimension (mm)	3.87 × 0.16	0.81 × 0.87	φ 5.6	9 × 0.1 (YBCO 0.5 μm thick)
I_c (A) (1 μV/cm) at 0 T, 77 K	38.1	2.1	283.5	2.1

Fig. 2. Dependence of critical current and n value on background field (Sample A: multilayered Bi2223 tape)

Fig. 3. Dependence of AC transport current losses on background field at 60 Hz. (Sample A)

Fig. 4. Dependence of AC transport current losses on frequency at 0 T. (Sample A)

increases. When $n = \infty$ (the Bean model holds in the wire), the losses are non-frequency-dependent hysteresis losses. However, when n is low, the losses tend to be lower at higher frequency [8] and this is the case for the sample A.

B. Sample B (Multilayered Bi2223 square wire)

Dependence of I_c and n value on the back ground field is shown Fig. 5, the AC losses dependent on the background field in Fig. 6 and the dependence of the losses on the

Fig. 5. Dependence of critical current and n value on background field. (Sample B: multilayered Bi2223/Ag sheathed square wire)

Fig. 6. Dependence of AC transport current losses on background field at 60 Hz. (Sample B)

Fig. 7. Dependence of AC transport current losses on frequency at 0 T. (Sample B)

frequency at 0 T in Fig. 7. Curves calculated by the Norris elliptical and strip models are also plotted in Fig. 6. As seen in Fig. 6, when the background field is zero, the measured losses follow the Norris' curve for the strip in the range $i = 0.3 \sim 1$. The losses depart from the strip model in the range $i < 0.3$ where the slope of the curve of measured data is more gentle than that of Norris' curve for the ellipse. When the background is applied, the loss data become closer to the Norris' curve for the ellipse. Detailed reasons for these loss behaviors are not clear. It is especially not clear why the loss data at 0 T follow the strip model in spite of the fact that the sample shape is square. At the moment, we considered those behaviors may be due to the inhomogeneous J_c distribution across the wire cross section which changes with the background field.

C. Sample C (Bi2212 rod)

The sample C had large I_c and was difficult to test in the background field. Therefore the background field dependence was not measured. The normalized AC transport current losses at 0 T are plotted against I_p / I_c for various frequency in Fig. 8.

The Norris curve in Fig. 8 is calculated from the elliptical (or round) model by assuming that the critical current density J_c is uniform across the cross section of the rod. Slopes of the Norris' and measured data curves are same but the measured data is lower than the Norris' curve, which may be because J_c is not uniform across the rod cross section. If J_c of the outer part of the rod is higher than that of core part, the result shown in Fig. 8 can be explained [9]. Regarding to the non-uniformity of J_c more studies are necessary. The losses decreased as the frequency increased, which may be caused by the relatively low n value.

D. Sample D (YBCO tape)

Dependence of I_c and n value on the background field is shown in Fig. 9, the AC transport current losses dependent on the background field shown in Fig. 10 and the frequency

Fig. 8. AC transport current losses vs. I_p / I_c for various frequency. (Sample C: Bi2212 rod)

dependence of the losses at 0 T is shown in Fig. 11. In Fig. 10, Norris' curves for elliptical and strip models are shown. As seen in Fig. 10, the loss data follow the strip model in the region of relatively high value of i when the background field is zero and when the background field is applied, the data

Fig. 9. Dependence of critical current and n value on background field. (Sample D: YBCO tape)

Fig. 10. Dependence of AC transport current losses on background field at 60 Hz. (Sample D)

Fig. 11. Dependence of AC transport current losses on frequency at 0 T. (Sample D)

move to the elliptical mode. In the region of relatively low value of i , the loss data depart from the strip model. As shown in Fig. 11 the losses increase as the frequency increases in the relative low i region, while the losses slightly decrease as the frequency increases in the relatively high i region. When the background field is not applied, it is considered the sample D, a thin film YBCO-deposited on Ag tape, has strip like current distribution and that the magnetization losses due to the transport current follow the strip model basically. However, the eddy current loss component in the Ag base tape becomes apparent when i and the magnetization loss become low. When the background field is applied, it is considered that the current distribution across the wire cross section becomes elliptical.

III. CONCLUSIONS

The transport current AC losses of different structures and different materials have been measured. Their dependence on the frequency and DC background field has been studied also. The results are compared with the Norris' elliptical and strip models and it has been found that there were discrepancies between the experimental data and theoretical calculations. The discrepancies were different by the samples and can be explained by inhomogeneity of J_c across the wire cross sections, the dependence of n value on the background field and the effect of eddy current losses. Therefore, by studying the discrepancies, the loss mechanism of wires of various structures can be studied.

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