Finite-element analysis and comparison of the AC loss performance of BSCCO and YBCO conductors

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Abstract. The AC loss performance of two BSCCO and two YBCO conductors of different geometry, characterized by the same self-field critical current of 150 A, is analysed and compared quantitatively. The comparison is made using the finite-element method with a non-linear $B$-dependent $E$-$J$ relation. A new shell-region model is utilised for the simulations of thin YBCO strips. Different AC working conditions are simulated: self-field, applied external field, and combined transport current and external perpendicular field application. Magnetic field and current density profiles are investigated in order to illustrate the reasons for the loss difference in the conductors. Depending on the application, the advantages of using BSCCO or YBCO conductors with specific geometry are outlined.

1. Introduction

The manufacturing technology of BSCCO wires, often referred to as first-generation superconductors, is presently well developed and high-quality BSCCO tapes are available commercially in km-lengths with critical current $I_c$ up to 150 A. On the other hand, YBCO coated conductors, referred to as second-generation superconductors, are still at the R&D stage for lengths above 100 m. The potential of YBCO as a lower-cost conductor with higher $I_c$ than BSCCO is undeniable. However, the aspect of its AC loss performance in comparison with BSCCO has not been well evaluated yet, even if experimental data for the AC losses in YBCO tapes have been published [1,2].

Table 1. Geometry and properties of the BSCCO and YBCO conductors

| Conductor          | Dimensions     | $S_{HTS}^a$ (mm$^2$) | $J_{cl}$ (A/mm$^2$) | $n$-value |
|--------------------|----------------|-----------------------|---------------------|-----------|
| BSCCO tape (37)    | $3.3 \times 0.3$ mm | 0.37                  | 650                 | 25        |
| BSCCO wire (16)    | $1.2 \times 1.2$ mm | 0.43                  | 650                 | 25        |
| YBCO strip         | $10 \times 1$ $\mu$m | 0.01                  | 16,500              | 25        |
| YBCO stack         | $4 \times 2.5 \times 1$ $\mu$m | 0.01                  | 16,500              | 25        |

$^a$ $S_{HTS}$ is the superconducting cross-section.
$^b$ The filament number for the BSCCO conductors is given in brackets.
$^c$ The inter-strip distance in the YBCO stack is 150 $\mu$m.

The purpose of this paper is to present a quantitative comparison between the AC loss performance of BSCCO and YBCO conductors by means of numerical analysis. Finite-element method (FEM) simulations are used in order to calculate precisely the AC losses, the current density, and magnetic...
field profiles in different operating conditions. A comparison is made between two wires of standard geometry, a 37-filamentary BSCCO flat tape and a single YBCO strip, and two wires with a modified geometry – a 16-filamentary BSCCO square wire with symmetric filament arrangement, and a stack of four narrower YBCO strips. Table 1 gives the details of the four geometries, shown in figure 1.

2. Numerical modelling

The simulations were performed with the FEM electromagnetic software package FLUX [3], in which the non-linear power-law characteristic of HTS materials $E = E_c (J/J_c(B))^n$ with magnetic field dependence of $J_c$ has been implemented [4].

YBCO conductors pose a real numerical challenge for FEM models because of their very high geometric aspect ratio; typically YBCO strips are 10 mm wide and 1 to 5 µm thick, which corresponds to aspect ratios of 2,000 to 10,000. Aspect ratios exceeding 1,000 require a very fine mesh with a huge number of elements, which would result in an enormous consumption of CPU time and memory. A possible FEM approach is to ‘approximate’ the thin strip by increasing its thickness and thus decreasing artificially the aspect ratio of the conductor by a factor of 10 to 1000 [5], [6]. Another possibility is to treat the problem as one-dimensional and in this way to avoid creating a 2D region and FEM mesh in the $y$-direction for the YBCO strip [7], and we have employed a similar approach.

In this paper, we have used the “shell” region in FLUX (also called a “line” region) in order to model a superconducting YBCO strip [8]. The shell region is a 1D region – a curve or a straight line, as is the case with the YBCO strip, which is meshed only in one dimension, e.g. along $x$-axis (the width of the strip), with no mesh assigned along the $y$-axis. In this way, a sufficiently fine mesh can be obtained with 100 line elements along the width of a 10 mm-wide strip. The details about the use of shell regions in the FLUX software package as a new model for YBCO strips are given in a recent work of ours [8], where a comparison with analytical solutions for thin strips is presented as well.

![Figure 1. Geometry of the BSCCO and YBCO conductors used for the FEM simulations. Not drawn to scale for YBCO.](image1)

![Figure 2. Self-field AC losses for different values of the applied current ratio $i = I_{peak} / I_c$. The self-field $I_c$ is 150 A for all four conductors.](image2)

The critical current of HTS materials decreases in the presence of magnetic field [4], [9]. For describing more accurately the behavior of BSCCO and YBCO conductors, we have implemented a power-law with $J_c(B)$ dependence for each material [8]. A constant $n$-value of 25 has been used. The dependence for BSCCO is anisotropic [4], with $J_c$ depending on both field components:

$$J_c(B) = \frac{J_{c0}}{48 - 6.8e^{8.76 - 40.2e^{-8.76}}}$$  \hspace{1cm} (1)
As far as YBCO is concerned, it is much less anisotropic material than BSCCO at low magnetic fields (below 0.2 T). Using a fit to the average experimental data for $J_c(B)$ in fields of varying orientations, presented in [2], we have modeled the $J_c(B)$ dependence for YBCO as follows [8]:

$$J_c(B) = J_{c0} \times \begin{cases} 1 - 3.13 |B| - 433.8 |B|^2 + 7007.8 |B|^3 & \text{for } |B| \leq 0.03 \text{ T} \\ \left(1 + |B|/0.069\right)^{-1} & \text{for } |B| > 0.03 \text{ T} \end{cases}$$  \hspace{1cm} (2)

The $J_{c0}$ values for each material are given in Table 1. All four conductors have the same effective critical current $I_c$ of 150 A in self-field [4, 8]. The simulations were performed with AC transport current with frequency $f$ of 50 Hz and (or) external AC magnetic field in phase with the current.

3. Results: applied AC transport current

The transport current AC losses (no external field present) have been calculated for a current ratio $i$ ($I_{\text{peak}}/I_c$) up to 1.3 for the four conductors; the results are shown in figure 2. There is a clear change of slope near the critical current ($i \approx 1$) for all four AC loss curves due to the developed flux-creep and flux-flow resistance in the superconductor close to $I_c$ [4].

The single YBCO strip has the lowest losses among conductors with different geometry, and its self-field loss is in agreement with Norris’s analytical prediction for infinitely thin strip. The other three conductors – the BSCCO wire and tape, and the YBCO stack – have higher self-field AC losses (a factor of 2 or more at low currents and a factor of 1.5 to 2 near $I_c$) than the single YBCO strip. The self-field losses of the other three conductors can be well approximated by Norris’s equation for a wire with elliptical cross-section in the whole current range [8].
In order to illustrate the reasons for the loss differences in the YBCO conductors, figure 3 shows an example of the magnetic self-field distributions in the YBCO single strip and in the two upper strips of the YBCO stack for applied transport current of 150 A, equal to \(I_c\). The field profiles are traced for three different values of the time step and show clearly that the self-field in the single strip is very well screened – even at \(I_c\) the central region of the strip (more than 1/3 of the whole width) is still field-free at any instant of the cycle, whereas at the same time steps the strips of the stack are almost completely penetrated. In addition, the magnitude of the self-field in the single strip (a maximum of 21 mT) is much lower than in the stack (a maximum of 38 mT).

The current density profiles at the peak of transport current with amplitude of 150 A (\(Z_t = 3\)), shown in figure 4, also demonstrate clearly why the strip has the most optimal geometry in self-field. The FEM software calculates the AC losses in the superconductor using the dot product of \(E\) and \(J\),

\[
Q_{ac} = \int_0^{V/f} \int_S J \cdot E \, dS \, dt,
\]

so that a higher \(J/J_c(B)\) ratio leads to higher AC losses. That is why figure 4 shows also the \(J_c(B)\) curve, calculated from the corresponding magnetic field profiles in the strip and in the stack. As can be seen in figure 4a, \(J\) exceed \(J_c(B)\) near the edges of the single strip, whereas in the central region the ratio \(J/J_c(B)\) is less than one. As a consequence, the power dissipation in the single strip is not very high. On the contrary, in the strips of the stack \(J\) exceeds considerably the local \(J_c(B)\) across the whole width (except for a narrow central region in the middle strips) and so the ratio \(J/J_c(B)\) is much larger than one. The regions with \(J/J_c(B) > 1\) dissipate most of the power in the superconductor [4], and accordingly the total power losses in the stack are considerably higher (up to a factor of 2) than in the single strip when only transport current is applied.

### 4. Results: applied AC perpendicular magnetic field

The AC loss results for applied external field of perpendicular orientation are displayed in figure 5. For validation of the shell-model, used for the YBCO strips, we have also plotted the loss in a thin superconducting strip, analytically calculated by Brandt [10]. All loss curves change their slope on a log-log plot near the full penetration field \(B_p\). The losses of the two BSCCO conductors increase approximately with \(B_a^3\) below \(B_p\), while the losses of the two YBCO conductors scale with \(B_a^4\) at low fields; this is in accord with the analytical solutions for multifilamentary superconductors and thin strips, given in [11] and [10], respectively. Above the penetration field, which depends on \(J_c\) and the geometry, all four conductors have a loss slope of one, which means that the magnetization losses are linearly proportional to the applied field.

It is known from theoretical considerations that superconductors with higher aspect ratio (the ratio between the width and the thickness) have higher AC losses in perpendicular magnetic fields, which is due to their stronger demagnetizing effect [11]. The FEM simulations showed that the YBCO strip, being the conductor with the highest aspect ratio, has indeed the highest AC loss, which fits closely the analytically derived loss for a strip with the same dimensions, calculated by Brandt [10]. In applied external magnetic field, the aspect ratio of the conductor and the associated demagnetizing effect are the most important factor that determines the magnitude of the AC losses. Tapes and strips in parallel field have a low demagnetizing effect and very low AC losses, whereas the same conductors in perpendicular field have a strong demagnetizing effect, and consequently very large AC losses.

The YBCO stack has much lower AC losses than the strip: the difference is a factor of 38 at 1 mT, and decreases to a factor of 4.5 at 150 mT. The loss difference is much more important than one could expect from reducing the width (the strips in the stack are four times narrower and have the same thickness as the single strip). In fact, in applied perpendicular field, the losses scale with the square of the strip width and are inversely proportional to its thickness [10], so that by using four independent narrower tapes, the loss reduction would have been a factor of \(16/4 = 4\); the factor 16 comes from the square of the width and the factor 4 in the denominator comes from the fact that there are four strips in the stack. The higher loss reduction in the stack can be explained by the coupling of the four strips:
they do not behave independently and there is a substantial reduction of the field penetration compared to the single strip [8]. Thus, the coupling of the four strips in the YBCO stack is very favourable in applied fields, because the aspect ratio and the demagnetizing effect, and hence the AC losses of the composite conductor are greatly reduced compared to a single thin strip. This is very encouraging for applications of YBCO stacks with external magnetic fields present.

As far as the two BSCCO conductors are concerned, the square wire has considerably lower losses than the 37-filamentary tape, which is due the weak demagnetizing effect of a conductor with aspect ratio of one in applied perpendicular field. The loss difference reaches a factor of 7.5 at a field of 10 mT, and decreases to a factor of 2.5-3 at fields higher than 70 mT. Above the full penetration field (determined qualitatively on figure 5 by the change of slope of the loss curves), the induced currents are fully occupying all filaments of the tape and the wire, and the current density exceeds everywhere the local $J_c$. In this case, the stronger reduction of $J_c(B)$ for the tape in perpendicular field implies less induced current (because of the increased resistivity), and correspondingly lower losses as well. This explains the decrease of the loss difference between the tape and the square wire at high perpendicular fields.

5. Results: applied transport current and AC perpendicular magnetic field
The 2D analysis of the interaction between the self-field, generated by the transport current, and the applied external field is rather complicated even for simple geometries in the critical state model. Therefore, for modelling the magnetic field and current distributions in HTS with $B$-dependent $E$-$J$ power law, numerical methods are particularly useful and necessary tools.

For all the conductors, the losses in this combined current and field case are higher than the simple sum of the separate transport-current and magnetization loss contributions. This is due to the strong interaction of the self-field and the perpendicular external field, observed experimentally in both BSCCO and YBCO tapes [2, 12]. This interaction is stronger in conductors with large aspect ratio (tapes and strips) because both the self and the external field start their penetration from the edges, which results in substantial increase of the total losses.
In order to quantify the interaction between the self and the external field, we have calculated the ratio between the total AC loss \(Q_{\text{tot}}\) for a given transport current in applied external field, and the sum of the separate self-field loss \(Q_{\text{sf}}\) and magnetization loss \(Q_{\text{mag}}\) contributions. Figure 6 shows the ratio \(Q_{\text{tot}}/(Q_{\text{sf}} + Q_{\text{mag}})\) for a transport current of 90 A. This ratio gives an indication about the degree of interaction between the self and the external field – the higher the ratio, the higher the interaction and the increase of the total loss.

At low amplitudes, the penetration of the external field is not large, except for the YBCO single strip, so there is no important interaction with the self-field; the self-field loss is dominating and that is why the ratio \(Q_{\text{tot}}/(Q_{\text{sf}} + Q_{\text{mag}})\) is close to one. At intermediate fields, the self-field and the external field are of similar magnitude and the interaction increases since both penetrate the conductors from the edges. At higher fields, the applied field (and the magnetization loss) is increasingly dominating the self-field and the interaction decreases with the field amplitude. For YBCO, the magnetization effect is stronger because of the large aspect ratio of the strips, so that the intermediate fields are lower than for BSCCO, where the self-field has a more important contribution to the total loss. Thus, due to the strong interaction between the external and the self-field, the total losses in all four conductors are considerably larger (up to a factor of 3.5) than the simple sum of the separate transport-current and magnetization loss contributions. Otherwise, the total AC loss for fields above 30 mT is dominated by the magnetization loss [8], and the geometry considerations for applied field only remain valid as well.

6. Conclusions

Using the finite element method as a basis for numerical analysis, we have shown that standard YBCO tapes made of one single YBCO thin film have low losses in self-field only, and may be suitable for transport current applications, i.e. in superconducting cables. However, in a cable configuration, the influence of the self-field of the neighbouring tapes and the adjacent layers cannot be neglected and needs further investigation. YBCO has the potential of a second-generation HTS conductor for power applications with much higher critical current than BSCCO. Assuming the same critical current, however, the BSCCO square wire is the HTS conductor with the optimal AC loss performance in magnetic fields with a strong perpendicular component, which will be the case in applications, such as transposed or stranded cables or transformer coils. The YBCO stack has AC loss performance similar to the one of the BSCCO tape since their aspect ratios and demagnetizing effects are not very different. The stack was shown to have considerably lower losses than the single strip in the presence of external magnetic field. Therefore, the use of stacks with different configurations needs to be further examined and seems promising for optimizing the AC loss performance of YBCO conductors for high-current AC power applications.

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