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SCALING LAW FOR FILAMENTARY SUPERCONDUCTOR HYSTERESIS LOSSES IN SUPERIMPOSED dc AND ac MAGNETIC FIELDS

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Abstract - Hysteretic losses of multifilament superconductors have been considered in transverse, superimposed ac and dc magnetic fields. These losses scale following a law in which the ratio of the ac field to the penetration field is the only important parameter. The advantages and the limits of such a scaling law are discussed.

INTRODUCTION

In some technical applications like in tokamak magnets for nuclear fusion, high field multifilament superconductors are exposed to a magnetic dc field superimposed by an ac field component. Both may vary locally over the magnet volume, and form also different angles between them and also with the superconductor axis. In the past /1,2/ we have therefore investigated the less complicated case where the hysteresis losses in the superconducting filaments depend on the dc field component $B_S$ and the ac field amplitude $B_0$ when both are applied in parallel to each other and perpendicular to the superconductor axis. One of the main results was that $q_h$, the hysteresis loss per superconducting filament volume unit, has, as a function of the dc-field, for fixed ac field amplitude $B_0$ a maximum value $q_h = 4/3 \mu_0^{-1} B_0^2$. It is independent on the superconducting properties and the radius $r$ of the filaments.

In this paper we want to show that our experimental hysteresis loss data for a variety of dc and ac magnetic field values can be described by a scaling law which can also be derived under certain limitations from known hysteresis loss equations.

THEORY

V. Zenkevich et al /3/ and A. Campbell et al /4/ have derived the following equations for the hysteresis losses of a highly irreversible Type II superconducting cylinder (filament) exposed to a perpendicular ac magnetic field with cycle $\Delta B = 2 B_0$ under the simplifying assumptions that the critical current density $J_c$ is constant during the cycle, and $|J_c|$ is also locally constant in the inner of the filament (linear flux density profiles).

The filament penetration field is:

$$B_p = \frac{2}{r^2} \cdot \mu_0 \cdot J_c \cdot r$$

(1)

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For $B_0 \gg B_p$ hysteresis loss/(cycle\*volume) is:

$$q_h = \frac{8}{3} \cdot \frac{B_0^2}{B_p} \cdot \mu_0^{-1} \cdot \left(\frac{B_0}{B_p} - \frac{1}{2}\right)$$  \hspace{1cm} (2)

For $B_0 \leq B_p$:

$$q_h = \frac{8}{3} \cdot \frac{B_0^3}{B_p^2} \cdot \mu_0^{-1} \cdot \left(1 - \frac{B_0}{2B_p}\right)$$  \hspace{1cm} (3)

Dividing eqs. (2) and (3) by $B_0^2$ we get instead of (2):

$$\frac{q_h}{B_0^2} = \frac{8}{3} \cdot \mu_0^{-1} \cdot \frac{1}{y} \cdot (1 - \frac{1}{2y})$$  \hspace{1cm} (4)

and instead of (3):

$$\frac{q_h}{B_0^2} = \frac{8}{3} \cdot \mu_0^{-1} \cdot y \cdot (1 - \frac{y}{2})$$  \hspace{1cm} (5)

with $y = \frac{B_0}{B_p}$.

So, according to (4) and (5), the reduced hysteresis losses $q_h/B_0^2$ are only a function of the reduced ac field amplitude $B_0/B_p$.

Fig. 1 - Theoretical dependence of the reduced hysteresis loss per volume $q_h/B_0^2$ on reduced ac magnetic field amplitude $B_0/B_p$. The factor $8/3 \mu_0^{-1}$ is omitted.

In Fig. 1 this reduced loss function, given by eqs. (4) and (5) is displayed omitting the constant factor $8/3 \mu_0^{-1}$. Similar results have been derived numerically by M.N. Wilson /5/.

Unfortunately the loss equations (2) and (3) and the derived scaling law equations (4) and (5) cannot generally be applied. For larger $B_0$-values, the assumption of a constant $j_c$ over the whole cycle is bad as it is also, for larger filament diameters, the assumption of linear flux density profiles in the filaments, especially in the low magnetic field range where $j_c$ is high. But in our case, where a dc magnetic field is superimposed only by a small ac field, and the filament diameter is of moderate thickness, we can try to apply this scaling law to the hysteresis losses.
The magnetic field cycle is symmetrical to dc field $B_S$, and we use $j_c(B_S)$ as approximate mean value over the cycle. So

$$B_p = \frac{(2/\pi) \cdot \mu_0 \cdot j_c(B_S) \cdot r}{f(B_S)} \quad (6)$$

If we measure the hysteresis losses as a function of $B_S$ for a given $B_0$, then all the experimental loss curves with the different $B_0$ values as parameters should fall together if we display the reduced losses $q_h/B_0^2$ as a function of reduced ac amplitude $B_0/B_p(B_S)$.

$B_p(B_S)$ can be determined from (6) using experimental $j_c(B_S)$ values or, better, directly from the transition width of the experimental magnetization curves at the field $B_S$.

**EXPERIMENTS**

In Fig. 2 we show from paper /1/ our experimental hysteresis loss curves for a NbTi multifilament wire, with 78 filaments ($\Phi = 31 \mu m$) in a Cu matrix, as a function of dc field $B_S$ with ac field amplitude $B_0$ as parameters. The losses were determined by combined magnetization and calorimetric measurements. There was no transport current. Other experimental details can be found in paper /1/. Using the experimental $B_p$ curve measured /1/ as a function of $B_S$, we display in Fig. 3 the loss data from Fig. 2 in the reduced way $q_h/B_0^2$ as a function of reduced amplitude $B_0/B_p(B_S)$. The losses measured over the large range of $B_S$ follow as expected a scaling law, and all curves of Fig. 2 fall together.

The solid curve represents the eqs. (4) and (5) without any fitting to the experimental data. The experimental scaling curve is slightly shifted to smaller $B_0/B_p$ values having the maximum near $B_0/B_p = 0.9$, while the theoretical maximum occurs at $B_0/B_p = 1$. The reason for this shift is still unknown to us. In Fig. 4 are displayed our earlier /2/ hysteresis loss measurements of another multifilament

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*Fig. 2 - Hysteresis losses of a multifilament wire with 78 NbTi filaments ($\Phi = 31 \mu m$) measured as a function of the dc field $B_S$ and the superimposed ac field amplitude $B_0 = \Delta B/2$.**
wire with 61 NbTi filaments ($\phi = 34 \mu m$) and in Fig. 5 we have tried again to scale these data using the experimental $B_p = f(B_S)$ curve of this conductor. Also here the reduced hysteresis losses follow a scaling law. The solid line is again the unfitted theoretical curve.

![Graph showing scaling of loss data](image)

**Fig. 3** - Scaling of the loss data from Fig. 2 divided by $B_0^2$ with reduced amplitude $B_0/B_p$. The solid curve is the unfitted, theoretical loss expression given by eqs. (4) and (5).

Hysteresis losses in superimposed dc and ac magnetic fields have also been measured by us on a single core NbTi superconductor with core diameter $\phi = 200 \mu m$. $B_S$ ranged from 0 up to 2.5 Tesla and $B_0$ from 0.18 up to 0.6 Tesla. Using the also measured $B_p = f(B_S)$ curve we could not find satisfactory scaling, while the maximum values of $q_h/B_0^2$ were identical with the theoretical ones. This result must be expected from the inherent limitations of the loss-and scaling law eqs. (2) - (5). For such a large filament diameter, and in this low dc field range with correspondingly high $j_c$-values, the assumption of linear flux density profiles is too far away from reality, as it is also the use of a mean constant $j_c$ during the cycle.

**CONCLUSIONS**

When a multifilament superconductor with thin filaments is exposed to a dc magnetic field superimposed by an alternating field component with small amplitude (both perpendicular to the conductor axis), then the experimental hysteresis loss values obey a scaling law, which is also predicted by theory. This allows one to get the losses for a variety of dc and superimposed ac field values. For this purpose it is preferable to use the experimental scaling curve which can be obtained from a few measurements. It contains already the influence of the demagnetization factor, and the contribution to the magnetic field by neighbouring filaments and wires. On the other side, the theoretical curve for the scaled losses is rather close to the experimental one.

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**Fig. 4** - Experimental hysteresis loss data of another superconductor with 61 NbTi filaments ($\phi = 34 \mu$) in superimposed dc and ac fields.

**Fig. 5** - Scaling of the reduced losses from fig. 4 with the reduced amplitude. The solid line is again the unfitted theoretical expression.

**REFERENCES**


