AC Loss Characteristics of Multifilamentary HTS Tapes

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***Abstract*—AC losses in multifilamentary HTS tapes can be classified to hysteresis loss, coupling loss, and eddy current loss from the viewpoint of their generation mechanism. From the viewpoint of the major magnetic field component generating them, they can be classified to magnetization loss, transport loss, and total loss. Dividing superconductor to fine filaments, twisting filaments bundle and increasing transverse resistivity are effectively reduce magnetization loss and total loss when the external magnetic field is relatively large. Recently, twisted multifilamentary Bi 2223 tapes with pure silver matrix were fabricated and the reduction of magnetization loss was proved experimentally in the parallel magnetic field to the tape wide face. However, when the perpendicular magnetic field is applied, increasing transverse resistivity is required essentially to reduce the AC losses. The transverse resistivity was increased successfully by the introduction of resistive barrier between filaments.**

I. INTRODUCTION

Understanding AC loss characteristics is one of important issues in research and development of HTS tapes for AC application. In this paper, first, the mechanism of AC loss generation is explained briefly. Second, AC losses are classified by the magnetic field component gererating them; magnetization loss, transport loss and total loss. The characteristics of magnetization loss and transport loss are explained analytically. Next, numerically calculated total loss in the tape carrying their transport current and exposed to the external magnetic field are shown. Then, an experimental result on magnetization loss measurement of twisted multifilamentary Bi 2223 tapes with pure silver matrix is presented. Finally, performance of a inter-filament barrier to increase transverse resistivity is described.

II. MECHANISM OF AC LOSS GENERATION [1]

When a magnetic flux penetrates into type II superconductor, fluxoids motion driven by Lorentz force against pining force results in energy dissipation. This energy dissipation is AC loss called hysteresis loss.

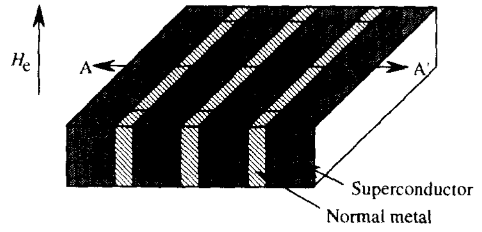
Hysteresis loss can be reduced by decreasing thickness of superconductor. Therefore, in practical superconducting wires, superconductor is divided to fine filaments and embedded in normal metal matrix. Superconducting wire with such a structure is called multifilamentary wire. Recently, multifilamentary Bi 2223 tapes are fabricated by a number of manufacturers. Silver or silver alloy is used as matrix in multifilamentary Bi 2223 tapes. When the external magnetic field is applied to a multifilamentary HTS tape, shielding current might flow through a path consisting of superconducting filament and matrix. In this case, Joule loss in matrix is called coupling loss. Eddy current loss is Joule loss due to the shielding current flowing matrix only.

III. MAGNETIZATION LOSS, TRANSPORT LOSS, AND TOTAL LOSS OF MULTIFILAMENTARY HTS TAPES [1]

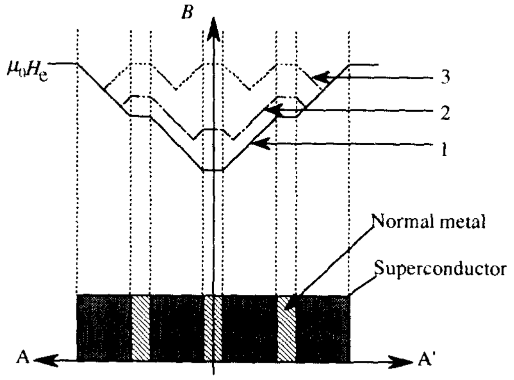
AC losses in multifilamentary HTS tapes can be classified by the magnetic field component that is the source of AC loss. Magnetic field can be classified to the external magnetic field and self magnetic field produced by the transport current of the tape. The AC loss generated by the external magnetic field is called magnetization loss. The AC loss generated by the self magnetic field is called transport loss or self field loss. The AC loss in HTS tape carrying AC transport current and exposed to AC external magnetic field is called total loss.

A. *Magnetization Loss*

In Fig. 1(a), a multifilamentary HTS tape is modeled with a sandwich structure of superconductor and normal metal.



(a) Sandwich structure of superconductor and normal metal



(b) Magnetic flux distribution

Fig. 1 Model of multifilamentary HTS tapes.

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When the external magnetic field that is perpendicular to the tape axis is applied, the shielding current flows through normal metal and superconductor as shown in Fig. 1(a) with a solid line. Unless this shielding current decays rapidly, filaments are coupled, and the magnetic flux distribution is almost same as that in not divided monofilament tape as the line denoted 1 in Fig. 1(b). In such a situation, hysteresis loss cannot be reduced by dividing superconductor. To reduce the decay time constant of this shielding current to decouple filaments, that is, to reduce hysteresis loss, twisting filament bundles and increasing transverse resistivity between filaments are effective. As the shielding current through normal matrix decays, the magnetic flux distribution changes from1 to 3 in Fig. 1(b).

In Fig. 2, magnetization loss of multifilamentary HTS tapes where filaments are decoupled or coupled is plotted against the applied magnetic field. Here, the applied transverse magnetic field is parallel to the tape wide face. In tape where the filaments are decoupled or coupled, each filament or filamentary region is approximated with the slab of superconductor to calculate the hysteresis loss, respectively. In large magnetic field region that is important practically, the loss is reduced when the filaments are decoupled.

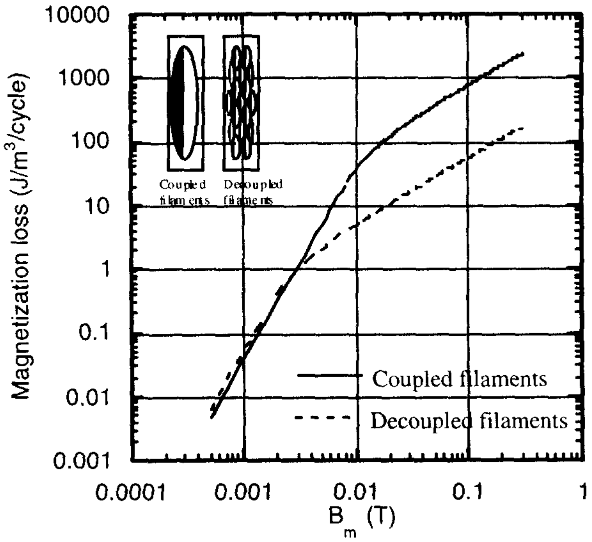


Fig. 2 Magnetization loss of multifilamentary HTS tapes where filaments are decoupled or coupled.

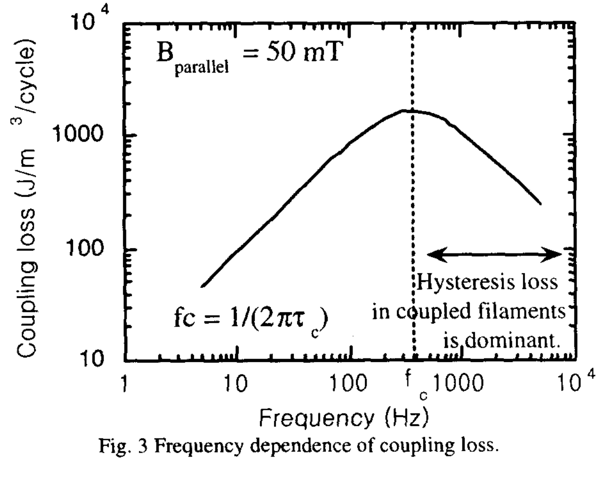


Fig. 3 Frequency dependence of coupling loss.

In Fig. 3, coupling loss per cycle in a twisted multifilamentary HTS tape is plotted against frequency. It is to be noted that coupling loss per cycle becomes maximum at a frequency, $f_c = 1/(2\pi\tau_c)$, where τ_c is the coupling time constant. At frequency lager than f_c, coupling loss decreases with increasing frequency, but the filaments are coupled to increase hysteresis loss. In this region, large hysteresis loss in the coupled filaments is the dominant component of AC loss.

When the operational frequency becomes much smaller than f_c, both of coupling loss and hysteresis loss becomes small. Therefore, coupling time constant must be decreased to reduce the magnetization loss effectively. The coupling time constant of multifilamentary HTS tape is given in [2]. It can be decreased by decreasing twist pitch and / or increasing transverse resistivity between filaments.

B. Transport Loss

When multifilamentary HTS tape carry their transport current, the almost azimuthal self magnetic field penetrates into the tape from its surface. Peripheral filaments are coupled against the self magnetic field, and the transport loss is the hysteresis loss of these coupled peripheral filaments. Twisting filament bundle and increasing transverse resistivity are almost meaningless to decouple filaments against the self magnetic field, that is, to reduce the transport loss. Norris gave analytical expressions of the transport loss based on Bean's critical state model [3]. Usually, the cross sectional shape of filamentary region of multifilamentary Bi 2223 tapes is approximated with ellipse to apply the Norris's theory. In Fig. 4, the transport is plotted against I_t / I_c by Norris's theory.

C. Total Loss

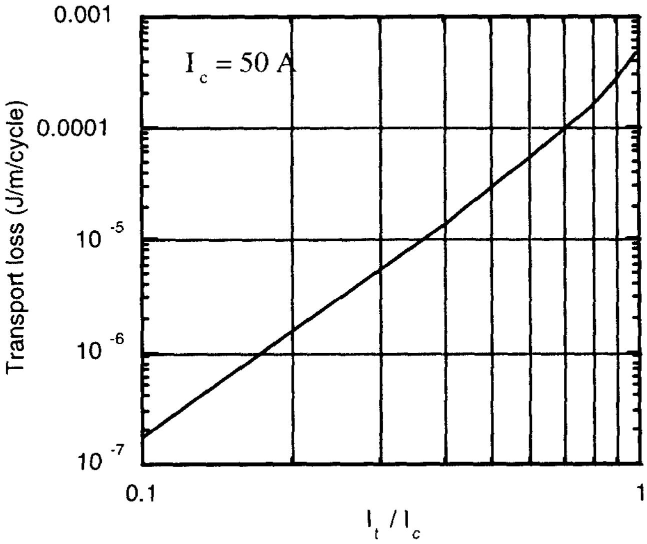


Fig. 4 Analytical transport loss where I_c = 50 A.

In electrical power apparatuses, HTS tapes must carry their transport current in the external magnetic field. Therefore, the total loss in such a condition is practically important, but any general analytical expression of the total loss has not been derived. As shown bellow, numerical calculations are useful to estimate the total loss.

IV. NUMERICAL CALCULATION OF TOTAL LOSS

A. *Theoretical Method [4, 5]*

The temporal evolution of current and magnetic flux distribution in multifilamentary Bi 2223 tapes is calculated numerically by the FEM to evaluate the total AC loss. Superconducting property is represented with a power law *E-J* curve. An equivalent conductivity of superconductor is derived from the power law *E-J* curve. Ohm's law with this equivalent conductivity is used as the constitutive equation to solve Maxwell's equation. Twisted structure can be represented by tensor equivalent conductivity.

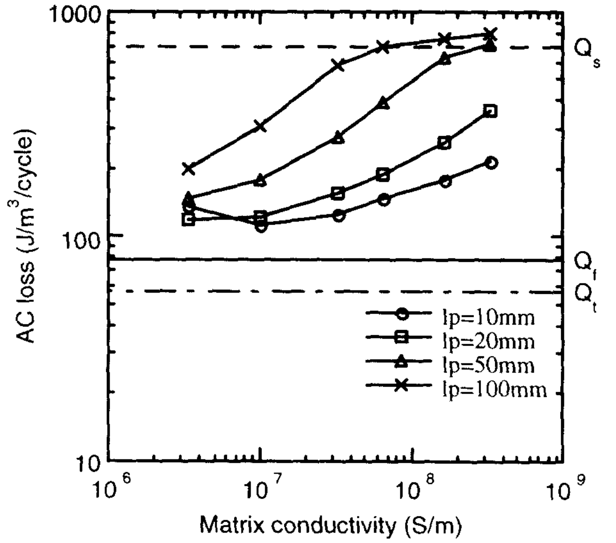
B. *Total Loss in Twisted Multifilamentary HTS Tapes [6]*

As described in III. *A*, twist pitch and transverse resistivity, that is, matrix conductivity, are important parameters to reduce the AC loss against the transverse magnetic field. In Figs. 5(a) and (b), the total loss in a tape carrying its transport current in parallel and perpendicular magnetic field are plotted against the matrix conductivity for various twist pitches where $I_t / I_c = 0.7$. As shown in Fig. 5(a), the total loss in parallel magnetic field can be reduced by decreasing twist pitch, while silver whose conductivity is 3.3×10^8 S/m is used as matrix, as well as decreasing matrix conductivity. However, in perpendicular magnetic field, Fig. 5(b) shows that decreasing matrix conductivity, or increasing transverse resistivity, is required essentially to reduce the total loss.

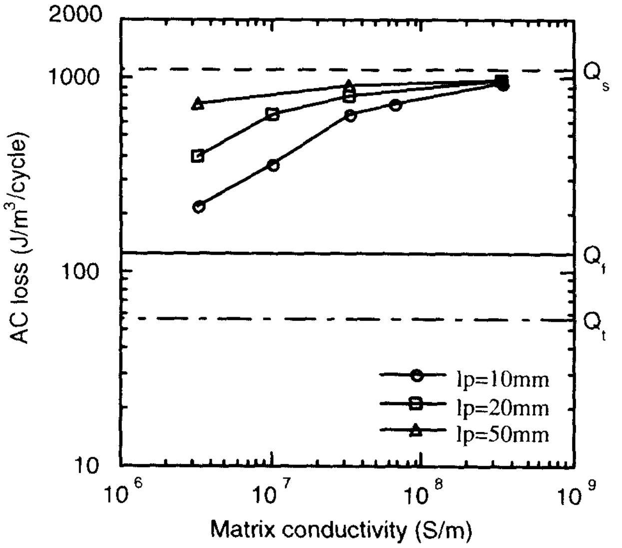
V. CHARACTERISTICS OF ADVANCED MULTIFILAMENTARY BI 2223 TAPES [6]

A. *Twisted Multifilamentary Bi 2223 Tape With Pure Silver Matrix*

To confirm the effect of twisting, the inter-filament bridging must be suppressed. The spacing between filaments was increased to ensure the suppression of the inter-filament bridging. AC magnetization loss was measured for twisted and untwisted Bi 2223 tapes with pure silver matrix. Fig. 6 shows the measured loss factor that is the loss normalized the magnetic field energy of vacuum. Theoretical values of tapes where filaments are coupled or decoupled are also shown. Measured loss of the untwisted tape almost agrees with the theoretical value of the tape where filaments are coupled.



(a) In parallel magnetic field of 0.1 T



(b) In perpendicular magnetic field of 0.01 T

Fig. 5 Total loss in twisted Bi 2223 tapes where $I_t / I_c = 0.7$ [6].

The magnetic field giving the maximum loss factor is the full penetration field. The full penetration field decreases by twisting. This means that the filaments are decoupled by twisting, though the loss of the twisted tape at 61 Hz contains coupling loss component . The measured loss of the twisted tape at 1 Hz almost agrees with the theoretical value of the tape where filaments are decoupled.

B. *Multifilamentary Bi 2223 Tape With Inter Filament Resistive Barrier*

As shown in IV.*B*, increasing transverse resistivity is required essentially to reduce the total loss. To increase the transverse resistivity, introduction of resistive barrier between filaments is effective. A seven-filament Bi 2223 tape with inter filament barrier of Bi 2201 was fabricated by Sumitomo Electric Industries [7], and its characteristics have been tested at Yokohama National University [7]. Its cross

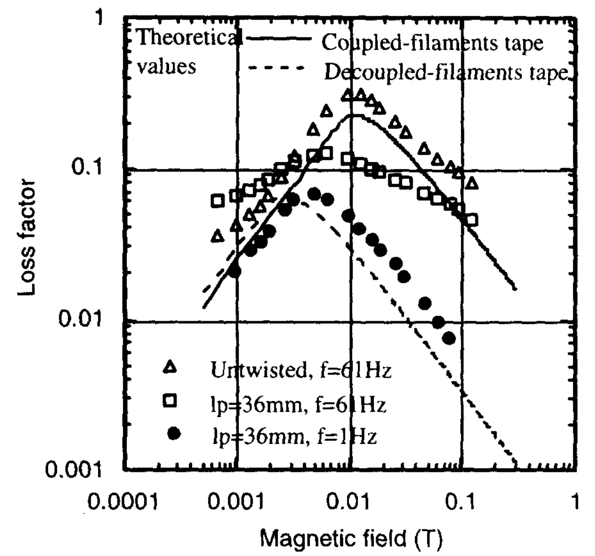


Fig. 6 Magnetization loss of twisted Bi 2223 tapes with pure silver matrix in parallel magnetic field [7].

section is shown in Fig. 7. Bi 2201 phase that is not superconducting at 77 K can be used as material for resistive barrier. To evaluate the transverse resistivity of the tape, frequency dependence of the magnetization loss was measured with a 20 mm piece of the tape as shown in Fig. 8. The transverse resistivity estimated from the frequency giving the peak in this curve is 4.7×10^{-8} Ωm. This is 16 times larger than the resistivity of pure silver at 77 K.

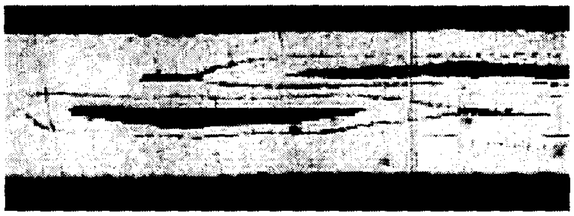


Fig. 7 Cross section of Bi 2223 tape with Bi 2201 barrier [7].

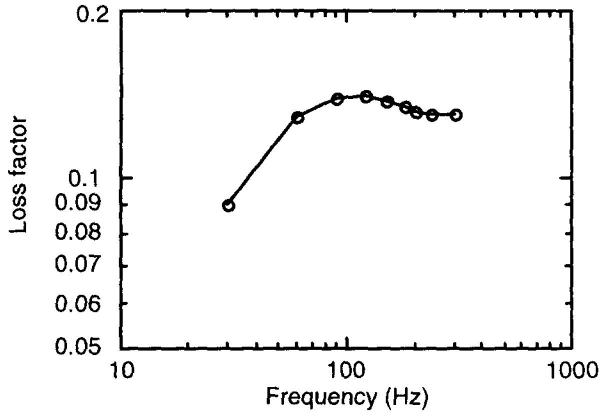


Fig. 8 Frequency dependence of magnetization loss of 20 mm piece of Bi 2223 tape with Bi 2201 barrier measured at $B_m = 0.5$ mT [7].

VI. CONCLUDING REMARK

The AC loss characteristics of multifilamentary HTS tapes are substantially influenced by the major magnetic field component generating it. Dividing superconductor to fine filaments, twisting filaments bundle and increasing transverse resistivity are effectively reduce magnetization loss and total loss when the external magnetic field is relatively large. Recently, advanced multifilamentary Bi2223 tapes have been developed based on these ideas to reduce AC loss. They are expected to lead to the realization of superconducting electrical apparatuses.

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