Origins of errors in AC transport current loss measurements of HTS tapes and methods to suppress errors

O. Tsukamoto, J. Ogawa, M. Cizek, D. Miyagi, I. Okazaki, Y. Niidome and S. Fukui

Abstract—This paper addresses an electrical measurement method of AC transport current losses in HTS tapes. In the method, there are various origins of errors e.g. improper arrangement of leads from the voltage taps on an HTS tape, phase errors of a current measuring device and inductive voltage cancellation device, external magnetic field, magnetization of neighboring tapes and common mode noise in the voltage signal from the sample. Influence of those errors are studied, and methods to suppress the errors are discussed. In the paper, some techniques which can minimize the errors are recommended.

Index Terms—HTS tape, AC transport current loss, electrical measurement error.

I. INTRODUCTION

Power transmission cables, transformers and current limiters are the most promising future applications of high T_c superconductors (HTS). The knowledge of AC losses and understanding of loss mechanisms in HTS wires are important to design those AC power devices and develop low AC loss HTS wires and windings. To obtain those, it is necessary to develop a method of measuring the losses with high accuracy and resolution.

Energy is dissipated in a wire when it is affected by AC transport current, and/or external AC magnetic. The AC transport current loss is caused by a current source connected to a wire and the AC magnetization loss is caused by the external magnetic field.

In this paper, some methods which improve the accuracy and resolution of electrical measurement techniques for AC transport current losses are described.

II. SETUP FOR ELECTRICAL MEASUREMENT OF AC TRANSPORT LOSSES AND ORIGINS OF ERRORS

A typical measurement circuit of the AC transport current loss of an HTS tape is illustrated in Fig.1 [1]. An AC transport current $i(t)$ is applied to the sample wire through a current transformer which is necessary to avoid direct

electrical contact between the measurement current and the power supply. The transport current is expressed as $i(t) = I \cos \omega t$ where I and ω are the amplitude and angular frequency, respectively. The voltage $e_p(t)$ between the voltage taps attached to the sample contains resistive and inductive components and is expressed as follows.

$$e_p(t) = E_r \cos \omega t + E_i \sin \omega t \quad (1)$$

where E_r and E_i are amplitudes of the resistive and inductive components, respectively. If we can properly measure E_r by a lock-in amplifier and I by a shunt resistor, the AC transport current loss power is given by $E_r I / 2$. However, there are some possible sources of errors in existing electrical measurement systems.

i) Errors caused by voltage measurement loop arrangement.

The HTS conductors are usually tape-shaped with a high aspect ratio. It has been pointed out that the voltage measurement loop should include the magnetic flux over a distance much larger than the tape's width in order to measure losses correctly [2]. However, the wide voltage loop covers a large area, which induces a large inductive voltage causing errors. The rectangular loop picks up spurious loss signals due to neighboring tapes when multiple tapes are assembled. We solved these problems by a new voltage leads arrangement where the leads from the voltage taps on the tape are wound spirally on a cylindrical surface enclosing a tape under investigation [3].

ii) Errors caused by phase errors

It is well known that a phase error in measuring the sample current causes a serious error because E_i becomes 100~1000 times larger than E_r . Therefore, a cancellation of E_i is necessary to bring its level down to the same level of E_r .

Fig. 1. Schematic circuit of AC transport current loss measurement.

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O. Tsukamoto, J. Ogawa, M. Cizek, D. Miyagi, I. Okazaki, and Y. Niidome are with the Yokohama National University, Faculty of Engineering, Yokohama 240-8501, Japan (telephone: +81-45-339-4121, e-mail: osami@tuskalab.dnj.yun.ac.jp).

S. Fukui is with the Niigata University, Faculty of Engineering, Niigata 950-2181, Japan (telephone: +81-025-262-6731, e-mail: fukui@eng.niigata-u.ac.jp).

because the sensitivity range of a lock-in amplifier is the same for the both, in-phase, and out-of-phase channels. E_i is canceled usually by using a cancel coil as shown in Fig.1. In this case, we should be aware that there can be a phase error in the output voltage of the cancel coil.

iii) Common mode noise

A common mode noise appears in the measurement circuit. Although a typical lock-in amplifier has 100~120 dB common mode rejection ratio, the common mode noise may cause errors in the measurement because E_r is in the level of several nV in some cases [4].

III. METHODS TO SUPPRESS ERRORS

A. Spiral voltage loop arrangement

The spiral voltage loop arrangement compared with the conventional rectangular loop is illustrated in Fig.2. Here R_S is the radius of the cylindrical surface and R_R the distance between the center of the tape and the place where the potential wires are twisted together. The losses measured by the spiral and rectangular loops are denoted as P_S and P_R , respectively.

The AC transport current loss measurement using the spiral voltage loop has the following features:

1. P_S gives the correct value of the transport current loss regardless of R_S ($R_S > d/2$, where d is the width of the tape).
2. To obtain the correct value of the transport loss, voltage leads should be a spiral of a constant pitch on the cylindrical surface of constant radius and the number of turns of the spiral should be exact integer.
3. P_S gives the correct value even when the center axis of the tape deviates from the axis of the cylindrical surface, as far as the spiral loop encloses the wire.
4. P_S gives the transport current loss in the tape enclosed by the cylindrical surface even when the external magnetic field exists.
5. Positions of the two voltage taps on the tape do not affect the results, provided that the angle difference between the two taps in the cylindrical coordinate is 2π and that the number of turns of the spiral is integer.
6. The inductive component of the voltage of the spiral loop is smaller than that of the rectangular loop, because R_S can be close to $d/2$. In contrary, R_R should be larger than $d/2$ to make the error small.

Fig. 2. Illustration of spiral and rectangular voltage loop arrangement.

Those features are proven by theoretical and/or numerical analyses and also by experiments. Theoretical works for the proof have been presented in [3] and additional results of numerical analyses and experiments are given here.

In the numerical analysis, the Bean model and elliptical cross section of the superconductor are assumed. The magnetic field produced by the wire carrying the transport current is calculated analytically [5]. By calculating linkage fluxes of the voltage loops the values of P_S and P_R are calculated. Specifications of the HTS wire used for the numerical analysis are listed in Table.1.

TABLE. 1. SPECIFICATION OF HTS TAPE FOR CALCULATION

Width of tape (mm)	3.4
Thickness of tape (mm)	0.24
Thickness of superconducting zone (mm)	0.196
Width of superconducting zone (mm)	3.2
Critical current (A)	41.2

i) Comparison of spiral and rectangular voltage loops

Fig.3 shows dependence of P_S on R_S and that of P_R on R_R for different I/I_c (I_c : the critical current of a wire), for the case of an isolated single wire. P_S and P_R are normalized to the loss P_0 calculated from the Norris equation of the elliptical model [5]. Obviously, P_S does not depend on R_S and gives the true value P_0 . Whereas P_R significantly deviates from the true value, especially for small R_R and I/I_c . Theoretically, there is an error caused by deformation of the cylindrical surface on which the spiral loop is wound but according to a numerical analysis, the error is not significant as far as there is no apparent deformation [6].

ii) Rejection of influence of external magnetic field

Fig.4 shows the analytical result of the influence of the external magnetic field produced by a neighboring wire carrying a transport current. Voltage taps are attached to the left side tape of the two parallel tapes arrangement as shown in Fig.4 a). The AC transport current with an amplitude of I is applied only to the right side tape. Voltages appearing in the

Fig.3. Calculated P_S and P_R vs. R_S and R_R for single tape configuration.

spiral and rectangular loops attached to the left wire are calculated. The arrangements of the loops are shown also in Fig.4 a). In the actual case, a shielding current and voltage is induced in the left wire by the magnetic field produced by the other wire. However, for the purpose to study the influence of the external field, it is valid to assume that no shielding current appears in the left wire and that transport current distributed in the cross section of the right side wire follows the Bean model. Apparent losses P'_S and P'_R are calculated by multiplying the resistive components of the voltages of the spiral and rectangular loops by I . In Fig.4 b), P'_S and P'_R normalized to P_0 are plotted against R_S and R_R . Obviously, the rectangular loop picks up spurious voltage due to the magnetization of the neighboring wire, whereas the spiral loop cancels the influence of the neighboring wire.

iii) Reduction of inductive voltage

Fig.5 shows comparisons of the measured inductive and resistive voltage components in the spiral and rectangular loops. The data were obtained by the measurement setup shown in Fig.1 but without the cancel coil. The sample wire was a Bi/Ag sheathed tape of 3.4 mm wide and 0.24 mm thick. The R_S and R_R were 2 mm and 12 mm, respectively. The inductive voltage component of the spiral loop was about one third of that of the rectangular one. The inductive component was one to two orders of magnitude higher than the resistive component even for the case of the spiral loop in the lower range of I . Therefore, a proper cancellation of the inductive

Fig.4. Influence of magnetic field by a neighboring wire on values of P'_S and P'_R .

Fig. 5. Measured values of the inductive and resistive voltage components of spiral and rectangular loop voltages. (I_c of the sample tape is 49.5 (A) at 1(μ V/cm)).

voltage component is necessary.

B. Phase errors

There are phase errors in the current signal from the shunt resistor $i'(t)$ and the inductive voltage signal from the cancel coil $e_{can}(t)$. The $i'(t)$ and $e_{can}(t)$ can be expressed as follows

$$i'(t) = I' \cos(\omega t + \Delta\theta_i) \quad (2)$$

$$e_{can}(t) = E_{can} \sin(\omega t + \Delta\theta_{can}) \quad (3)$$

where $\Delta\theta_i$ and $\Delta\theta_{can}$ are the phase errors, and I' and E_{can} are the amplitudes of $i'(t)$ and $e_{can}(t)$, respectively. Usually the error between I' and I is negligibly small. The input to the lock-in amplifier is $e_i(t) = e_p(t) - e_{can}(t)$. Taking $i'(t)$ as the phase reference, the measured resistive component of $e_i(t)$ which is in the same phase of $i'(t)$ is given by $\langle e_i(t) \cos(\omega t + \Delta\theta_i) \rangle$ ($\langle \rangle$: average value). The measured transport current loss P_m is given by multiplying this component by I' . Assuming phase error $\Delta\theta$ is small and putting $\sin\Delta\theta \approx \Delta\theta$ and $\cos\Delta\theta \approx 1$, P_m is given by

$$P_m \approx \{E_i I' - (E_i - E_{can}) I' \Delta\theta_i - E_{can} I' \Delta\theta_{can}\} / 2 \quad (4)$$

The second and third terms on the right side of (4) are errors caused by the phase errors and the first term is the real loss. Taking $e_{can}(t)$ as the phase reference, the measured resistive component of $e_i(t)$ which is orthogonal component to $e_{can}(t)$ is expressed as $\langle e_i(t) \cos(\omega t + \Delta\theta_{can}) \rangle$ and P_m is given by

$$P_m \approx \{E_i I' - E_i I' \Delta\theta_{can}\} / 2 \quad (5)$$

The second term of the right side of (5) is the error caused by the phase error and the first term gives the real loss. When E_{can} is adjusted almost equal to E_i by careful tuning of the cancel coil, the errors in P_m calculated by (4) or (5) becomes $\sim E_i I' \Delta\theta_{can} / 2$. Fig.6 shows measurement errors $E_i I' \Delta\theta_{can} / 2$ vs. $\Delta\theta_{can}$ which are calculated from the values of E_i shown in Fig.5 for the spiral and rectangular loops. In Fig.6 the errors are normalized to the real loss $E_i I' / 2$ which is $\Delta\theta_{can} E_i / E_r$.

We investigated the phase error characteristics of ordinary type and non-inductive type shunt resistors as well as a variable mutual inductance cancel coil. A configuration of the

Fig. 6. Relative measurement error vs. phase error of cancel coil

cancel coil is illustrated in Fig.7. The outer cancel coil is made of two coils, a current and voltage coils. The outer current coil is wound of a litz wire to flow a sample transport current. The inner voltage coil is wound of a thin wire. A litz wire and thin wire are used for the current and voltage coils to suppress eddy currents in the coil wires which cause the phase errors. The mutual inductance between the two coils is adjusted by rotating the voltage coil placed in the current coil. Fig.8 shows the characteristics of phase errors vs. frequency. In Fig.8 the phase error is defined as the phase difference between the signal from the non-inductive shunt resistor and that form the ordinary type shunt resistor voltage. In the case of the cancel coil, the phase error is defined as the phase difference between the signal from the cancel coil subtracted from 90° and that from the non-inductive shunt. The phase error of the ordinary resistor is significant and that of the cancel coil becomes significant at a frequency higher than $\sim 200\text{Hz}$.

C. Common mode noise

Source of common mode noise is sometime difficult to identify. However, if the common mode noise is expressed as a voltage source shown in Fig.1, then the common mode noise can be suppressed by connecting a ground line from the tap on the sample to the chassis ground of the lock-in amplifier [4]. It is also effective to measure the resistive voltage twice by changing the polarity of the transport current and taking the average of the two values.

Fig. 7. Configuration of cancel coil

Fig.8. Frequency dependence of phase error defined by taking the phase of the non-inductive shunt as the standard.

IV. CONCLUSIONS

In summary, the followings are recommended to suppress errors in measurements of the AC transport current loss.

1. The spiral voltage loop is preferable to the rectangular loop for reduction of the induction voltage, cancellation of the influence of the external field and saving space for the voltage loop.
2. The cancel coil is necessary to measure the loss in the wide range of I , but proper cares should be taken to suppress the phase error. To suppress the phase error of the cancel coil, it is recommended to wind the current coil with a litz wire and the voltage coil with a thin wire for avoiding eddy currents in the coils. It is also recommended to adjust the number of turns of the voltage coil for the angle θ between the faces of the current and voltage coils to be as small as possible, and any metallic material should be removed away from the cancel coil.
3. To suppress the common mode noise, it is effective to measure twice the voltages by changing the polarity of the transport current and take average of the two data.

REFERENCES

- [1] M.Ciszek, O.Tsukamoto, N.Amemiya, D.Miyagi, J.Ogawa, M.Ueyama, and K.Hayashi, "Power loss in Ag/Bi-2223 tape due to AC transport current and AC external magnetic field," *Advances in Cryogenic Engineering (materials)*, Vol.46, 739-746, 2000.
- [2] A.M.Cambell, "AC Losses in High Tc Superconductors," *IEEE transactions on applied superconductivity*, Vol.5, No.2, June, 1995
- [3] S.Fukui, Y.Kitoh, T.Numata, and O.Tsukamoto, "Transport current AC losses of high-Tc Superconducting tapes exposed to AC magnetic field," *Advances in Cryogenic Engineering (materials)*, Vol.44, 723-730, 1998.
- [4] L.Jansak, "AC self-field loss measurement system," Review of scientific instruments, Vol.70, Number 7, 3087-3091, July, 1999.
- [5] W.T.Norris, "Calculation of hysteresis losses in hard superconductors carrying ac: isolated conductors and edges of thin sheets," *J Phys* D3489, pp.489-507, 1970.
- [6] S.Fukui and O. Tsukamoto, "Measurement method of AC transport loss in High Tc Superconductors", to be published in J. IEEJ (Japanese).