Study on Relation between AC Characteristics and Critical Current Distribution in YBCO Tape

Osami Tsukamoto and Daisuke Miyagi

Faculty of Engineering, Yokohama National University, Yokohama, 240-8501 Japan

Abstract — We measured AC transport current loss of a high current density YBCO tape conductor. The tape conductor was made by depositing YBCO thin layer of $\sim 1\mu\text{m}$ thick on a LaAlO_3 single crystal substrate and its critical current was around 100A at 0T and 77K. The loss data deviated from the Norris curves for the elliptical and strip models. We made an analytical model to numerically calculate the AC transport current loss. In the model, critical current density (J_c) distribution in the wire cross section is taken into consideration. It is shown by the analysis based on the model that the deviation of the measured AC loss from the Norris equations is due to inhomogeneous J_c distribution in the cross section of the tape. The J_c distribution was investigated by subdividing the YBCO layer along the longitudinal direction. The results of the investigation are compared with the J_c distribution deduced from the analysis. The loss data showed frequency dependency, which can be explained by assuming that the loss has hysteretic and eddy-current-like loss components.

I. INTRODUCTION

A current limiter is one of most promising HTS power devices. A thin layer YBCO conductor has a property suitable for a super-to-normal transition type current limiter because the resistivity of a thin layer YBCO is high when it is quenched. Thin layer YBCO tape conductors with non-metallic substrates were developed for current limiters by Toshiba [1]. The YBCO layer of $1\mu\text{m}$ thick was deposited by a pulsed laser abrasion method on a single crystal LaAlO_3 substrate of 100mm long, 10mm wide and 1mm thick. The critical current I_c of the conductor was around 100A and the J_c was 10^6 A/cm^2 at 77K and 0T. AC transport current loss is an important characteristic of conductor used for a current limiter and we measured the AC transport current loss of the YBCO tape. The loss data deviated from the Norris curves [2] for the elliptical and strip models. We studied a reason for this deviation to understand AC transport loss characteristics of HTS tapes. We assumed that the deviation of the measured loss data from the Norris curves was due to inhomogeneous J_c distribution in the cross section of HTS tape and made an analytical model to numerically calculate the AC transport current loss due to magnetic hysteresis of the tape considering E - J characteristics also[3]. Based on this model, we estimated a J_c distribution for the analytical results to fit to the measured data. To investigate the validity of our model, we estimated J_c distribution of the tape by subdividing

the YBCO layer along the longitudinal direction. The J_c distribution thus experimentally measured was compared with that analytically estimated.

In the paper, experimental and analytical results are presented and the validity of our analytical model to calculate the AC transport current loss is examined.

The transfer current loss showed frequency dependency. The frequency dependency is explained also in this paper by assuming that the AC transport current loss has hysteretic and eddy-current like loss components.

II. AC TRANSPORT CURRENT LOSS MEASUREMENT

The AC transport current losses of the YBCO tape conductor were measured by the four terminal methods using a lock-in amplifier. I_c of the tape was 98A ($1\mu\text{V/cm}$) at 77K and 0T. In the experiment a peak of an AC current was more than 100A. Therefore, special cares need to be taken to reduce inductive voltage component in the signal from the potential taps attached on the tape conductor. The potential leads arrangement and measurement circuit used in our experiment are schematically shown in Fig. 1 [3]. By putting the sample in liquid nitrogen, we measured the losses for the frequency range $f = 30 \sim 960\text{Hz}$. The results are shown in

Fig. 1. The potential leads arrangement and block diagram of measurement circuit

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Figs. 2 and 3. In the graphs Figs. 2 and 3, the AC transport current losses per cycle are normalized by I_c^2 (Q_T [J/m/cycle/ I_c^2]) and the peak value of the transport current I_p is normalized by I_c ($i = I_p/I_c$). Fig. 2 shows Q_T vs. i for various values of f . In Fig. 2, the Norris curves for the elliptical and strip models are also shown and the measured data deviate from both of those curves. Fig. 3 shows the dependence of Q_T on f for various values of i . As seen in Fig. 3, the frequency dependency of Q_T is not obvious for higher values of i but becomes obvious for lower values of i .

III. AC TRANSPORT CURRENT LOSSES OF WIRE WITH INHOMOGENEOUS J_c DISTRIBUTION

In the Norris models calculating hysteretic AC transport current losses, it is assumed that J_c is constant in the cross section of the wire and that the current distributes according to the Bean model in the wire. We consider the main reason that the measured AC transport current losses of the tape were deviated from the Norris curves is inhomogeneous J_c distribution in the cross section of the tape. We made an analytical model to investigate influences of the

Fig. 2. Q_T vs. i for various values of f

Fig. 3. Frequency dependence of Q_T for various values of i

inhomogeneous J_c distribution on the AC transport current losses due to hysteretic losses [3]. In the model, we assumed the cross section of a wire was round for the simplicity of the analysis. We also assumed that the time dependent local current density $J(r,t)$ and the local critical current density $J_c(r)$ of the wire at r from the center of the wire are radially symmetric and that the local electric field $E(r,t)$ which is also radially symmetric follows the power-law E - J characteristics;

$$E = E_0 \times (J/J_c)^n \quad (1)$$

Where E_0 is the electric field where J_c is defined. When an AC transport current is applied to the wire, $J(r,t)$ and $E(r,t)$ are obtained by solving electromagnetic equations considering the E - J characteristics of Eq. (1). Then the AC transport current loss per one cycle Q_T is calculated from E and J . The calculated results using our model of the round wire are applicable to the elliptical wire without error if the n value in Eq. (1) is infinity (the Bean model) but there appear some errors for low n value. To check the validity of our model, we compared the AC transport current loss of an elliptical wire calculated using the finite element method (FEM) with that calculated by our method. The errors between our analysis and the FEM analysis are 20 ~ 25% [3] and small enough for the studies in this paper.

According to the analysis using the Bean model by Gomory et al. [5], the AC transport current losses are lower than the Norris curve for the elliptical wire whose J_c is higher at the edge area than at the center area of the superconducting region. Considering this, we assume a pattern of the J_c distribution in the wire as shown in Fig. 4. The comparison of the measured loss data with the analytical result is shown in Fig. 5. The analytical result well fits to the measured losses for $f = 30$ Hz.

IV. INVESTIGATION OF J_c DISTRIBUTION

The J_c distributions in the cross sections of the YBCO tape conductor were investigated by subdividing the tapes along the longitudinal direction. Only YBCO layer of the tape was subdivided into 3 strips, Strips I, II and III, by applying laser beam as schematically illustrated in Fig. 6. Gaps between the strips are about 20 μ m. Flowing a DC current through each strip independently, I_c of the strip was measured by detecting the voltage across the potential taps on the strip (I_c was defined by 1 μ V/cm). Some part of I_c was lost by subdividing and total of I_c 's of three strips was 85.4A. The average J_c determined from I_c of each strip is shown in Fig. 7.

V. DISCUSSIONS

A. J_c distribution

It is shown in Fig. 5 that the analytical and experimental results of the hysteretic AC transport current losses agree well if it is assumed that J_c in the edge area is higher than that in the center area as shown in Fig. 4. However, the measured J_c distribution shows that the J_c in one side of the edge area is higher than in the center area and that J_c in the other edge area is lower than in the center area. This discrepancy can be

Fig. 4. Assumed patterns of the J_c distribution (J_{c1} , J_{c2} , J_{c3}) in the wire.

Fig. 5. Comparison of measured and analytically calculated result

Fig. 6. Schematic illustration of subdivided YBCO tape (Dimensions in mm)

explained as follows. In the analysis, we assumed that the J_c distributions were radially symmetric for the simplicity of the analysis. However, the analytical values are not much changed even if the J_c distributions are modified to be radially asymmetric, as explained in Fig. 8, at least until the outer highest J_c area is saturated. In the analysis, co-centric round shape J_c distributions were assumed (Fig. 8 a)) and, in the modified J_c distribution, the centers of J_c distributions for J_{c2} and J_{c3} are departed from the center for J_{c1} (Fig. 8 b)). The modified round shape J_c distributions of Fig. 8 b) became as shown in Fig. 8 c) when the round shape is transformed to an elliptical shape. Then, average J_c of the subdivided strips become as show in Fig. 8 d). In Fig. 9, J_c distributions in the tape thus estimated from the analytical J_c distributions are shown and compared with the measured average J_c s in the subdivided strips. The analytically estimated J_c distributions reflect qualitatively the measured results. We consider that the discrepancy between the measured AC transport current

Fig. 7. Measured J_c s in strips I, II and III in Fig.4. Fig. 8. Modification of J_c distribution

losses due to the hysteresis and the Norris curve is caused by the inhomogeneous J_c distribution in the cross section of the tape.

B. Frequency dependency

We consider that the frequency dependency of the AC transport current losses (Fig. 3) can be explained by assuming that eddy-current-like, loss component Q_{ed} [J/cycle/ I_c^2] is mixed in the losses together with a hysteretic component Q_h [J/cycle/ I_c^2]. We assume Q_T is expressed as follows.

$$Q_T = Q_h + Q_{ed} \quad (2)$$

Q_{ed} is considered proportional to i^2 and f and expressed as $Q_{ed} = \alpha i^2 f$ where α is a constant. We consider the loss is dominated by the hysteretic component in a relatively low frequency region. Therefore, we assume Q_h in Eq. (2) is given by the analytically calculated losses which are fit to the measured curve for $f = 30\text{Hz}$ (Fig. 4). The value of α is determined by fitting Eq. (2) to the measured Q_T vs. f curve for a low value of i ($i=0.11$) in Fig.3, because in the range of low i , Q_h is low and frequency dependence of Q_T is more obvious. In Fig. 10, Q_T vs. f curves calculated from Eq. (2)

Fig. 9. Comparison of J_c distributions measured and analytically deduced. J_c 's in the strip I and III are normalized by that in the center strip II for both of measured and analytically deduced distributions.

using the determined value of $\alpha (=1.08 \times 10^{-13})$ are plotted for various i and compared with the measured data. The agreement is reasonably good. Therefore, we consider the frequency dependent AC transport current losses contain eddy-current-like loss component. The tested tape conductor has no normal metallic components except small parts of silver coating for current leads and potential taps. Therefore, We consider the eddy-current-like losses are occurring in the superconducting layer.

VI. CONCLUSIONS

We measured AC transport current losses of the YBCO tapes. The losses were deviated from Norris curves for the elliptical and strip models and had frequency dependency. We studied causes for those phenomena. The conclusions of the study are as follows;

1. The AC transport current losses of the YBCO tape conductor contain hysteretic and eddy-current like loss components.
2. The eddy-current like loss component Q_{ed} can be estimated by a term $\alpha i^2 f$. The coefficient α can be determined from the measured Q_T vs. f curve for a relative low value of i .
3. The hysteretic loss component was deviated from the Norris curves for both of elliptical and strip models. This deviation can be explained by inhomogeneous J_c distribution in the cross section of the tape conductor. The analytical results well coincide with the measured results provided that the J_c distributions are properly assumed.
4. J_c distributions of the tested tapes were measured by subdividing the YBCO layers on the substrates. There was a discrepancy between the J_c distribution assumed in

Fig. 10. Comparison of measured Q_T vs. f and calculated curves

the analysis and that measured. However, this discrepancy is explained by assuming radially asymmetric J_c distributions. Therefore, we can conclude that the deviations of the measured AC transport current losses from the Norris curves can be explained by inhomogeneous J_c distributions in the cross section of the tape.

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