Investigation of Intertape Coupling Losses in YBCO-Stacked Cables*)

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We investigated intertape coupling losses in yttrium barium copper oxide (YBCO)-stacked cables. YBCO stacked cables are being researched and developed as candidates for large 100 kA-class conductors for nuclear fusion. Here, we report intertape coupling losses in a conductor of 50 stacked tapes measured in liquid nitrogen. The measured conductor consists of soldered intertape connections. A copper layer surrounded the YBCO tape in the sample conductor. Fifty YBCO tapes were stacked, and the entire sample was bound with a copper tape and then impregnated with solder. This sample was approximately 100 mm long without twisting. The intertape coupling current flowed over the entire length of the sample conductor due to nontwisting. First, intertape resistance was estimated by comparing the measured and theoretical coupling losses. Subsequently, the coupling current paths in the cross-section of the sample were investigated. We found that intertape resistances were affected by the copper tape used to bind the stacked YBCO tapes.

Keywords: intertape coupling loss, stacked cable, rare-earth barium copper oxide

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1. Introduction

The application of multiple layers of tape-shaped rare-earth barium copper oxide (REBCO) tapes stacked and twisted together as conductors for superconducting magnets in nuclear fusion experimental devices is being investigated [1–4]. Given that these conductors are exposed to a changing magnetic field during the excitation and discharging of magnets, coupling and hysteresis losses are generated simultaneously in the conductors when the tapes in the conductors are electrically connected and twisted [5–8]. Our previous study measured the AC loss properties of a model sample conductor composed of stacked and soldered yttrium barium copper oxide (YBCO) tapes under transverse AC magnetic fields [9]. In the sample, hysteresis and coupling losses were simultaneously generated. However, the influence of the diamagnetism of the superconducting strip on coupling losses in such conductors has not been observed. Therefore, coupling losses could be evaluated based on the calculated linked magnetic flux between tapes, considering only the magnetic fields parallel to the flat face of the YBCO tapes. Knowing the magnitude of the resistance between tapes and the paths of the coupling current is necessary to estimate the properties of coupling losses and current distributions in actual conductors and to design optimized conductors. Intertape resistances are affected by several factors, such as conductor or coil structures and wind conditions. Coil structures and conditions can change the surface compaction between tape faces or the conditions of the tape surface; as a result, intertape resistances are strongly affected by their conditions. Therefore, the only way to evaluate the characteristics of actual conductors quantitatively is to measure fabricated prototypes. Nevertheless, this approach is difficult due to the limitations of costs and measuring systems.

This study aims to obtain basic knowledge of the intertape resistances of stacked REBCO tape conductors. For this purpose, we performed experiments and analyses on a soldered model conductor consisting of 50 stacked YBCO tapes. First, the intertape resistance was estimated by comparing the measured and theoretical coupling losses. Then, the coupling current paths in the cross-section of the sample were investigated. Our results showed that intertape resistances were affected by the copper tape used to bind the stacked YBCO tapes.

2. Evaluation of Coupling Losses

In this paper, we discuss the magnitude of the intertape electrical resistances of conductors made of stacked YBCO tapes with solder connections between tapes. For this purpose, a straight conductor approximately 100 mm in length was used as a sample for measurement. Although this sample conductor was not twisted, the whole

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Fig. 1 Overview of the model conductor [9].

Table 1 Parameters of the YBCO tape.

Width	6 mm
Substrate material	Hastelloy C276
Thickness of substrate	63 ± 3 µm
Thickness of the silver layer	2 µm
Surround copper layer	20 µm per side
Manufacturer	SuperOx

[a] s.f: self-field

Table 2 Parameters of the samples.

Superconducting material	YBCO
Width	6mm
Thickness	7mm
length	96mm
Number of tapes	50
Ic of a tape	200A
Refrigerant	Liquid nitrogen

length of the samples formed a closed loop of 100 mm in length. Therefore, the changing magnetic field component parallel to the tape face caused the coupling current to flow between tapes via intertape resistances in a closed loop 100 mm in length. Therefore, intertape coupling losses were generated in the conductors. The intertape resistances of the soldered samples composed of the stacked YBCO tapes were estimated from the measured coupling losses in Ref. [9]. Measurements were conducted under the condition that intertape coupling losses in the samples are mainly observed by applying a magnetic field parallel to the tape face of the stacked tapes in the sample. The magnitudes of intertape resistances were evaluated by comparing the analyzed and measured coupling losses. This section describes the details of the samples, the method for measuring AC losses in the samples, and the results of the measurements.

2.1 Parameters of the sample conductor

The external view of the sample conductor is shown in Fig. 1, and the parameters are listed in Tables 1 and 2 [9]. The soldered sample was prepared as follows: 50 layers of YBCO tape (SuperOx) with a thickness of 0.11 mm and a width of 6 mm were laminated with indium solder and fixed by wrapping a 4-mm wide, 0.1-mm thick copper tape around them. Then, the entire conductor was impregnated with solder. All work was carried out in the atmosphere.

2.2 Measuring method

AC losses in the samples were measured via the pickup coil method. The arrangement of the measuring system is shown in Fig. 2 [9]. For the measurement of the unsoldered sample, the angles formed by the applied magnetic field and the flat face of the tape were set to 0°. The amplitude of the applied magnetic field was 3.2 - 77.0 mT, and the frequency was 1 - 100 Hz.

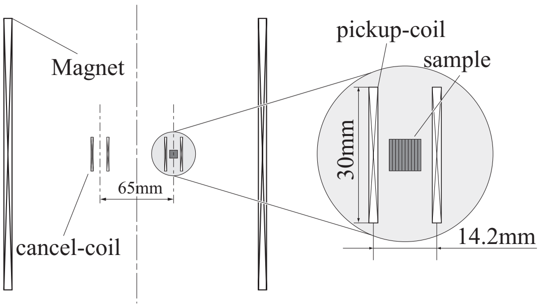

Fig. 2 Measuring system [9].

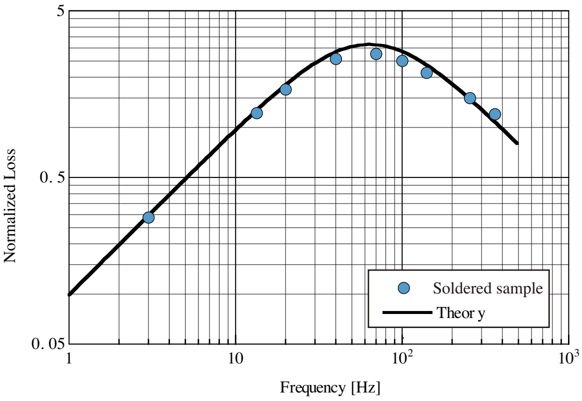

Fig. 3 Frequency dependence of coupling losses in the sample [9, 10].

2.3 Results

The frequency dependence of the normalized AC losses in the sample is shown in Fig. 3 [9]. The vertical and horizontal axes represent normalized AC losses and frequency, respectively. Normalized losses are defined by normalizing losses per unit volume of the sample and per cycle of the applied ac magnetic fields by $\mu_0 H_m^2$, where μ_0 is the permeability in a vacuum and H_m is the amplitude of magnetic fields. The measured losses in the sample were proportional to the square of the amplitude of the applied magnetic field. This finding indicated that the measured losses were mainly coupling losses.

The obtained frequency dependences of the coupling losses followed the Debye curve [10].

3. Discussion

3.1 Calculation of intertape resistance

Intertape coupling losses in the samples were theoretically calculated to estimate intertape resistances. Intertape resistances were estimated through the comparison of measured and calculated coupling losses. First, the procedure used to obtain the coupling loss time constant from measured coupling losses to indicate magnitude losses for omitting the effect of the applied magnetic field waveform is reported. Second, the theoretical coupling loss expression of the samples is explained. Finally, the comparison with measured and calculated coupling losses is described.

This method's resistance values are estimated under uniform contact between the tapes. In the samples, the resistance between tapes may not be uniform. However, it is considered that the nonuniformity of resistance between the tapes in the present samples was not significant, because the samples had a relatively simple stacked-tape structure. If irregular contact exists between tapes in the samples, the coupling current loop becomes more complex, and multiple time constants may exist in the sample. However, since the actual important values are the total quantity of the coupling losses, an appropriate coupling loss time constant can be defined as a representative value. The average resistance would determine this value.

To estimate intertape resistances, the coupling loss time constant must be determined from the coupling loss obtained experimentally. The procedure is explained below.

The following equation, which uses the magnetic permeability μ_0, expresses the coupling losses W_c that are generated in the multifilamentary superconducting wires with round cross-sections when AC magnetic fields of amplitude H_m are applied to the wires:

$$W_c = A^*Q^*\mu_0 H_\mathrm{m}^2, \tag{1}$$

$$Q^* = \pi\frac{\omega\tau}{1+(\omega\tau)^2}, \tag{2}$$

where A^* represents a factor that varies with the cross-sectional shape of the wire, and Q^* is the normalized loss determined by the coupling time constant τ and the applied magnetic field waveform [10]. The coupling time constant τ is the decay time constant of the coupling current flowing between the filaments in the wires. The normalized loss A^*Q^* is obtained by normalizing W_c by $\mu_0 H_\mathrm{m}^2$. When the applied magnetic field is sinusoidal and $\omega\tau \ll 1$ in actual operation, the normalized loss is expressed by the following equation:

$$A^*Q^* = A^*\pi\omega\tau, \tag{3}$$

$A^*\tau$ is defined as the coupling loss time constant as an indicator of the magnitude of coupling loss to omit the effect of the applied magnetic field waveform and amplitudes. $A^*\tau$ can be obtained from the measured coupling loss in the low-frequency region, in which the coupling loss is proportional to the frequency. The coupling loss time constants for the sample are 4.3×10^{-3} s.

To clarify whether Eqs. (1), (2) can be applied to the present sample, we compared the frequency dependence of the coupling loss in the sample with the theoretical value. The frequency dependence is shown in Fig. 3. The solid line is the value of the circular cross-section obtained by multiplying Eq. (2) by $A^* = 2$. Given that the sample cross-section is close to a square, using $A^* = 2$ is a good approximation. The measured and theoretical results were in very good agreement. Therefore, the properties of the sample can be expressed using a single coupling time constant. This finding indicated that the sample had uniform tape-to-tape resistance.

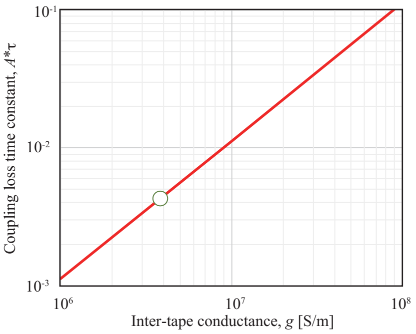

Fig. 4 Coupling loss time constants vs. intertape conductance. Intertape conductance was estimated to be 3.8 MS/m from the measured coupling loss time constant of 4.3 ms by using Eq. (4).

The theoretical expression of normalized coupling losses in the parallel superconducting tapes is as follows:

$$A^*Q^* = \frac{1}{3V_\mathrm{s}} g d^2 \pi^2 f {L_\mathrm{s}}^3 \mu_0, \tag{4}$$

where the thickness of the conductor is d, the length of the conductor is L_s, the volume is V_s, and the intertape conductance per unit length between tapes is g. This expression was calculated under the application of changing magnetic fields on the conductor. The magnetic fields were assumed to change with a sinusoidal waveform. The relationship between the coupling loss time constant and intertape conductance is shown in Fig. 4. Equation (4) and the coupling loss time constant estimated from measured coupling losses by using Eq. (3) are represented by a solid line and plot, respectively.

Intertape conductance can be obtained from the estimated coupling loss time constant of 4.3 ms and Eq. (4). As a result, the intertape conductance of the sample was estimated to be 3.8 MS/m. This value is shown as an open circle in Fig. 4. Therefore, the intertape resistance was estimated to be 0.26 μΩm from the inverse of the conductance.

3.2 Estimation of the conductance of one tape

The conductance of the one tape was estimated from experiments and FEM analyses to investigate the validity of the value of intertape resistance. In the experiments, a DC of 2 A was conducted from the Hastelloy side to the superconducting side of the YBCO tapes with a copper layer, as shown in Fig. 5. The thickness of the copper layer was 20 μm. The width of the tape was 4 mm. The distributions

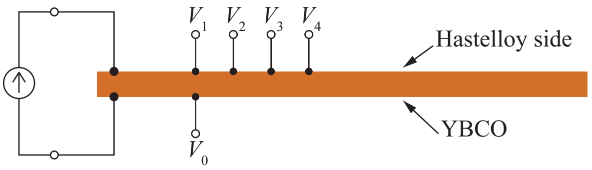

Fig. 5 Potential distribution measuring setup.

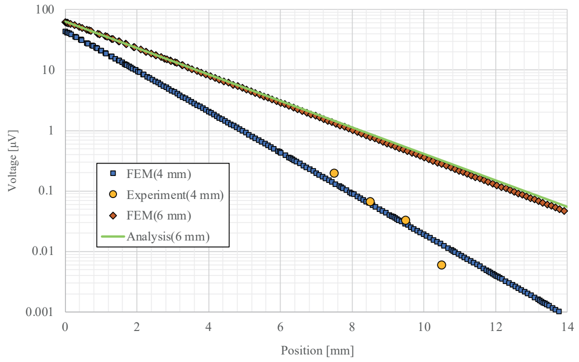

Fig. 6 Distributions of potentials along the tape.

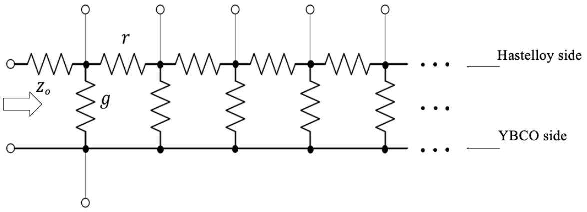

Fig. 7 Distributed constant circuit model of the YBCO tape.

of the potentials along the tape were measured. The measured potential distributions are shown by circles in Fig. 6. 3D-FEM analyses were carried out on the same sample dimension. The results are presented in Fig. 6. The experiment and FEM analyses were in good agreement. Therefore, the validity of the FEM analyses was confirmed.

Next, the YBCO tape with the same parameters as the sample used to measure coupling losses was subjected to 3D-FEM analyses. The diamond plots in Fig. 6 depict the results. The solid line in Fig. 6 shows the fitting curve based on the distributed constant circuit model. The distributed constant circuit model of the YBCO tape under DC is illustrated in Fig. 7. The longitudinal resistance per unit length is r, and the transverse conductance per unit length is g. The potential distribution along the tape is expressed by

$$V = Z_0 I \frac{\cosh \gamma (L - x)}{\sinh \gamma L}, \tag{5}$$

where γ, Z_0, and L represent the propagation constant, characteristic impedance, and sample length, respectively. γ, Z_0 are expressed by

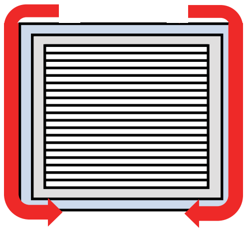

Fig. 8 Current path flowing into the outer copper tape.

$$Z_0 = \sqrt{\frac{r}{g}}, \tag{6}$$

$$\gamma = \sqrt{rg}. \tag{7}$$

From the fitting parameters, g is estimated to be 16 MS/m. In the case of 50 stacked YBCO tapes, intertape conductance was estimated to be 0.32 MS/m. However, this value was only below 1/10 of the value of 3.8 MS/m estimated from coupling loss. This finding indicated that another current path existed in the sample.

The copper tape surrounding the sample was considered another current path. Figure 8 illustrates the current path. FEM analyses were carried out on the model with a space in place of the YBCO-stacked tape conductor. The estimated conductance between the top and bottom was 6.4 MS/m. The intertape conductance evaluated from intertape coupling losses was 3.8 MS/m, whereas the conductance due to the outer copper tape was 6.4 MS/m. This difference suggested that electrical resistance existed between the stacked cable conductor and the copper tape on its outer surface. This resistance was believed to be due to the solder. This finding indicated that coupling loss properties were strongly affected by the outer shell surrounding the stacked cable. Therefore, when actual conductors are designed, the resistance between the main conductors and the outer jacket with metal should be considered alongside the resistance between tapes in the inner main stacked conductor consisting of REBCO tapes. Intentionally inserting a resistive layer between the outer normal-conductive jacket and the inner stacked-tape conductor, as in the solder layer in this sample, effectively reduces intertape coupling losses. Notably, the resistance of this resistive layer must be determined by taking into account even the effect of improved stability due to current transfer to the normal-conductive jacket from the inner conductor.

4. Conclusions

Intertape coupling losses in stacked YBCO tape conductors with soldering were measured, and intertape resistance was estimated. The intertape resistance per unit length was 0.26 μΩm. The outer copper tape surrounding the stacked cables was the main coupling current path. Therefore, when actual conductors are designed, the resistance between tapes and that between the outer jacket and inner stacked cable must be considered.

Acknowledgments

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