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The influence of filament arrangement on current distribution and AC loss in Bi-2223/Ag tapes

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Abstract

State-of-the-art deforming techniques allow the preparation of composite Bi-2223/Ag tapes with well controlled filament arrangement. This would allow tailoring of the tape's electromagnetic properties according to specific applications. We studied the possibility to reduce, through a suitable filament ordering, the hysteresis losses caused by an external magnetic field perpendicular to the tape's wide face. For this purpose, the distribution of shielding electrical currents in multifilamentary superconducting arrays, as a response to a perpendicular AC magnetic field, was investigated both theoretically and experimentally. We show that due to optimizing of filament arrangement, the hysteresis loss can be suppressed by one order of magnitude.

1. Introduction

In this work we discuss the hysteresis loss due to magnetic field perpendicular to the wide face of Bi-2223/Ag composite tapes. This is the essential loss component in the winding of an electrical machine such as a power transformer, that would also remain when the coupling losses were completely eliminated by a proper filament twisting and increase of the matrix effective resistivity. When trying to predict its value, the following difficulty is encountered: analytical or phenomenological formulae exist just for simple shapes like a slab [1], strip [2], disc [3] or strip with elliptical crosssection [4], while the tapes considered for application contain tens of filaments, often with rather irregular shape. Then it is also doubtful whether the formulae derived for regular stacks or arrays containing an infinite number of filaments [5] could be applied. It is obvious that the loss considerations should include the influence of magnetic fields produced by shielding currents circulating in the neighbouring filaments. This is a problem that has not yet been fully resolved; however, some essential results have already been achieved. In particular, we show that the shielding in the low-field regime, when filaments behave diamagnetically, provides a significant hint for the loss performance in the whole range of AC fields. Because this situation can be suitably studied with the help of commercial FEM codes, estimation of hysteresis loss in different types of filamentary tapes can be achieved. We confront here the theoretical predictions concluded following this approach, with experimental data on three Bi-2223/Ag tapes: one tape with quite common filament arrangement, and two tapes prepared on purpose to exhibit reduced hysteresis loss.

2. General features of AC loss behaviour

The curves of AC loss dependence on the amplitude of applied field, predicted by theoretical models for three simple shapes (slab in parallel field, thin strip and strip with elliptical crosssection in perpendicular field), follow a common pattern (figure 1). A kink divides them in the low field part, where



Figure 1. Theoretical predictions for the hysteresis loss in external field for samples of different shapes. The same penetration field (1 mT), cross-section (1 mm^2) as well as the aspect ratio (10) has been assumed for the three shapes.



Figure 2. The behaviour of AC susceptibility (imaginary part) for three simple shapes: slab, thin strip and elliptic strip.

the loss increases with the fourth (thin strip) or the third (slab, elliptic strip) power of the applied field, and the high field part, where the loss increases with the first power for all the shapes. The similarity in loss behaviour can be even better demonstrated when expressing the AC loss through χ'' , the imaginary part of the AC susceptibility:

$$q = S_{\text{shape}} \frac{\pi}{\mu_0} \chi_0 B_a^2 \chi_{\text{int}}^{\prime\prime}(y) \text{ (J m}^{-1}).$$
(1)

Here, S_{shape} is the area of the shape's cross-section, $\mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1}$, χ_0 is the initial susceptibility in diamagnetic state of filaments, and $\chi''_{\text{int}}(y)$ follows the corresponding function that the theory predicts for each shape. The independent variable in this function is $y = B_a/B_p$, where B_p is the penetration field defined in each model. To evaluate the AC loss in a monocore tape using expression (1), one needs to choose the shape that at best describes its cross-section, and

then use the formulae for χ_0 and χ''_{int} derived for that shape. The behaviour of $\chi''_{int}(y)$ is strikingly similar for the three models see figure 2. To compare the shapes better, the values on both axes have been scaled to the point when the susceptibility is maximal. The relative shift caused by this scaling is not substantial, as the theoretical predictions for the peak value, χ''_{max} , lie in a quite narrow interval: 0.239 for the slab, 0.2365 for the thin strip and ~0.2 for the elliptic strip. This leads to an important conclusion: regarding the absolute level of AC loss, it is the value of χ_0 that could make a substantial difference.

Previous results have been calculated for a single core. In the case of a multifilamentary tape, the individual filament is supposed to interact with the applied field, now modified by shielding currents in other filaments. Therefore it is not clear whether one could apply the conclusions derived for a simple shape on such a composite structure. In the following we present experimental data showing that for certain kinds



Figure 3. Cross-sections of three tapes used in the study, together with the results of FEM calculation for magnetic field distribution in the diamagnetic state. To show the details of magnetic flux penetration better, just the central part of calculated distributions is shown, and the scales on the two axes are different.

of multifilamentary tapes such extrapolation is possible, and it can be used to develop the filamentary architectures with reduced AC loss.

3. Samples and experiments

Evaluation of losses, due to AC magnetic field perpendicular to the tape's wide face, was performed for three tapes from Bi-2223 in a silver matrix. Micrographs of these tapes are presented in the upper part of figure 3. The reference tape of common filamentary architecture contains 19 filaments. It has been manufactured by uniaxial rolling from the original cylindrical arrangement of cores, and the filaments form an overlapping structure. Using the tape-in-rectangular-tube process [6], a tape containing 60 extremely flat filaments in four dense stacks as well as a tape where 21 filaments are arranged in the perpendicular direction with respect to the tape's wide face, have been prepared.

The value of χ_0 for these structures was determined with the help of a finite element method calculation, using commercial software. The distribution of the magnetic field was calculated for a state where the filaments are assumed to be perfectly diamagnetic. As previously shown [7], from this distribution of magnetic field, calculated in two dimensions, the value of χ_0 is derived as

$$\chi_0 = \frac{1}{S_{\text{tape}}} \int_{S_{\text{box}}} \left[\left(\frac{B}{B_{\text{applied}}} \right)^2 - 1 \right] \mathrm{d}S \tag{2}$$

where S_{tape} is the area of the tape's section, S_{box} is the area in which the magnetic field is calculated (this should be much bigger than that of the tape), and B is the local value of the magnetic field in the presence of the sample when the field B_{applied} is applied. The results of the magnetic field modelled for a diamagnetic state of filaments with the help of the commercial software ANSYS are also presented in figure 3. It is due to the definition of χ_0 that the magnetostatic formulation of the problem, with relative permeability close to zero (e.g. equal to 10^{-6}), could be utilized. The field distribution calculated in static conditions is characteristic also for the critical state at weak AC field, provided that the shielding currents-flowing with critical current density-fill only a very narrow surface sheath in any of the filaments. From the time evolution during the AC cycle, the instant when the applied field just reaches its amplitude value represents the shielding ability of the sample at best. Then, the value of χ_0 can be identified with the absolute value of the real part of the external AC susceptibility, χ'_{ext} , at low applied AC field. This idea, allowing us also to determine the value of χ_0 experimentally, has been clearly confirmed by our previous investigation [8], where the values of χ_0 established by both the FEM modelling and AC susceptibility experiments on samples with quite different architectures have been found to agree nicely.

Looking at the field distributions in figure 3, one can see large differences between the electromagnetic properties of the three tapes under study. In the sample with interlacing filaments, the magnetic flux could hardly find a way through the structure. In the sample with columnar filament arrangement, the gaps between stacks form channels for the penetration of magnetic flux, which then becomes heavily concentrated in these channels. The easiest passage for magnetic flux represents the structure of the tape with filaments perpendicular to the tape's wide face. This is because the filaments appear parallel to the field applied perpendicular to the tape's wide face.

The results of this kind of calculation do not depend on the absolute value of assumed applied magnetic field, because the perfect diamagnetism of the filaments is an integral part of the model. The only factor influencing χ_0 is the distribution of the shapes and positions of filaments. Thus, χ_0 can be considered a geometrical characteristic of the sample. Geometrical data of the tapes, together with χ_0 calculated according to formula (1) from the distributions presented in figure 1, are given in table 1. As expected, the results for χ_0 express qualitatively the difference observed by a simple examination of the field distributions in the figure 3: providing the passage for transversal magnetic flux is an effective means for the reduction of χ_0 .

Our interest in field distribution in a diamagnetic state of filaments was motivated by the fact that in the case of simple shapes we have observed that the loss is directly proportional to χ_0 . If this conclusion is also valid for multifilamentary structures, this would provide an effective means to predict AC loss. Our experimental data support such consideration, as demonstrated in figure 4. The apparatus as well as the experimental procedure for the evaluation of AC loss has been described elsewhere [9]. The loss was measured on a single short piece (~5 mm long) cut from the tape, at AC field frequency of 21 Hz. In these circumstances, the coupling loss would be insignificant. This was proved by checking the frequency dependence, that up to ~100 Hz has been



Figure 4. Loss density in three tapes. f = 21 Hz, T = 80 K. Because of the short sample length, only the hysteresis loss in the filaments contributes to the total loss.



Figure 5. Comparison of AC loss from figure 4, recalculated per unit length of tape and divided by its critical current.

Table 1. Properties of tapes.					
Таре	Number of filaments	Overall tape cross-section (mm \times mm)	Fill factor (%)	Average filament cross-section $(\mu m \times \mu m)$	χο
1 2 3	19 4 × 15 21	2.5×0.14 3.8×0.28 2.2×0.55	18 26 39	320×10 533×8 60×342	12.4 3.93 1.37

negligible, and confirmed by estimations using the established model for coupling loss calculation [10]. The plot shows only the data taken at a temperature of 80 K; nevertheless, the relation between losses in the three tapes remained the same at temperatures up to 95 K.

The experimental data confirm that the common structure used for commercial multifilamentary tapes, with interlaced filaments, is that least favourable from the point of view of hysteresis loss in an external field perpendicular to the tape's wide face. One can also clearly see that the value of χ_0 is the key parameter in AC loss estimation. Thus, the arrangement of filaments in parallel to the applied field,

as in the case of the tape with filaments perpendicular to the tape's wide face, is that recommended for the reduction of AC loss. The results show that a loss reduction by more than one order of magnitude compared to a common filamentary architecture has been reached. Unfortunately, for such a structure it is quite difficult to get a satisfactory texture of the superconducting material. As a consequence, the current density in this tape was only 2800 A cm⁻² (77 K self field), contrasting 10 000 A cm⁻² in the tape with the common arrangement and even 16 000 A cm⁻² achieved in the tape with columnar filamentary structure. For a complex evaluation of the tape's performance from the engineering point of view, it

F Gömöry et al

is reasonable to compare the loss per unit length, divided by the critical current. Such a comparison is given in figure 5. We can see that, in spite of much lower critical current density, the complex performance of the tape with filaments perpendicular to the wide face is still better than that of the tape with common filament arrangement. However, in the low-field range it is now surpassed by the tape with columnar structure. In this tape, relatively good AC loss reduction-due to the filamentary structure providing channels for flux penetrationis combined with the excellent texturing achieved in extremely flat filaments. It seems that this kind of filamentary architecture represents an optimum solution, combining excellent critical current density and decent reduction of AC loss for applications where the tape would experience a perpendicular component of magnetic field less than \sim 5 mT. For larger fields, the performance of the tape with perpendicular filaments remains superior.

Before making a general conclusion regarding the magnetization loss reduction by a proper filamentary architecture, one should take into account that our study deals with just one loss mechanism. Therefore, the effect of the coupling currents was intentionally suppressed to extract just the hysteresis loss in filaments. It is beyond the scope of the present work to compare how suitable the different tape structures would be when the coupling loss reduction by e.g. twisting and introduction of resistive barriers were the priority.

4. Conclusions

We have experimentally tested the theoretical prediction about the possibility to estimate the AC loss in multifilamentary tape due to applied external field, from its shielding properties at low fields. This shielding includes the effect of inter-filament magnetic coupling, and can be quantitatively characterized by the value of AC susceptibility in a diamagnetic state of filaments, χ_0 . It was indeed found, by comparing the loss behaviour of three tapes with different architecture of the filamentary zone and value of χ_0 ranging within one order of magnitude, that this parameter plays an essential role in the hysteresis loss when the magnetic field is perpendicular to the tape's wide face. It is not difficult to establish its value theoretically, with the help of commercial finite element code. The calculations we performed, as well as the experiments on three tapes, have shown that the structure of low loss tape should provide enough channels parallel to the applied field, to allow easy penetration of magnetic flux. The lowest losses have been measured in the tape with filaments arranged in parallel to the external field.

When applying this conclusion to a concrete case of tape architecture design, one should also take into account other factors that have not been treated here. In particular, the accomplishing of a structure that is optimal from the point of view of AC loss is often accompanied by difficulties in reaching satisfactory critical current density. Here we show that the arrangement of filaments in regular columns allows reduction of the loss simultaneously with achieving good critical current density. Also, our results refer to only one mechanism of AC loss, namely the hysteresis loss due to flux pinning in the superconductor. For the case when the coupling loss due to currents that connect the filaments through the metallic matrix play a significant role, the reduction of hysteresis loss would not be the key issue. In this regard, the means of coupling loss reduction that concern more the structure of the winding than the filamentary structure of the tape will be compatible with the conclusions presented here.

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