Decrease of ac losses in high Tc superconducting tapes by application of a dc current

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Abstract

The ac losses in a silver-gold alloy sheathed Bi-2223 tape were measured by the null calorimetric method while a dc current was superimposed onto the ac current. As expected through computer simulations, a Clem valley was observed for the larger ac currents. A reduction of ac losses of approximately 50% at the valley minimum is observed in accord with the calculations. At lower ac currents, the data fit the calculated behavior with a single parameter, a Meissner current of 21.8 A. It is shown that a surface barrier current is incompatible with the data.

Introduction

The question of ac losses in superconducting tapes was raised long before the advent of high Tc superconductors. For example, McConnell and Critchlow [1] reported ac loss measurements on NbTi wires in 1975. On the theoretical side, Bean [2] proposed his now well known critical state model in 1964 while considering the hysteresis losses in a type II superconductor due to alternating magnetic fields. According to this model, the losses increase as the third power of the magnetic field amplitude (for amplitudes that are small with respect to the full penetration field). A similar behavior was predicted by Norris [3] when a transport current replaces the magnetic field as long as a circular or elliptical cross section is considered. In the case of a thin strip however, the losses vary as the fourth power of the current, again for small currents. These behaviors have all been confirmed experimentally by a number of workers [4].

The fact that ac losses always seem to increase with current or magnetic field amplitude represents a major concern in the pursuit of superconductivity applications. An interesting
exception occurs however when a dc magnetic field or current is superimposed onto the ac field or current. It was observed by Thompson, Maley and Clem that an increasing dc-bias magnetic field added to an ac field decreases the losses initially before the inevitable increase occurs. The minimum defines what is now known as the Clem valley. It was only recently that this valley was observed with transport currents rather than magnetic fields. Furthermore, this observation involved high Tc superconducting tapes, more specifically those of silver-gold alloy sheathed Bi–2223. While these were the first measurements showing explicitly the Clem valley in high Tc materials, a reduction in losses can be seen in the data of Oomen et al. in their plot of losses as a function of magnetic field amplitude with and without a dc current as they attempted to separate intragrain and intergrain effects. Their curve obtained with a dc current is lower than the one without a dc current.

In this paper, we extend the measurements and analysis of the data illustrating the Clem valley with transport dc and ac currents in Bi–2223 silver-gold alloy sheathed tapes. More data points have been obtained and the computer simulations include surface barrier effects as well as Meissner currents and take into account the elliptical cross-section of the tape.

![Figure 1: Hysteresis loops with fixed surface barrier and alternative currents.](image)

**Theoretical considerations**

We will proceed with the Bean model which, in spite of its simplicity has had remarkable success in interpreting data on ac losses in superconductors following the application of ac magnetic fields or ac transport currents. In our case however, complications arise due to the addition of a dc current to the ac current. The flux density profiles are no longer symmetric. Furthermore we include the possibility of either a Meissner current $I_m$ or a surface barrier current $I_{sb}$. Finally we do not restrict ourselves to a tape of circular cross-section but consider
one with an elliptical cross-section in the computer simulations of the ac losses. LeBlanc et al.\cite{8} had performed such simulations to show in detail how the reduction of ac losses comes about with the addition of a dc current in the context of cylindrical symmetry. We follow the lead of LeBlanc et al except for consideration of an elliptical cross-section and extend the project to fit experimental curves of the phenomenon. Our consideration of an elliptical cross-section inserts a form factor into the analysis given by

\[
\int_0^{2\pi} \sqrt{1 - e^2 \cos(p^2)} \, dp
\]  

(1)

where \( e \) is the eccentricity of the ellipse. More details on the simulation calculations will be given elsewhere\cite{9}.

We show in Figures 1 and 2 the spatial average of the magnetic flux density as the ac current goes through one cycle. The area enclosed by a hysteresis loop is proportional to the ac loss per cycle. Each loop has four horizontal lines of length \( I_{sb} \). Note that all currents are expressed in terms of the critical current \( I_C \). In Figure 1, Iac is larger than Isb. For zero dc current, the loop is symmetric with respect to the abscissa. For increasing dc currents, the loops shift upwards and to the right and the horizontal lines of the left side of each loop approach each other and eventually merge when \( I_{DC} = I_{AC} - I_{sb} \) such that the net area of the loop decreases. It is this decrease that leads to the decrease in ac losses and to the Clem valley.

![Figure 2: Hysteretis loops with a fixed surface barrier current, \( I_{DC} = I_{AC} \) and \( I_{AC} \leq I_{sb} \).](image)

In Figure 2, ac currents less than Isb are considered. We fix \( I_{DC} = I_{AC} \) such that the maximum losses for the given ac current are calculated. With this representation the minimum current for each loop corresponds to zero total current in order to illustrate an important result. The loops decrease in area with decreasing ac current until the zero area condition is reached i.e. \( I_{AC} \) equal to or less than \( I_{sb}/2 \). Another important result can
be found if $I_{DC} \leq I_{AC}$ a condition found in this figure. If one were to increase $I_{dc}$ while maintaining $I_{AC}$ constant, the loop would merely shift upwards and to the right without changing in area. Indeed this is the maximum area for the given ac current as implied above.

Figure 3: AC losses with a fixed surface barrier current and an AC current greater than half the surface barrier current. Regime $\alpha$ occurs when no losses arise, regime $\beta$ begins when losses increase and regime $\gamma$ occurs when losses are saturated (plateau).

The evolution of the ac losses with dc current is summarized in Figure 3 although $I_{sb}$ has been increased to encompass a larger number of situations. When $I_{AC} = I_{sb}$, losses appear for any non-zero dc current. For smaller values of $I_{AC}$, no losses are encountered below a threshold dc current (the $\alpha$ region defined in Ref.[8]). If one reduces the ac current even further such that $I_{AC} \leq I_{sb}/2$ no losses are encountered regardless of the dc current. Beyond the $\alpha$ region, losses appear as in the $\beta$ region. The $\gamma$ region is the plateau which appears suddenly as soon as the dc current reaches $I_{AC}$. This corresponds to the loop area becoming constant as discussed in the context of Figure 2.

The first three figures have described the situation with a surface barrier current $I_{sb}$. With a Meissner current instead, there is a horizontal line of length $2I_m$ in the center of the upper part of the loop and a similar one in the lower part of the loop as illustrated in Ref.[6, 8] (rather than four horizontal lines of length $I_{sb}$ at the extremities of the loop as in Figure 1). A consequence of this is the absence of a zero loss condition analogous to the one with a surface barrier current ($I_{AC}$ less than $I_{sb}/2$) i.e. losses arise when $I_{DC} + I_{AC} < I_m$, a condition that can always be fulfilled by increasing $I_{DC}$. The general appearance of the $\alpha$, $\beta$ and $\gamma$ regions remains although with different conditions. As with $I_{sb}$, $I_m$ leads to a Clem valley in the losses for large values of $I_{AC}$ as shown in Figure 4. Here, the calculated losses are normalized with respect to the zero bias condition. These behaviors are similar to the ones predicted by LeBlanc et al. who considered a cylindrical geometry.
RESULTS AND DISCUSSION

The measurements reported here were obtained on a silver-gold alloy sheathed Bi-2223 tape fabricated by the powder-in-tube method in the Hydro-Québec laboratories. It is monofilamentary with a cross-section of $2.10^{-3}\text{ cm}^2$ and a length of approximately 30 cm. The critical current was determined by fitting the $V-I$ characteristic with the double integration of the sum of gaussian curves. Initially a value of 29 A was obtained but excessive heating decreased this value to 25 A. Thus data will be presented with both values of critical current. The losses were determined by the null calorimetric technique which is described elsewhere [4, 10]. This technique was developed by the authors over the last few years and has the advantage of measuring the total losses as well as being adaptable to complex environments.

We show the results with a critical current of 29 A and low ac currents in Figure 5. These data were taken at 559 Hz rather than at a lower frequency to increase the losses and thus the signal to noise ratio since the losses are low when the ac current is less than half the critical current. It had been verified that the frequency does not affect the shape of the curves. The $I_{AC}$ values in the figure correspond to the amplitude of the current as defined above and not to the rms readings of the instrumentation. The curves through the points are the results of a fit to be discussed below.

At higher ac currents the data were taken at the lower frequency of 55 Hz since the losses are greater and more easily measured. Again with a critical current of 29 A, a minimum in the losses is observed (inset of Figure 5) as anticipated in the theoretical section above. After the critical current had been reduced to 25 A, even clearer minima were observed as shown in the main part of Figure 5.

Returning now to the low ac current data of Figure 5, we note that the losses display an initial plateau for each ac current value before the increase, reminiscent of the a region
of Figure 3. The non-zero level of the plateau however is perplexing, unless we recall the granular nature of the Bi-2223 tape. The intergrain material has a low critical current density and act as weak links between the grains. Even in the absence of a dc current and with low ac currents, vortices are free to move in the intergrain material and losses occur. These losses (at zero dc current) increase at a rate given by $I_{AC}^n$ where $n$ is roughly 3.5, i.e. between the predictions of Norris for an elliptical cross section and a thin strip, a plausible result. Thus a first step before attempting to fit the data to the theory discussed above would be to add a constant, equal to the appropriate plateau, to the losses calculated for each curve of Figure 5. However another hurdle appears when one notes the position of the end of the plateau say for the lowest curve with $I_{AC} = 4.2$ A. This excludes the model with $I_{sb}$ since we are in the condition $I_{AC} < I_{sb}/2$, for which no extra losses are allowed. Thus we are forced to exclude this model and to continue the analysis with $I_m$ instead. A single fitting parameter of $I_m = 21.8$ A for all curves yields a relatively good fit of the data. This fit is improved if, as in Figure 5, $I_C$ is set at 27 A instead of the measured value of 29 A.

Higher values of ac current are considered in Figure 6. The data in the inset apply to the sample with $I_C = 29$ A. A plateau and an increase in the losses is observed for $I_{AC} = 25.5$ A but a minimum is finally observed for $I_{AC} = 31.1$ A. The fact that this is beyond $I_c$ is not a problem in that the quoted value applies to the tape as a whole rather than only to the grains. Also the criterion for determining $I_C$ is somewhat arbitrary. A similar effect is observed with the critical current reduced to 25 A. The first appearance of the minimum is observed with $I_{AC} = 26.2$ A. Due to the complex nature of these curves, no fit was attempted, the curves being merely a guide for the eye. Nevertheless, the predicted minimum is approximately 50% lower than the level without a dc current in agreement with the predictions shown in Figure 4.
As in Ref.[8], we consider either a Meissner current or a surface barrier current. We are forced to reject the latter due to the position of the end of the a region defined by our experimental results. On the other hand, as in Ref.[6], we cannot accept the Meissner current option without any questions. Such a current would be of the order of $10^{-5}$ A whereas we obtain 21.8 A. Again we must refer to the granular nature of the high temperature superconductor in the tape. The flux lines penetrate easily into the intergrain material which has a low critical current. An increase of the dc current forces the flux lines to penetrate into the grains thereby increasing the losses. These even display two minima for $I_{AC} = 26.9$ A, possibly a reflection of the excursion of flux lines in a cycle which include one and then two grains. This picture will be elaborated in a forthcoming article [9].

**Conclusion**

These results add support to the observation by this group of a decrease of ac losses when a dc current is superimposed onto an ac current that is large with respect to a postulated $I_m$ or $I_{sb}$. The detailed behavior is complicated by the granular nature of the silver-gold alloy sheathed Bi–2223 tape but the observed reduction of approximately 50% of losses compared to the ones without a dc current correspond to the calculated result. At lower ac current, computer simulations succeeded in fitting the data with a single parameter $I_m = 21.8$ A whereas a surface barrier model is incompatible with the data. Nevertheless the latter model should not be discarded completely since it considered the barrier as being at the surface of the tape as a whole although it is in reality at the surface of each grain. Finally we recall that for the first time, the simulations took into account the elliptical nature of the tape cross-section.
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