A method to obtain the critical current in tapes by AC losses analysis

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Abstract

In AC regime, the peak current, $I_p$, in a superconducting tape can surpass the critical current, $I_c$, so that the circuit is superconducting only part of the time and normal the rest. Up to the limit $I_p = I_c$, the losses in the tape are the typical AC superconducting losses. But for $I_p > I_c$ part of the losses are from the Joule heat in the normal tape resistance. Analysis of the plot of loss per cycle against peak current gives $I_c$ as the point of change of the trend.

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INTRODUCTION

In order to obtain a simple, practical method to estimate the AC losses in superconducting coils in the design of electrical superconducting systems, the different components of such losses have been studied [1, 2] as a function of external parameters (e.g., current, \( I \), magnetic field, \( B \), or frequency, \( f \)), and several mathematic models have been proposed. This can be used in the reverse sense in that variation of the relative weights of the loss components under different conditions can permit one to estimate when these conditions change.

The critical current is one of the parameters which can be estimated most easily from such a study of the losses [3, 4, 5]. A procedure to do this with superconducting tape coils is presented in this work. The advantage of the method is to get directly and easily the critical current of the tape with an actual working shape, position, and external parameters. This practical critical current, \( I_c \), which is of great interest in electrical design, may be different from the rated critical current given by the manufacturers.

First we present the experimental \( I-V \) relations of the coil for different peak currents, \( I_p \), varying from 0 to a value, \( I_{max} \), sufficiently larger than \( I_c \) to distinguish the normal and superconducting states.

Second we measure the losses, \( Q_c \), in the different current cycles by means of the lock-in amplifier method [1, 2]

Third we plot the curve \( Q_c-I_p \) and study it in two parts: one up to a certain \( I_p \) clearly smaller than \( I_c \), the other from a certain \( I_p \) clearly larger.

Finally we make separate fits for the two parts to a three-parameter function and look for \( I_c \) where these two fits meet.

EXPERIMENTAL

The measurements were made at a frequency, \( f \), of 50 Hz. Two coils were tested, made with different tapes. The characteristics of the coils under test (CUT) are summarized in Table 1.

<table>
<thead>
<tr>
<th>Characteristics of the coils</th>
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<tbody>
<tr>
<td><strong>CUT-1</strong></td>
</tr>
<tr>
<td>Tape reference</td>
</tr>
<tr>
<td>Width (mm)/ Thickness (µm)</td>
</tr>
<tr>
<td>Superconductor</td>
</tr>
<tr>
<td>Matrix/Dielectric coating</td>
</tr>
<tr>
<td>Rated ( I_c ) (A)</td>
</tr>
<tr>
<td>Nº of turns</td>
</tr>
<tr>
<td>Diameter (cm)/leng (cm)</td>
</tr>
</tbody>
</table>

The coils were fed from a variable autotransformer as shown in Fig. 1. An analogical data acquisition board (DAB) is used to measure the coil voltage and current. The latter is measured indirectly through a calibrated resistance, \( R_i \), in series with the coil. The DAB sampling rate is programmed to be much faster than \( f \) so that the waveform will be well defined. The process is managed by an application developed under LabVIEW software. The application displays both the current and voltage waveforms and the \( I-V \) curve, and extracts the peak and RMS values from the waveforms and the power of the losses, \( P_{loss} \), calculated as the mean of the product \( IV \) over one period. The losses over one period are calculated as:

\[
Q_{loss} = \frac{P_{loss}}{f} \quad (1)
\]
All these values are presented on numerical displays.

Fig. 1. Schematic of the feeding and measuring circuit.

To carry out the measurements, the current in the coil is increased from 0 in steps of approximately 2 A and a DAB sampling procedure is done at each step. Figures 2 and 3 show the $V$-$I$ graphs in the user interface output after sampling — Fig. 2 with a low current ($I_p < I_c$) and Fig. 3 with a large current ($I_p > I_c$). One can clearly see the difference between the cycles due to the voltage increase when the current is larger than $I_c$.

Fig. 2. $V$-$I$ graph in user interface output when $I_p < I_c$.

Fig. 3. $V$-$I$ graph in user interface output when $I_p > I_c$.

**DATA PROCESSING**

After the tests, the losses, $Q_{loss}$, are represented versus $I_p$ (Fig. 4). As losses when $I_p > I_c$ have an extra significant component (the Joule heat due to transport through the silver matrix of the tape, $Q_m$), the fit of these points (we shall call it the *high segment*) have to be different from the fit when $I_p < I_c$ (*low segment*).

Observation of the $I$-$V$ graphs permits one to select some points clearly belonging to the low segment (points with $I$-$V$ graphs like that of Fig. 2) and some others clearly belonging to the high segment (points with $I$-$V$ graphs like that of Fig. 3). The intermediate points are rejected by the fitting process.

The best fit using simple functions for the segments was found using a programmed spreadsheet. Several functions were tried at the beginning of the study, however, the functions finally selected as the most suitable for this practical study were the potential function
\[ P_p = \frac{1}{AI_p^B + K} \]  

and the exponential function

\[ P_p = Ae^{B/I_p} + K, \]

where \( K \) is selected to get the best fit, and \( A \) and \( B \) are the constants returned by the fitting application.

![Graph](image1.png)

Fig. 4. \( I_p-Q_{loss} \) graph from CUT-1 test. A similar graph is obtained from CUT-2 test.

For each coil, the pair of best fits for the low and high segments are selected for the study of \( I_c \). In all the cases, the coefficient \( R^2 \) of the goodness of the fit was greater than 0.98.

While the potential function gave good fits for both segments (with separate parameters for each case), the exponential function only appeared to be useful for the low segment. This was to be expected in view of the shape of the cycle when \( I_p > I_c \) that recalls the work of Steinmetz on \( B-H \) ferromagnetic hysteresis [6]. Curiously therefore, fitting the high segment with a potential function for the design of superconducting electrical systems reflects that classical work of more than a century ago.

![Graph](image2.png)

Fig. 5. Potential function fit for the high segment and exponential function fit for the low segment

We compared the high-segment potential-function fit with the two low-segment fits, potential and exponential, extended over the entire current range. Figure 5 shows the CUT-1 low- and high-segment function fits to the measured losses. Each function is a
good fit to its corresponding segment ($R^2$ very close to unity), but quickly deviates from the rest of the points. The relative errors of the two fitting functions are plotted in Fig. 6. The relative errors of the low-segment function are very small up to a certain value of the peak current (the last point used to fit this segment was $I_p = 22.8$ A), but from here onwards the errors increase very fast. The case is similar for the high-segment function.

The heuristic that we propose to determine $I_c$ is simply to add together the two relative errors and find the position of the minimum. (In other words, the critical current is where the two fits are still both reasonably applicable.) This summed curve is also plotted in Fig. 6.

![Fig. 6. Relative errors and sum to determine the practical $I_c$.](image)

The results obtained for CUT-1 and CUT-2 practical $I_c$ are summarized in Table 2 using both potential-potential fit (pot-pot fit in the table) and exponential-potential fit (exp-pot fit in the table). The values obtained are lower than the rated critical current as expected due to the particular tape conditions in the coil.

<table>
<thead>
<tr>
<th></th>
<th>pot-pot fit</th>
<th>exp-pot fit</th>
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<tbody>
<tr>
<td>CUT-1</td>
<td>22.76</td>
<td>25.76</td>
</tr>
<tr>
<td>CUT-2</td>
<td>31.17</td>
<td>31.17</td>
</tr>
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</table>

**CONCLUSIONS**

It is easy to find good fits with simple, low-dimensional, functions to the AC losses of superconducting tapes when the peak current is either clearly less than or larger than the practical critical current under specific working conditions.

A three-parameter potential function, suggested by the analogy with the classical work of Steinmetz, was found to be entirely suitable, but a three-parameter exponential function can also be used to fit the losses for currents clearly less than the critical current.

We described a first proposal for a straightforward heuristic to determine the critical current. This is to find the peak current at which the two descriptions of the losses, one clearly above the critical regime and the other clearly below, are together the “least bad”, i.e., the sum of their relative errors is a minimum.
REFERENCES


