Losses in Bi-2223/Ag tape at simultaneous action of AC transport and AC magnetic field shifted in phase

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Abstract. Investigation of AC loss under simultaneous action of transport AC and external AC field is of prime importance for reliable prediction of dissipation in electric power devices like motors/generators, transformers and transmission cables. The experimental rig allowing to perform AC loss measurement in such conditions on short (10 cm) samples of tapes from high-temperature superconductor Bi-2223/Ag has been designed and tested. Both the electrical and thermal method have been incorporated, allowing to combine better sensitivity of former one and a higher reliability of the latter one. Our main aim is to see how the AC loss depends on the phase shift between the current and the field. Such a shift could acquire rather different values in various applications. While in transformer winding, the maximum phase shift at full load will probably not exceed a few degrees, in a three phases transmission cable in tri-axial configuration it is around 120°. Therefore we explored the whole range of phase shifts from 0 to 360°. Surprisingly, the maxima of dissipation do not coincide with zero shift as expected from qualitative considerations.

1. Introduction
AC loss is of particular importance for design of power devices like transformers, generators and transmission cables. In these devices the superconductor carrying the AC transport current is exposed to the AC magnetic field simultaneously. Moreover, transport current and magnetic field are usually not in phase. Investigation in such real conditions is necessary for reliable prediction of AC loss in these applications.

Theoretical expressions were derived in [1] and measurements using thermal method were performed [2, 3] to investigate the AC loss. Thermal method is of high reliability, but its sensitivity is low. Alternatively, the electromagnetic measurement method allows to measure separately the magnetization loss and the transport loss. Total loss is then determined by the sum of these two parts. Electrical method has higher sensitivity and enables the measurement of AC loss in wide range of
current and field. On the other hand, there is a high risk of false voltage signals measurement. Therefore, this method has been used only in the case when current and field were in phase. Here we show that it is possible to utilize it also for the case when the transport current and the magnetic field are not in phase. Correctness of the results measured by this method were confirmed by thermal one in the whole range of the phase shift between transport current and magnetic field.

Experimental AC loss results were compared with the predictions of numerical simulations performed by three methods.

2. Experimental

Experiments were made by two independent methods: Electromagnetic and thermal. The same sample Bi-2223/Ag tape with critical current $I_c = 38$ A (Australian Superconductors) was used in both cases. Two sinusoidal signals with frequency of 72 Hz have been generated by 2-channel signal generator. After amplifying, these signals were used for AC magnetic field generating and for supplying of the AC transport current to the sample, respectively. The magnetic field, perpendicular to the tape wide face, is generated by the racetrack shaped magnet made from copper wire. Current to the magnet is delivered from a power amplifier directly. To achieve the required amplitude of the transport current, a power transformer immersed in liquid nitrogen is used on the output of a second amplifier. Both the currents to the magnet and to the sample are measured by lock-in using Rogowski coils.

2.1. Electromagnetic method

Measurement set-up is illustrated in figure 1. For measurement of transport loss the loop perpendicular to the wide face of the tape is used. AC loss per unit of length is determined by formula:

$$P_T = I_T^* U_T / L$$

where $I_T$ is the RMS value of transport current, $U_T$ is the part of RMS value of voltage from measuring loop which is in phase with transport current, and $L$ is loop length. Perpendicular arrangement reduces the false voltage signal induced by external field. Fine compensation of the remaining false voltage is performed with the help of an adjustable mutual inductance linked to AC magnet current. Similar compensation is used in the case of the magnetization loss measurement, but linked now to the sample current. By this way the false signals were reduced satisfactorily. To measure the magnetization loss, the measuring coil is used – figure 1. A compensation coil of the same dimensions is connected in opposite. The measurement of magnetization loss was calibrated using the superconductor sample with known magnetization loss, in which the loss was measured using an absolute method [4]. Magnetization loss is then determined by the formula:

$$P_M = I_M^* U_M^* C_C$$

where $I_M$ is RMS value of magnet current and $U_M$ is part of RMS measuring coil voltage, which is in phase with magnet current. $C_C$ is calibration constant. Total AC loss is then determined by the formula:

$$P_{tot} = P_T + P_M$$

2.2. Thermal method

Measurement set-up of thermal method is illustrated in figure 2. For thermal insulation of the sample, two blocks made from polyethylene foam are used. Differential method utilizing two type-E thermocouples connected in series is used to probe the increase of the sample temperature due to AC total losses. One thermocouple is placed on the tape surface and second one is placed in the liquid nitrogen as reference. Both wires of thermocouple were twisted to reduce the voltage induced by applied ac magnetic fields. Measurement of AC transport loss (i.e. in self field) was used for calibration. This method can be used only in limited range of currents and fields. In our set-up, the minimum ac loss to have measurable increase of the sample temperature is 0.1 W/m, and the upper limit to avoid the decreasing of the critical current due to temperature rise is 1 W/m.
3. Results and discussion
The figure 3 is presented to show the agreement between electromagnetic method and thermal method when AC loss in typical case of transport current of 23.5 A and 26.2 mT AC field was determined. Based on such agreement one can trust the results measured by electromagnetic method in conditions when AC current and AC field are not in phase.

Figure 4 shows the dependence of two measured quantities, the transport loss and the magnetization loss, on the phase shift for some combinations of AC parameters. As one can see, at low field both contributions are comparable. When external field increases, magnetization loss increases more rapidly than transport loss. This chart shows that the maximum of magnetization loss is shifted about –20°. It remains fixed at this value of the phase shift regardless of the AC magnetic field. On the other hand, the maximum shift of the transport loss varies from 20° up to 60° in the range of the used measurement parameters.

In the figure 5 the total AC loss dependence on the phase shift measured at four different AC fields and sample current 17.7 A is shown. Shifting of the total loss maximum is evident and is due to strong shift of the transport loss maximum (figure 4). Tendency of the phase shift variation of the loss maximum is displayed as a guide for eye.

4. Comparison with numerical simulation
The most striking feature of our experimental observations is that the maximum of total loss does not occur for the zero phase shift between AC current and AC field. To check whether this is a plausible behavior, several numerical simulations have been employed: The home-made simulation in Matlab
based on the Brandt method [5] as well as the use of the commercial software Flux3D [6] both assume a smooth power-law type of the current-voltage dependence in the superconductor. The third numerical method used for comparison is the minimum magnetic energy variation (MMEV) procedure, corresponding to the original concept of critical state as an abrupt change of the local current density [7].

In figure 6 are the results of these simulations compared with experiment. The simulation using Flux3D and Brandt’s method are in excellent agreement. The result found by MMEV is a bit smaller. This is not surprising taking into account the different $j(E)$ used. Anyway, all the three methods predict qualitatively similar behavior, in particular that the phase shift at maximum loss is not zero although a difference to the position found in experiment remained. Encouraging is also that the absolute values of predicted loss agree quite well.

5. Conclusion
Set-up for measurement of AC loss at simultaneous action of transport current and magnetic field shifted in phase was developed and tested. Experimental results obtained by electrical measurement are in excellent agreement with that obtained by thermal method. Moreover, the results obtained on a standard Bi-2223/Ag tape are in good agreement with theoretical prediction of three numeric methods. All these methods show that the maximum loss is not at zero phase shift, and its position depends on the AC amplitude of current and field.

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