Influence of the Shape in the Losses of Solenoidal Air-core Transformers

Pilar Suárez, Alfredo Álvarez, Member, IEEE, Belén Pérez, Dolores Cáceres, Eduardo Cordero, and José-Maria. Ceballos

Abstract—The losses in an HTS tape depend strongly on the perpendicular magnetic field. In order to avoid this magnetic field component in an air core transformer, a toroidal geometry was proposed and studied in previous work. Due to the difficulties that one finds in constructing toroidal coils, the straight solenoidal geometry is now under study. In this case, the magnetic field close to the ends of the coil is not parallel to the axis and a perpendicular component appears. In the present work, the losses due to this component are studied as a function of the coil geometry—i.e., the ratio between length and diameter—and a practical formulation is found.

Index Terms—Magnetization losses, superconducting transformer, Bi-2223 coil.

I. INTRODUCTION

HIGH temperature superconducting transformers are lighter, smaller and have a higher efficiency than conventional transformers [1]. The windings of most superconducting transformer prototypes have been built with Bi-2223 tapes [1-4]. These prototypes have used very different geometries, but when the ferromagnetic material is taken out and one wants to maintain a high coupling factor it is necessary to look for a geometry to confine the magnetic field. In a previous paper [5], we studied a superconducting toroidal transformer and described a method to measure AC losses.

Due to the difficulties that one finds in constructing toroidal coils, the straight solenoidal geometry is now under study. In this case, the magnetic field close to the ends of the coil is not parallel to the axis and a perpendicular component appears. But when a transformer is constructed from these coils, there are also losses due to the parallel magnetic field. The present work analyzes the losses due to these components, taking the influence of the coil geometry into account.

II. DESIGN OF THE SOLENOIDAL TRANSFORMER

A prior step to constructing the solenoidal transformer is to show the behaviour of a coil alone. The minimum coil radius before it loses its superconducting characteristics had been evaluated previously [6], and based on that work several coils were constructed by winding with Bi-2223 tape. The specifications of the HTS tape are presented in Table I. In order to reinforce the coil structures, the Bi-2223 coils were wound onto glass-fibre solenoids [7], [8] and several prototypes of transformers were formed by placing these coils concentrically. The characteristics of the two sets of coils constructed are given in Table II, where N is the number of turns of each coil, R the respective radius, and L the respective length. Figure 1 shows one of the prototypes ready to be tested.

### TABLE I

<table>
<thead>
<tr>
<th>Specifications of the HTS Tape</th>
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<tbody>
<tr>
<td><strong>Tape</strong></td>
</tr>
<tr>
<td>superconductor</td>
</tr>
<tr>
<td>type</td>
</tr>
<tr>
<td>manufacturer</td>
</tr>
<tr>
<td>width</td>
</tr>
<tr>
<td>thickness</td>
</tr>
<tr>
<td>critical current, I_c</td>
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<tr>
<td>matrix</td>
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<td>coating</td>
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### TABLE II

<table>
<thead>
<tr>
<th>Characteristics of Solenoidal Coils</th>
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<tbody>
<tr>
<td><strong>Prototype 1</strong></td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Coil 1</td>
</tr>
<tr>
<td>Coil 2</td>
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<tr>
<td>Coil 3</td>
</tr>
<tr>
<td>Coil 4</td>
</tr>
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Manuscript received October 4, 2004. This research is funded in part by the Inter-ministerial Commission of Science and Technology of Spain and Government of Extremadura.

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III. MEASUREMENT OF THE LOSSES

A. Measurement of total losses

The transformer losses were measured by the electrical method. Figure 2 shows the circuit used. Since the only energy entering the system comes from the power supply, this method gives the total AC losses of the transformer as the mean value of the product of $v(t)$ and $i(t)$ during an integer number of periods. The readings of the voltages and currents were taken by means of a DAQ card. Voltages were read directly from the taps on the transformers, and currents were read by means of a Hall probe as is shown in figure 2. The data were processed by a routine written in LabVIEW, evaluating the losses by integrating the product of voltage and current. Figure 3 shows the total losses in each coil of prototype 2. Similar curves were obtained with prototype 1.

B. Measurement of transport losses

In order to measure the transport losses, the same setup was used. In this case pairs of consecutive coils were connected in series and supplied with current in opposite senses to annul the magnetic field and therefore the losses due to it. The measurements thus give us twice the transport losses in one of the coils. The results were similar in all the coils. Figure 4 shows the mean results.

IV. THEORETICAL HYPOTHESIS

When magnetization losses are measured in a sample of superconducting tape the contribution of the perpendicular magnetic field is much greater than that of the parallel field. But when losses are studied in solenoidal transformers, there are some differences. The total losses in the transformer depend on which coil is supplied (figure 3). This effect can be explained with the aid of figure 5, where the expected magnetic field is shown. An observation of the figure suggests the following hypothesis: When the inner coil (coil 1) is supplied, the main contributions to the losses are due to the transport current and the perpendicular magnetic field at the ends of all the coils:

$$P_1 = P_T + P_\perp$$  \hspace{1cm} (1)

where $P_1$ is the quantity of total losses, $P_T$ the transport current contribution and $P_\perp$ the perpendicular magnetic field contribution in all the coils.

But an additional contribution appears when another coil (intermediate or outer) is supplied.
This new contribution is due to the parallel magnetic field along the remaining of the coils inside the supplied one. I.e., when coil 3 is supplied the effects of the parallel magnetic field are twice those when coil 2 is supplied. Similarly, when coil 4 is supplied the effects of the parallel component are three times those when coil 2 is supplied. Assuming that the contribution to the losses of the perpendicular magnetic field is similar in all the cases, one has:

\[ P_i = P_1 + (i - 1) P_{\parallel} \], with \( i = 2, 3, 4 \)  

(2)

where \( P_{\parallel} \) is the contribution of the parallel magnetic field in one coil.

The contribution of the parallel magnetic field due to the supplied coil in the others, \( P_{\parallel} \), can be obtained from (2):

\[ P_{\parallel} = P_i - P_1 = (i - 1) P_{\parallel} \], with \( i = 2, 3, 4 \)  

(3)

The assumption that the contribution to the losses of the perpendicular magnetic field is similar in all the cases is based on a previous work [9]. In this, we studied the dependence of the magnetization losses in solenoidal coils on the coil geometry (coil radius, density of turns, coil length,…). Figures 6 and 7 show the main results of that work for a set of three solenoidal coils with different radii and numbers of turns.

Applying these results to the values in table II shows the magnetization losses to be similar.

\[ P_{\parallel} = 1.92 P_{\parallel}, \text{ with a regression coefficient } R^2 = 0.93 \]

\[ P_{\parallel} = 2.90 P_{\parallel}, \text{ with a regression coefficient } R^2 = 0.97 \]
VI. CONCLUSIONS

The losses in solenoidal superconducting transformers depend on which coil is supplied. The magnetization losses include a very important contribution from the parallel magnetic field, because this component affects much more of the length of the superconducting tape than the perpendicular component. Furthermore, the influence of geometric factors (coil radius and length) has also to be taken into account.

REFERENCES