AC loss of the YBCO coated conductor in high magnetic fields

E Seiler and L Frolek
Institute of Electrical Engineering, Centre of Excellence CENG,
Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia
E-mail: eugen.seiler@savba.sk

Abstract. The AC losses of the YBCO coated conductor in the perpendicular applied AC magnetic field were investigated by means of the complex AC susceptibility measurements. A harmonic homogenous AC magnetic field was applied perpendicularly to the wide face of the YBCO coated tape. Together with this AC field, a parallel background DC magnetic field up to 14 T was applied perpendicularly to the tape. The measurements were performed at several constant temperatures in the range 3 K – 50 K. In the region of high background DC fields (8 – 14 T) no influence of the tape’s ferromagnetic substrate was detected, despite of the low measurement temperatures employed. The estimate of the critical current density ($j_c$) at 20 K and 14 T, based on the position of the imaginary AC susceptibility peak, gives the value $j_c = 0.53 \text{ MA/cm}^2$.

1. Introduction
The YBCO coated conductors [1] are being considered as the next generation of high-temperature superconducting wires and are believed to allow broader application of the superconducting wires in the practice, due to their lower cost and better performance in magnetic field compared to the BSCO tapes.

The YBCO coated conductor has the form of a long flat tape with the thickness of typically 0.1 – 0.2 mm and the width 3 mm to 10 mm. It is composed of a metallic substrate tape on which a thin buffer layer is deposited, followed by a few micron thick layer of $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) superconductor. From the point of view of the possible applications one of the mayor issues to be solved in the coated conductors’ development is the cut down of the AC losses. The AC losses of the coated conductors have been extensively studied over past few years [2][3][4], mostly in the conditions of the transport AC current [5][6][7][8]. To reduce the AC loss the possibility of creating a multifilamentary structure in the YBCO layer by striation [9][10] and the role of the ferromagnetic substrate tape [11][12] are explored.

2. Experiments and AC loss evaluation
In our experiments, we measured the 1st harmonic complex AC susceptibility of a short piece of the YBCO coated tape made by the American Superconductors company, labeled as the 344 wire (AmSC 344 wire). The tape is 4.4 mm wide and we have used a 6 mm long sample. The substrate tape of this wire is of a ferromagnetic Ni-W alloy.

In our experimental set-up, the sample was placed in the middle plane of the pick-up coil, with its wide face perpendicular to the coil’s axis. A homogenous harmonic AC magnetic field
was applied on the sample, perpendicular to the sample’s face. Parallel to this AC field also a homogenous constant DC magnetic field was applied. A second coil, called compensatory, stood empty during the measurement and sensed the pure induced voltage from the applied AC magnetic field. The differential voltage from the pick-up and compensatory coil, proportional to the sample’s magnetization, was measured by a phase sensitive lock-in amplifier. The AC system was placed inside the variable temperature insert of the helium-cooled superconducting DC magnet system from Oxford Instruments.

Our interest was focused on the coated tape’s properties at low temperatures and high DC magnetic fields. We performed susceptibility measurements in 14 T DC magnetic field at 50 K, 40 K, 20 K, and 3 K and made a short series of measurements in 8 T, 12 T and 14 T DC field at 20 K. The maximal AC field amplitude was approx. 60 mT and all the measurements were performed at the frequency 21 Hz.

2.1. AC losses

The hysteretic AC losses have been calculated from the AC susceptibility data in a very straightforward way. The volume density of the AC loss in the sample per cycle of the applied magnetic field \( q \) is coupled with the imaginary part of the 1st harmonic AC susceptibility \( \chi'' \) by a simple relation [13]:

\[
q = \chi'' \pi B_a^2 / \mu_0 ,
\]

where \( B_a \) is the amplitude of the harmonic applied magnetic field \( (B_a \cos \omega t) \) and \( \mu_0 \) is the permeability of vacuum.

It is more common, and also more useful for technical evaluation of the conductor’s performance, to express the AC losses in terms of the loss energy per meter of the conductor’s length, i.e. in J/m. These values of AC losses we denote as \( Q \) in this article. They can be easily obtained from the \( q \) values (eq. (1)) by multiplying with the superconductor’s cross-section (the cross-section of the YBCO layer) \( S_{sc} = w t \), when \( w \) is the width of the YBCO layer (width of the coated tape) and \( t \) is the thickness of the layer.

In practice, however, it is often very difficult to obtain reliable data on the YBCO layer thickness \( t \). Although it might seem that the usage of an improper value of \( t \) could affect the AC loss values \( Q \), this is luckily not the case. The thickness \( t \) enters also the evaluation of the AC susceptibilities from the voltages measured by the lock-in amplifier.

The quantity actually measured in the magnetization experiment described above is the magnetic moment of the superconducting sample \( m \) [14]. The sample’s magnetization is constructed as the volume density of this magnetic moment, \( M = m/V_{\text{sample}} \), where now \( V_{\text{sample}} = wtL \) (\( L \) is the length of the sample; \( L \times w \) builds the flat face of the conductor, perpendicular to the applied field). The susceptibility (\( \chi \)) is then proportional to:

\[
\chi \sim \frac{m}{V_{\text{sample}}H_a} = \frac{\mu_0 m}{wtLB_a} ,
\]

where \( B_a \) is the applied field. For the imaginary AC susceptibility from the equation (1) also holds \( \chi'' \sim t^{-1} \) and one can thus easily see that the AC losses \( Q = q wt \) are independent of the \( t \) value.

We have estimated the YBCO layer thickness of the AmSC 344 wire to be approx. 2 \( \mu \)m and we used this value for the AC susceptibility evaluation. However, as the uncertainty of this value is more than 50 \%, we express the AC losses in terms of the loss energy per meter of the coated wire.

3. Results

The normalized plots of the measured dependences of the real (\( \chi' \)) and imaginary (\( \chi'' \)) part of the internal AC susceptibility on the amplitude of the applied magnetic field (\( B_a \)) are shown
Figure 1. Normalized dependences of the real (left) and imaginary (right) internal AC susceptibility measured on an YBCO coated tape (symbols), together with the theoretical prediction of the model of thin rectangular strip (black line) and elliptical strip (gray line). In the legend, the respective DC field and temperature is indicated for each series.

in the figure 1. The applied field amplitude is normalized to the value $B_{a,\text{max}}$ at which the maximum of the imaginary susceptibility (denoted as $\chi''_{\text{max}}$) is reached. The values of $\chi''$ are normalized to the maximal value $\chi''_{\text{max}}$.

The predictions of two theoretical models applicable in the case of thin flat superconducting tape in a perpendicular field are also shown in the figure. The full black line represents a curve predicted by the model of thin rectangular strip [15] and the full gray line is the prediction of the model of elliptical strip [16].

It is visible that the experimental data are in much better agreement with the prediction of the model of thin rectangular strip. Nevertheless, some discrepancies exist in the region of low amplitudes, more pronounced in the $\chi''$ plots. This can be a consequence of the presence of a ferromagnetic layer (substrate tape) in the vicinity of the YBCO layer. Although the hysteretic losses in the ferromagnetic substrate should be negligible in the magnetic field range 8 – 14 T, and indeed we did not see any sign of such losses, the ferromagnetic layer still influences the local distribution of the magnetic field near the superconductor, possibly increasing the perpendicular field component at the tape edges.

The figure 2 shows the plots of the AC losses per meter of the conductor’s length ($Q$) in dependence on the applied AC magnetic field amplitude $B_a$ for the AmSC 344 wire at various temperatures and DC magnetic fields, as indicated in the legend.

As the changes of the temperature and DC applied field affect not only the AC loss itself but also the critical current ($I_c$) of the conductor, it is useful to recalculate the losses in terms of the loss energy per meter of the conductor’s length and per 1 Ampère of its critical current. To estimate the $I_c$ of the wire at the respective condition of each measurement (temperature, DC field) we again used the AC susceptibility data, namely the $\chi''(B_a)$ dependences.

On the basis of the theoretical models of the thin rectangular and elliptical strip mentioned above it is possible to estimate the critical current density $j_c$ of the YBCO coated wire. Both models [17] provide a simple relation between the $B_{a,\text{max}}$ and $j_c$:

$$B_{a,\text{max}} = k \mu_0 t j_c,$$

where $k$ is a numerical constant given by the model ($k \approx 0.78$ for thin rectangular strip; 0.6 for elliptical strip) and $t$ is again the thickness of the superconductor, i.e. the thickness of the YBCO layer. The critical current is calculated by multiplying the $j_c$ by the YBCO layer cross-section, $I_c = j_c w t$, and it is again visible that the thickness $t$ in the end does not enter in this
Figure 2. AC losses per meter of the coated conductor in dependence on the AC magnetic field amplitude $B_a$ measured at different temperatures and superimposed DC magnetic fields.

Figure 3. Critical current in dependence on the temperature in the 14 T DC magnetic field, as estimated from the AC susceptibility data on the basis of the model of thin rectangular strip ($k = 0.78$).

$I_c$ estimation. Figure 3 shows a dependence of the critical current values estimated in this way on the temperature $T$ for the measurements taken in 14 T DC magnetic field. The constant $k = 0.78$ of the model of thin rectangular strip has been utilized here.

The AC losses per meter of the wire and per 1 Amp of critical current, calculated simply as $Q/I_c$, are plotted on the figure 4. The direct influence of the critical current on the losses is eliminated in this graph and in the region of the highest amplitudes all the curves fall approximately on the same line. It can be also seen that the difference between the losses at the low (3 K, 20 K) and elevated (40 K, 50 K, 70 K) temperatures is here much more pronounced and covers 2-3 orders of magnitude. At 20 K, there is practically no difference between the losses in 12 T and 14 T DC field and the losses in 8 T are just slightly smaller. On the other hand, the shift of temperature to 3 K or 40 K leads to a considerable decrease or increase of the loss in 14 T DC field, respectively.
Figure 4. AC losses per meter of the coated conductor and 1 Ampère of its critical current in dependence on the AC magnetic field amplitude $B_a$ measured at different temperatures and superimposed DC magnetic fields.

4. Conclusion
We investigated the AC losses of the YBCO coated conductor in high magnetic field applied perpendicular to its wide face. We studied the hysteretic losses of the American Superconductors 344 wire at low temperatures (50, 40, 20 and 3 K) in high DC magnetic fields (8, 12 and 14 T).

From the obtained results it can be concluded that in high magnetic fields (∼10 T and more) the working temperature is crucial for the loss performance of the wire and the magnetic field has only small impact. No effect of the ferromagnetic substrate tape was observed in the AC losses. We suppose the ferromagnetic layer is fully saturated in the high magnetic fields utilized in the experiments.

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