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a.c. TRANSPORT CURRENT LOSSES IN TRANSVERSE AND LONGITUDINAL d.c. FIELDS

J.L. de Reuver, G.B.J. Mulder and L.J.M. van de Klundert

Twente University of Technology, Department of Applied Physics, P.O.B. 217, 7500 AE Enschede, The Netherlands

Résumé - Les caractéristiques de la dépendance sur les pertes en courant alternatif de l'histoire et de la direction du champ magnétique continu sont rapportées.

Abstract - Characteristics on a.c. transport current losses of the influence of direction and history of the d.c. field are reported.

Experiments in this field of research have been performed in an earlier period using an other measurement technique /1/. Results with the opposite experiment, consisting of a d.c. transport current and an a.c. magnetic field has been achieved by Ogasawara /2/. A next step in our research program will be the exposure of the wire to an a.c. current as well as an a.c. field. In advance, exclusive information on the critical current density dependence on the local magnetic field has to be obtained especially in the low field range. The used measurement technique has been described before /6/. The test length, in this case, is 60 mm.

THEORY

1. Transverse d.c. field.

During a.c. transport current operation without an applied a.c. field the selffield effect occurs in multifilamentary wires. This feature enables us to calculate the current distribution in the same way as in the case of single core wires.

The critical current density \( j_c \) can be obtained by an averaging procedure. The \( j_c \) dependence on \( B \) is usually described by the Kim model:

\[
j_c(B) = \frac{J_0}{(1 + |B|/B_0)}
\]  

(1)

Assuming the Critical State Model the magnetic and electric fields can be determined by the reduced Maxwell equations:

\[
\mathbf{\nabla} \times \mathbf{B} = \mu_0 j_c(B) \quad \text{and} \quad \mathbf{\nabla} \times \mathbf{E} = -\mathbf{B}.
\]

(2)

In general an application of a d.c. field will cause a decrease of \( j_c \). Especially in the high field range the influence of the magnetic field due to the transport current will be negligible. It is justified to fix \( j_c \) at the value that belongs to \( B_{dc} \). The loss per cycle may be written as:

\[
Q = \frac{\mu_0 I_0^3}{6\pi^2 R^2} \frac{B_{dc}}{j_c}
\]  

(3)

for low current amplitudes compared with the critical current. Substitution of \( j_c(B_{dc}) \) gives:

\[
Q = \frac{\mu_0 I_0^3}{6\pi^2 R^2} \frac{B_{dc} + B_0}{J_0 B_0}
\]  

(4)

A property of the twisted multifilamentary wire is that the current distribution remains radial symmetric. The current per filament will be determined by the spot were the filament gets saturated. At this spot the field has a maximum and therefore the critical current a minimum. As the filament is not saturated everywhere, magnetisation currents due to the magnetic d.c. field occur as well. Anticipating on the results and discussion here the importance of the history of the d.c. field is mentioned. When the field is swept from a high to a low level the field inside the
The magnetisation area of the filament is higher than the external field. Sweeping in the other direction, the internal field is lower than the external field. To avoid this, the superconductor can be brought into the normal state by increasing its temperature above $T_c$ using a heater. Doing this at a certain d.c. field level, flux gradients disappear. After a return into the superconductive state no magnetisation currents appear, due to the fact that Type II superconductors do not show reversibility.

The introduction of highly conductive matrix material generally increases the losses with increasing frequency. This loss contribution will be additive for practical cases.

2. Longitudinal d.c. field.
The influence on the a.c. transport current losses, applying this fieldtype, has been investigated before /3/. The theoretical background is based on the issue of the longitudinal field effect /4/. In terms of the critical current density, a dependence on the longitudinal field is an appropriate empirical approach /5/ to describe the loss behaviour. In the framework of the Critical State Model a justification can be obtained by comparing the results of the V-I characteristic method and the magnetisation method. The loss measurement belongs to the latter category.

### Table 1 - Test wires.

<table>
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<th>No</th>
<th>manufacturer</th>
<th>$\phi$ wire [mm]</th>
<th>$n_{fill}$</th>
<th>$\phi_{fill}$ [mm]</th>
<th>Cu:SC. material</th>
<th>twist pitch [mm]</th>
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</thead>
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<td>NbTi/CuNi</td>
<td>12</td>
</tr>
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<td>574</td>
<td>8.6</td>
<td>NbTi/CuNi</td>
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<td>MCA</td>
<td>.12</td>
<td>1</td>
<td>80</td>
<td>NbTi/CuNi</td>
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</tr>
<tr>
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<td>.20</td>
<td>10285</td>
<td>1.0</td>
<td>NbTi/Cu/CuNi*</td>
<td>1.1</td>
</tr>
</tbody>
</table>

* CuNi barriers of .18 $\mu$m

RESULTS AND DISCUSSION

1. Transverse d.c. field.
In Fig. 1 the a.c. transport current loss voltages against the applied d.c. field are given. From these plots, the parameters of the Kim model have been deduced as described before ($J_0 = 1.43 \times 10^{10}$ A/m² and $B_0 = 0.44$ T). These figures can be used in numerical calculations. A reconstruction of the loss curves with a accuracy of 5% can be achieved for the high field range. This reconstruction is based on the assumption that a vector summation of the external field and the field due to the current determines the actual local field and the fact that the current distribution is determined by the spot where the field magnitude reaches its highest magnitude. The summation, however, does not fit for the low field behaviour. To investigate the magnetisation influence, experiments with a d.c. field sweep through zero have been performed (see Fig. 2). Going from a high field amplitude to a low one we pass...
two minima. A rough indication of the magnetic field inside the filaments is that it is higher than the external field. Therefore the lowest fields inside the filaments occur at a field value after having passed zero. Calculations, using this model, indeed show a minimum after having passed zero. The first minimum has a lower value. This depends strongly on the assumptions made on the internal field dependence on the external field. To avoid magnetisation effects the wire was quenched at a stationary d.c. field, recovered and supplied with the a.c. transport current. The obtained results show two minima with symmetry according to the zero field axis. Similar experiments on a single core wire have been performed. See Fig. 3. The loss behaviour due to the d.c. field now does not only depend strongly on the sweep direction of the field but also on the point of return. Obviously the high magnitude of the magnetisation currents, possibly of the same order of magnitude as the transport currents, determines the behaviour rigorously.

An interesting, and perhaps an important, feature is the location of the minima. In the case of the single core wire this location depends on the current amplitude as has been seen before using slabs and a.c. fields superposed on a d.c. field \( /7/ \). In the case of multifilament wires, however, the location seems independent of the applied current amplitude. Testing another wire with thicker filaments the value of the field where the minimum occurs shifts to higher fields.

A typical feature of this measurement technique is that an unstable behaviour with respect to the external field and the possibility that the transport current remains existing can be observed accidentally. Experiments at high current levels show that the loss voltage spontaneously drops to the value, that can be obtained by quenching the wire and inserting the current afterwards as described before \( /8/ \). The wire tested for its current carrying properties has been investigated before for its a.c. field behaviour by Ogasawara \( /9/ \). The results on the transport current losses are shown in Fig. 4. No minimum occurs.

2. Longitudinal d.c. field.

In Fig. 5 the loss voltages against field magnitude are given for a single core wire. The losses decrease considerably with increasing field. Obviously the longitudinal field effect occurs. A related observation \( /10/ \) is that the equilibrium state is obtained after some cycles, in our cases three. After quenching the wire it takes again three cycles of the external field to reach a final level.

The behaviour of the multifilamentary wires is nearly identical to that of single core wire (Fig. 6). Until now no significant determination on the influence of filamentsize and twistpitch can be made.

In Fig. 7 the loss voltage against field of a wire with highly conductive matrix material is shown. A dependence of the sweep direction and of the sweep velocity has been observed. This effect depends on the shielding currents in the outer filaments which are coupled by the matrix \( /11/ \). These shielding currents decay in approximately 60 sec. The behaviour of the losses differs strongly from the observation made of the
other wires. After a decrease, a minimum occurs followed by a steady increase. This wire, however, has an extremely small twist pitch. Therefore the filaments have an angle with the field of $\alpha = 30^\circ$. Force free current effects are not likely now.

CONCLUSION

By measuring a.c. transport current loss voltages a better understanding of current distributions can be obtained in the cases that external fields are applied. The critical current density dependence on the magnetic induction can be determined in this way. The occurrence of a minimum in the losses at a certain level of the transverse d.c. field can be investigated in a proper way so that more comprehensive suggestions on the actual behaviour can be given. A continuous decrease up to 2T of the losses in a longitudinal d.c. field in the case of most wires give support to the idea that the critical current increases with increasing longitudinal field.

REFERENCES