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ISSN 0128-7389

MEASUREMENT OF AC LOSSES FOR APPLICATION OF Bi-2212 BULK SUPERCONDUCTOR IN FAULT CURRENT LIMITER

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ABSTRACT

A key issue for most applications of superconductivity involves AC losses. Designers need to understand the mechanisms of AC losses in order to lay out the conductors and windings correctly to predict the performance range in operation. AC losses in high temperature superconductor $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) bulk material used in a fault current limiter model have been investigated through the measurement of the actual specific heat of the sample and a time varying magnetic field. This paper derives simple, if approximate, expression for calculating the losses in the most important cases for practical purposes. Four different orientations of the sample with respect to the field were tested and the results are shown graphically. It will be shown also the comparison between experimental calorimetric results and theoretical analysis of various direction of the applied field. AC loss characteristics were employed to evaluate the nominal and activation current of the full scale fault current limiter.

INTRODUCTION

The discovery of high temperature superconductors (HTSC) has renewed the interest in application of superconductivity in the electric power industry. In the presence of an alternating transport current and / or an external magnetic field, the superconducting materials present energy dissipation. It is necessary to quantify and to minimize these losses in view of AC application which can be divided into two classes: the applications where the wire sees low or no magnetic field such as current leads, fault current limiters or power cables, and those where the wire sees a large magnetic field such as transformers, generator or superconducting magnet energy storage (SMES).

Different methods can be used to characterize the AC losses of high-T_c superconductors (HTSC), depending on the sample (shapes, materials, etc.) and on their applications. Magnetization measurements are used for the characterization of superconductors subjected to an external magnetic field. In this paper, we present the results obtained from the measurement technique which uses the equipment called thermometric selffield rig, measures the losses by detecting the actual heat generated within the HTSC pellet due to transport current.

This paper presents the experimental and theoretical analysis of AC losses in BSCCO 2212 (Bi-2212) operating in a fault current limiter.

EXPERIMENTAL

A superconducting sample exhibits energy loss when expose to a time varying magnetic field. In an ideal world, all this loss is converted into heat causing the sample's temperature to rise. If the sample is exposed to a certain magnetic field for a time Δt, and the initial and final temperature of the sample are recorded, the temperature rise can be related to the total loss as

$$P_L = \frac{\rho C_p \Delta T_s}{\Delta t} \qquad (1)$$

where P_L is the power loss (Wm^{-3}), ρ is the density of the material (kgm^{-3}), C_p is the specific heat ($Jkg^{-1}K^{-1}$) and ΔT_s is the temperature difference (K). Heat generation is assumed to be homogenous within the sample and heat transfer by convection is ignored as the sample is placed in vacuum. In the presence of radiation, some heat is radiated from the sample to the surroundings, such that

$$P_R = \frac{\alpha\sigma A}{V}\left(T_s^4 - T_o^4\right) \qquad (2)$$

where P_R is the radiated power (Wm^{-3}), α is the radiation coefficient of the surface of the sample, σ is the Stefan-Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4}), A is the radiation area, V is the volume of the sample and T_s and T_o is the final and initial temperature of the sample (K). Hence, the net heat giving rise to the increased temperature is

$$P_s = P_L - P_R \qquad (3)$$

and the resultant rate of temperature rise is

$$\frac{\partial T_s}{\partial t} = \frac{P_L V - \alpha\sigma A\left(T_s^4 - T_o^4\right)}{V\rho C_p} \qquad (4)$$

The system will reach a steady state temperature when $dT_s/dt = 0$ (when $P_L = P_R$) [1,2]. Solving the differential form of the radiation equation (equation 2) with an initial temperature rise of 0.5K indicates that the temperature decay of the sample due to radiation is a very slow process. Therefore it is not necessary for the sample to reach a steady-state temperature to measure the loss, but instead monitoring the initial temperature rise (~0.5K) of the sample as described below.

The measurement procedures started with recording the initial temperature of the sample, which is at liquid nitrogen temperature, prior to the application of the external magnetic field. The field is then switched on for a certain period of time, Δt causing the sample to heat up to about 0.5K, before switched off again. A short time is allowed (~2 minutes) for the magnetic field and switching effect to die out and the sample to acquire a bulk homogenous temperature, before another reading is recorded. This waiting time is not going to affect the measurement much because the temperature decay due to

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radiation is very slow, as shown above. The temperature different between the two readings is then used to calculate the loss from equation (1). To repeat the measurement for another value of field, the sample has to be cooled down to the initial temperature (77K).

To ensure accurate loss measurement, the actual specific heat of the sample (C_p in equation 1) has to be measured. The specific of the sample can be determined by injecting a known quantity of heat ΔQ to the sample via an electrically resistive wire. The change in temperature ΔT is then measured. Knowing the mass m, of the sample, the specific heat C_p can be determined from the formula:

$$\Delta Q = mC_p \Delta T \qquad (5)$$

Based on the measurement method discussed above, the experimental rig was designed and constructed. The main components for the AC loss measurement due to external magnetic field are the external field source (the electromagnet), the power supply unit, the cryogenic rig and the sample [3,4].

A high purity (>99%) Bi-2212 powder from Aldrich was used to prepare the samples. The powder was pelletized with 5-7 tons/cm^2 and undergoes a partial melt process at temperature of 870^{o}C for 5 minutes and then sintered at 845 ^{o}C for 24 hours. The heating and cooling rates from room temperature were the same at 10 ^{o}C per minutes and quench in furnace.

RESULTS AND DISCUSSIONS

The accuracy of the AC loss measurement depends on knowing the actual specific heat of the sample. The equation used to determine the AC loss is already shown above (equations 1-5) [5]. The specific heat is determined by injecting a known amount of heat to the sample and measuring the resulting temperature rise. Knowing the mass of the sample, the specific heat can be calculated from the relationship above. Heat was injected to the sample through an electric wire heater solder to the sample. The energy supplied to the heater was calculated from the relationship:

$$\Delta Q = I^2 R \Delta t \qquad (6)$$

where I = current supplied to the heater, R = resistance of the heater, and Δt = time the heater was on. The calculated value of specific heat, C_p for the sample is 281.84 ± 2.0 J/kgK.

A superconducting sample exhibits energy loss when exposed to a magnetic field. Neglecting heat leaks, all this loss is converted into heat causing the sample's temperature to rise. If the sample is exposed to a certain magnetic field for a time Δt, and the initial and final temperature of the sample are recorded, the temperature rise can be related to the total loss as equation (1). Four different orientations of the sample with respect to the field were tested (figures 1, 3, 5, 7) and the results are shown in tables 1-4. Figures 2, 4, 6, 8 show the plots of AC loss against applied magnetic field.

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(a) Applied field in parallel to x,y plane with longer edge nearest the poles

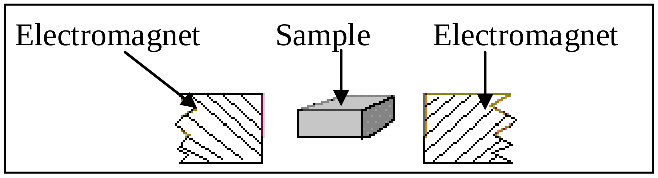

Figure 1: Position of sample in experimental (1)

Table 1 : AC losses with applied field parallel to x,y plane for experimental (1)

Field (T)	Resis. Before (Ohm)	Temp. Before (K)	Resis. After (Ohm)	Temp. After (K)	Temp. Rise (K)	Time (s)	Power Loss $(W/m^3) \times 10^4$
0.1	20.665	78.181	20.700	78.262	0.081	60	2.01
0.15	20.665	78.181	20.725	78.320	0.139	60	3.45
0.2	20.670	78.192	20.720	78.308	0.116	40	4.31
0.25	20.670	78.192	20.735	78.343	0.151	40	5.62
0.3	20.665	78.181	20.735	78.343	0.162	40	6.02

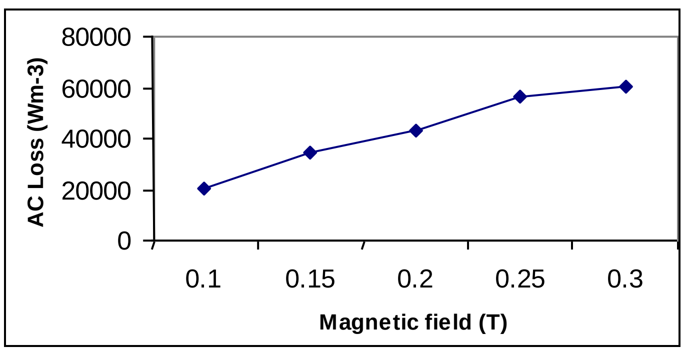

Figure 2: AC loss against magnetic field applied parallel to x,y plane for experimental (1)

(b) Applied field in parallel to x,y plane with short edge nearest the poles

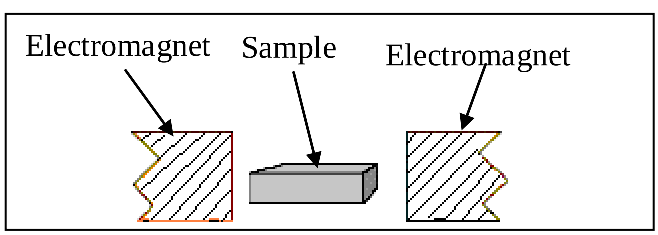

Figure 3: Position of sample in experimental (2)

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Table 2: AC losses with applied field parallel to x,y plane for experimental (2)

Field (T)	Resis. Before (Ohm)	Temp. Before (K)	Resis. After (Ohm)	Temp. After (K)	Temp. Rise (K)	Time (s)	Power Loss (W/m^3) x 10^4
0.1	20.650	78.146	20.705	78.273	0.127	90	2.10
0.15	20.645	78.134	20.715	78.297	0.163	90	2.69
0.2	20.645	78.134	20.720	78.308	0.174	60	4.31
0.25	20.655	78.157	20.730	78.331	0.174	50	5.18
0.3	20.650	78.146	20.345	7.366	0.220	50	6.55

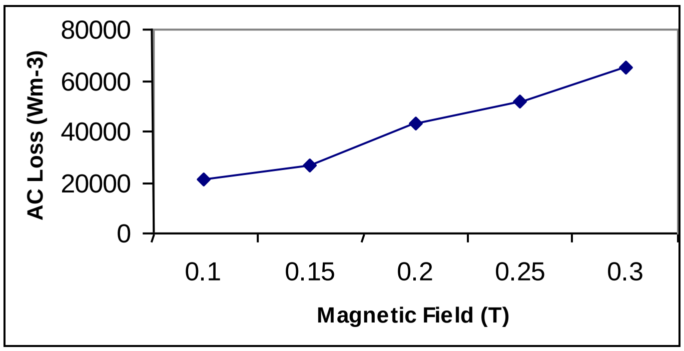

Figure 4: AC loss against magnetic field applied parallel to x,y plane for experimental (2)

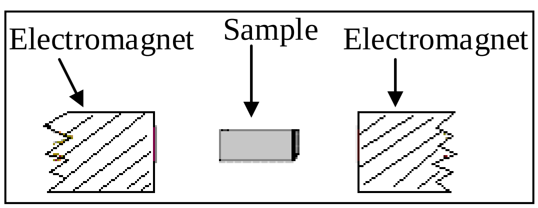

Figure 5: Position of sample in experimental (3)

Table 3: AC losses with applied field parallel to x,y plane for experimental (3)

Field (T)	Resis. Before (Ohm)	Temp. Before (K)	Resis. After (Ohm)	Temp. After (K)	Temp. Rise (K)	Time (s)	Power Loss (W/m^3) x 104
0.1	20.665	78.181	20.710	78.285	0.104	60	2.58
0.15	20.660	78.169	20.715	78.297	0.128	60	3.17
0.2	20.660	78.169	20.730	78.331	0.162	50	4.82
0.25	20.665	78.181	20.745	78.366	0.185	50	5.50
0.3	20.665	78.181	20.755	78.389	0.208	50	6.19

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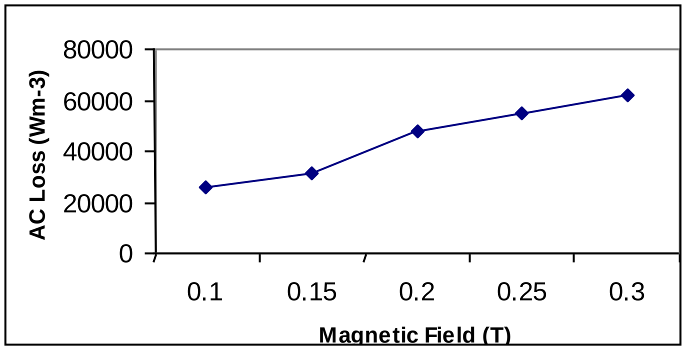

Figure 6: AC loss against magnetic field applied parallel to x,y plane for experimental (3)

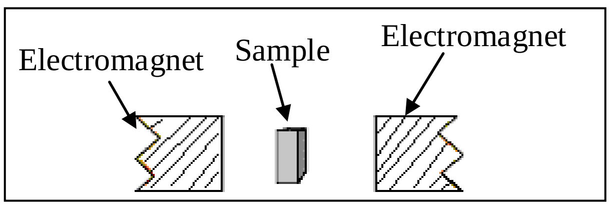

Figure 7: Position of sample in experimental (4)

Table 4: AC losses with applied field perpendicular to x,y plane for experimental (4)

Field (T)	Resis. Before (Ohm)	Temp. Before (K)	Resis. After (Ohm)	Temp. After (K)	Temp. Rise (K)	Time (s)	Power Loss (W/m^3) x 10^4
0.10	20.650	78.146	20.990	78.935	0.789	30	3.91
0.15	20.645	78.134	21.005	78.970	0.836	30	4.15
0.20	20.650	78.146	21.015	78.993	0.847	30	4.20
0.25	20.645	78.134	21.015	78.993	0.859	30	4.26
0.30	20.645	78.134	21.020	79.005	0.871	30	4.32

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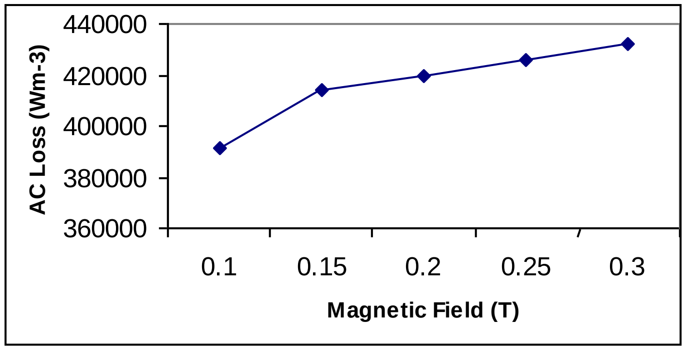

Figure 8: AC loss against magnetic field applied perpendicular to x,y plane for experimental (4)

The result above shows almost similar AC loss for field parallel to the x,y plane while losses in perpendicular plane are around one order of magnitude higher. The graph also shows that the AC loss has a linear relationship with the applied field and it will be shown that this is expected from the theoretical analysis.

The AC loss of a superconducting slab in a magnetic field with the penetration of the field parallel to the long face is given by

$$B_p = 2\mu_o J_c a \qquad (7)$$

where $\mu_o = 4\pi \times 10^{-7}$ H/m is the permeability of free space, J_c is the critical current density, and a is half the thickness of the slab.

The critical current (J_c) used in the AC loss calculation is the critical current obtained from the DC current/field characteristic of the superconducting slab divided by the cross-section of the slab. Using the following equations;

$$Q = \frac{B_m^2}{2\mu_o} \bullet \frac{\beta}{3} = \frac{B_m^2}{2\mu_o} \bullet \Gamma(\beta) \qquad (8)$$

for applied field causing partial penetration ($\beta < 1$), and

$$Q = \frac{B_m^2}{2\mu_o}\left[\frac{1}{\beta} - \frac{2}{3\beta^2}\right] = \frac{B_m^2}{2\mu_o} \bullet \Gamma(\beta) \qquad (9)$$

for applied field causing full penetration ($\beta > 1$), the theoretical AC loss (W/m^3) of the superconducting material was calculated for a given applied magnetic field and results are shown in table 5 below, where β is the ratio of applied field against the field for penetration to the centre of the sample and Γ is the loss factor [6–10].

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Table 5: Theoretical AC losses using Bean's model

B_m	J_c	$B_m^2/2\mu_o$	B_p	β	Γ	AC Loss
0.10	67567568	3949.4	0.016	6.09	0.1463	28881
0.15	56306306	8886	0.014	10.96	0.086	38075
0.20	55180180	15798	0.013	14.91	0.064	50605
0.25	52552553	24684	0.013	19.57	0.049	60915
0.30	46171171	35545	0.011	26.73	0.036	64828

The comparison between theoretical AC loss and experimental (1) is plotted against applied magnetic field as shown in figure 9.

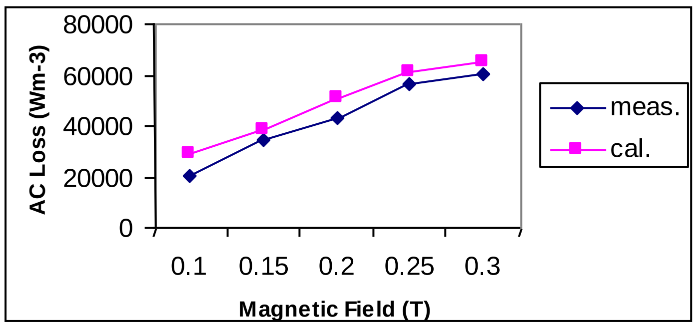

Figure 9: Theoretical AC loss against measured AC loss for field parallel to x,y plane

The theoretical AC loss can roughly be approximated to a very flat rectangular surface with width, a and thickness, b when exposed to a perpendicular magnetic field (for $B_m >> 2B_p$). The hysteresis loss per unit volume is expressed by

$$\frac{Q_h}{V} = \frac{1}{2} B_m J_c a \qquad (10)$$

where B_m is the applied field [7,11-13]
Table 6 shows the calculated AC loss. The comparison between theoretical AC loss and experimental (4) is plotted against applied magnetic field, is shown in figure 10.

Table 6: Theoretical AC losses for field perpendicular to x,y plane

B_m (T)	J_c $(A/m^2) \times 10^7$	AC Loss $(W/m^3) \times 10^5$
0.10	3.23	2.39
0.15	3.00	3.33
0.20	2.63	3.89
0.25	2.33	4.31
0.30	2.22	4.92

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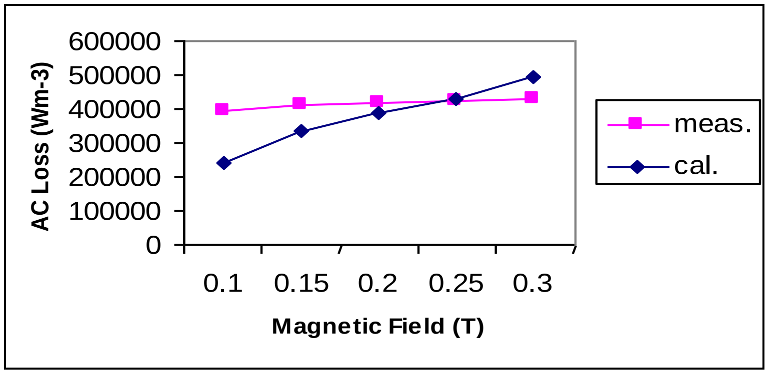

Figure 10: Theoretical AC loss against measured AC loss for field perpendicular to x,y plane

CONCLUSIONS

The AC loss of a HTSC Bi-2212 made in a configuration similar to that of a fault current limiter or a transformer coil had been measured using the thermometric method. It was found that the method is successful and gives good repeatability as seen from experimental (1) to experimental (4), where the sample were placed differently but have the same orientation of the sample to the magnetic field. The results also showed that the measured AC losses for an applied field perpendicular to the x,y plane, which is higher than the parallel field configuration.

The measured AC loss in parallel field is quite well described by the critical state model using the simple infinite slab geometry. This shows that it can be used to estimate the AC loss of superconductors in parallel field. There is, however, a little difference in the slope of the AC loss curve which may be due to errors made in the approximation of the overall sample geometry.

The results for AC losses in perpendicular field do not show good agreement between the measured value and the calculated value. The formulation used to estimate the AC loss may not be suitable for the case above and further research are required to gain a better result.

ACKNOWLEDGEMENTS

This project has been supported by IRPA Project No. 09-99-03-0024-EA001 from the Ministry of Science, Technology and Innovation, Malaysia. Invaluable help by Prof. Dr. Roslan Abd. Shukor from UKM is gratefully acknowledged.

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