A Comparative Study on Pre-Standardization of Total AC Loss Measurements for Oxide-Superconducting Tapes in Japan

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Abstract. We have been considering about standard methods to estimate total AC loss in oxide-superconducting tapes under practical electromagnetic conditions in future power devices. We adopt 4 candidates of the standard methods to measure the AC loss in superconducting wires exposed to AC transverse magnetic field and alternating transport current. We also introduce two pickup coil methods for comparative references of external magnetic field loss. The specimen is a Bi-2223 Ag-alloy-sheathed multifilamentary tape without twisting. 60-100 mm short pieces of specimen were cut from a terminal of a 50 m long specimen for 4 in 6 methods. A double-layer non-inductive coiled specimen was also prepared from the long specimen for the other 2 methods. The scattering in AC loss property among the short specimens prepared is less than 1% in the perpendicular field with the amplitude from 0.01 to 0.1 T at 10 Hz. The scattering in repeated measurements of the loss during 3 heat cycles is within 2-3%, which almost corresponds to that of the critical current in the long specimen. We processed the results measured by each method for the external field loss and total AC loss, summarized dispersion among the observed results of all methods and discussed about the candidates of the standard methods.

1. Introduction

We are studying the methods to measure total AC loss in Bi-2223 taped superconducting wires exposed simultaneously to transverse AC magnetic field and alternating current for the near-future standardization with support of the Ministry of Economy, Trade and Industry and the Japan committee of IEC/TC90.

We adopted the following candidates of the standard methods, a Poynting vector method PVM [1], a one-turn coil method with spiral loop OTSP [2], a linked pickup coil method with spiral loop LPVT [3], a simple electromagnetic method SIM [4] to measure the AC loss in superconducting wires exposed to AC transverse magnetic field and alternating transport current. We also introduce a saddle-type pickup coil method SPC [5] and the standard concentric pickup coil method CPC [6] for comparative references of external magnetic field loss. The characteristics of each method are summarized in table 1.

In the comparative study on the pre-standardization, the external-field loss and the total AC loss were observed both in the parallel- and perpendicular-field configurations. The observed results by all methods were compared statistically, and dispersion among them was summarized for the next step to pre-standardization of the total-AC-loss measurement.
Table 1. Characteristics of AC loss measurement methods

| Method | PVM | LPVT | OTSP | SIM | SPC | CPC |
|--------|-----|------|------|-----|-----|-----|
| Group  | Kagoshima Univ. | Yokohama N. Univ. | Yokohama N. Univ. | Kyushu Univ. | Kyushu Univ. | Kyushu Univ. |
| Collaborator | A. Kawagoe | N. Amemiya | O. Tsukamoto | K. Kajikawa | M. Iwakuma | K. Funaki |
| Measured loss | Total AC loss | Total AC loss | Total AC loss | Total AC loss | External-field loss | External-field loss |
| Specimen form | Short strip | Short strip | Short strip | non-inductive 2-layer coil | Short strip | non-inductive 2-layer coil |
| Temperature | LN$_2$ temp. | LN$_2$ temp. | LN$_2$ temp. | LN$_2$ temp. | LN$_2$ temp. | LN$_2$ temp. |
| Field direction | Transverse $\theta = 0, \pi/2$ | Transverse $0 \leq \theta \leq \pi/2$ | Perpendicular $\theta = \pi/2$ | Parallel $\theta = 0$ | Transverse $0 \leq \theta \leq \pi/2$ | Parallel $\theta = 0$ |
| Field amplitude | Up to 50 mT | Up to 60 mT | Up to 0.1 T | Up to 0.2 T | Up to 0.2 T | Up to 0.2 T |
| Current | Up to 80 A | Up to 80 A | Up to 81 A | Up to 43 A | — | — |
| Frequency | 10 – 70 Hz | 10 - 70 Hz | 10 - 90 Hz | 5 – 100 Hz | 1 – 60 Hz | 5 – 100 Hz |
| Calibration for external-field loss | Evaluation of Poynting vector | Measuring eddy-current loss of a Cu plate in LN2 | Theoretical | Comparing to co-axial pickup coil method | Using a Pb rod at LHe temperature | Pickup coils designed on the basis of IEC61788-8 |

2. Specimens and their characterization

We prepared two types of specimens, short pieces with a length of 60 mm and a non-inductive 2-layer coiled one, which were cut from a 50-m long piece of Bi-2223 multifilamentary Ag-sheathed tape without twisting fabricated by Sumitomo Electric. The former is for PVM, OTSP, LPVT and SPC, and the latter for SIM and CPC. The sizes of the cross-section are 4.1±0.2 mm wide and 0.22±0.02 mm thick. The silver ratio is about 2.2 and the critical current with a criterion of 1 $\mu$V/cm is 86 A with a dispersion of 2%, which was measured every 4 m over the whole length.

Before the comparative measurements, we estimated effects of heat cycles and the distribution of superconducting property along the wire axis on the AC losses by measuring a perpendicular magnetic field loss at 10Hz by SPC. The dispersion was within 1% during 3 heat cycles and 2-3% among the test pieces distributed to 6 cooperative groups listed in table 1, where the field angle $\theta$ is 0deg for the parallel field and 90deg for the perpendicular one. These results show we prepared almost uniform test pieces for the comparative measurements.

3. Method of comparative measurements

We performed the comparative measurements of AC losses for Bi-2223 tapes exposed simultaneously to the external AC magnetic field and the alternating transport current with the amplitude of 0, 50 and 93% of the critical current in self field. The external magnetic field was applied transversely in parallel or perpendicular direction to the wide surface of the tapes. The recommended ranges for the field amplitude and the frequency were 10 to 50 mT and 10 to 70 Hz, respectively, which were restricted by limits in application of each method under the existing circumstances, as listed in table 1. The AC losses were measured in liquid nitrogen by each method.

The calibrations in the present comparative measurements were not unified, but performed in a usual way by the individual methods, which are also summarized in table 1.

4. Results

4.1 External-field loss

As the first step, the AC losses of the Bi-2223 tapes were measured in the transverse-field configuration where the magnetic field was applied in parallel or perpendicular to the flat surface of the tape. The results by the measurement methods of total AC loss were evaluated in comparison with
those by the proper methods CPC and SPC for the external-field losses, which have been standardized and be in a pre-standardization step, respectively. As examples, the dependences of the parallel-field loss on the field amplitude $B_m$ at 10 Hz and on the frequency $f$ at the field amplitudes of 0.01, 0.05 and 0.10 T are plotted in figure 1(a) and (b), respectively. The amplitude $I_m$ of transport current is indicated with parentheses in an inset of each figure.

We estimated the coefficient of variance, COV, from a set of individual results of different measurement methods, which is defined by dividing the standard deviation by the average. The COV in the field amplitude of 0.01 and 0.05 T at the frequency of 10 Hz is 12.3% and 7.0% for the parallel-field loss and 7.6% and 9.9% for the perpendicular one, respectively. The results obtained are listed in table 2. In the estimation, the results with a definite deviation from a group of normal results were omitted, which can be seen in the higher frequency region of figure 1(b).

4.2 Total AC loss
Results observed are partly shown in figure 2(a) and (b) for the dependences of the total AC loss on the perpendicular-field amplitude at 10 Hz and on the frequency at the perpendicular-field amplitudes of 0.01 and 0.05 T. The COV for the measurements of total AC losses is also summarized in table 2, except for the case of $\theta = 90$ deg, $f = 10$ Hz, $B_m = 0.05$ T and $I_m = 80$ A, including flux-flow loss.
Table 2. Main statistical summary of comparative measurements

| θ    | $B_m$  | f          | COV ($I_m = 0$ A / 43 A / 80 A) | Methods (*only for $I_m = 0$ A) |
|------|--------|------------|---------------------------------|---------------------------------|
| 0 deg | 0.01 T | 5-10 Hz    | 12.3% | 30.4% | 4.9% | PVM, LPVT, SIM, SPC*, CPC* |
| 0 deg | 0.05 T | 60-70 Hz   | 19.7% | 37.1% | 7.7% | PVM, LPVT, SIM, SPC*, CPC* |
| 0 deg | 0.05 T | 10 Hz      | 7.0%  | 6.6%  | 2.2% | PVM, LPVT, SIM, SPC*, CPC* |
| 0 deg | 0.05 T | 60-70 Hz   | 5.5%  | 3.8%  | 7.2% | PVM, LPVT, SIM, SPC*, CPC* |
| 90 deg | 0.01 T | 10 Hz      | 7.6%  | 26.0% | 20.2% | PVM, LPVT, OTSP, SPC* |
| 90 deg | 0.01 T | 60-70 Hz   | 7.3%  | 17.6% | 9.7% | PVM, LPVT, OTSP, SPC* |
| 90 deg | 0.05 T | 10 Hz      | 9.9%  | 11.7% | --   | PVM, LPVT, OTSP, SPC* |
| 90 deg | 0.05 T | 60-70 Hz   | 5.1%  | 7.3%  | 28.9% | PVM, LPVT, OTSP, SPC* |

5. Discussion

According to the external-field loss, the COV is suppressed almost within 10% for levels of loss more than about 0.54 $\mu$J (10 J/m$^3$), which corresponds to the AC loss of the 60mm-long specimens in the parallel field with the amplitude of 0.01 T, in spite of individual calibration and measurement procedures in each method. This result shows from the statistical viewpoint that each method adopted for the measurement of the external-field loss has an accuracy of 10% COV under the conditions for the present comparative study.

The results of total AC loss are, on the other hand, scattered with the COV more than 10% even in the perpendicular field with the amplitude from 0.01 to 0.05 T and the transport current with the amplitude of 43 A as shown in table 2, where the amount of AC loss attains to 54-540 $\mu$J (10$^3$-10$^4$ J/m$^3$) 10$^2$-10$^3$ times larger than the lower limit for the external-field loss with 10% COV. It comes from some difficulties in the measurement of transport current loss. This result suggests that the COV for the total AC loss have to be improved by brushing up the methods to measure the component of transport current loss in the present candidates.

In the comparative study among the different kinds of methods to measure the AC losses, generally speaking, the minimum level of the COV surely shows the accuracy in each procedure of loss measurement with the individual calibration, while the maximum one suggests that each measurement is interfered by separate noise sources. Another aspect to be pointed out is that the common ranges of the field amplitude and the frequency are restricted by adopting different experimental setups in the candidates. In the next step of the pre-standardization, it is necessary to consider flexibility in the experimental ranges for selective candidates, in addition to the reduction in the COV.

References

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