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Possible method to improve the stability of twisted superconductors

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ABSTRACT

The resistivity of the normal region between neighboring and opposite superconducting stripes/strands/filaments in twisted structures should be large enough to obtain the coupling losses at acceptable level. The stability of such structures can be then very low, as the individual superconductors are more or less electrically insulated. In such structures, any electromagnetic perturbations or spatial inhomogeneities can be detrimental for the conductor and eventually for the whole design. Concentrating mainly on helically wound striated coated conductors, we show that placing some normal sheets on the superconductor tapes without increasing the coupling losses considerably can enhance the electromagnetic coupling. The results may be extended also to similar superconducting structures with not very high coupling losses, but requiring better stability, because current sharing between superconducting parts is necessary for electromagnetic stability of longer conductors.

1. Introduction

In many electromagnetic devices, using superconductors instead of copper is assumed to be advantageous [1,2]. Their application may result in reduced weight and size of the designs. The high critical currents of recently fabricated YBCO coated conductor (CC) tapes [3–5] created repeatedly new hopes for the possibility of replacing normal devices with superconductors in practical applications. To achieve this task, further decrease of AC losses is necessary, as the cooling efficiency at low temperatures is still a limiting factor. That is true not only at helium, but also at nitrogen temperatures, when using high T_c superconductors is possible. The hysteresis losses [6] could be strongly decreased for classical low T_c superconductors by decreasing the filament diameter, even to sub-micron level [7–11]. The analogous procedures lead only to partial success for high T_c superconductors, although considerable progress was reached for BiSrCaCuO (BSCCO) wires and mainly for YBaCuO (YBCO) coated conductors (CC) by striating the tapes [12,13]. As learned from the low temperature superconductors [14–16], twisting the samples is necessary for decreasing the coupling losses (CLs). This procedure is again connected with many complications for the high T_c superconductors. The Roebel technique [17–19] and recently the concept of “cable on round core” (CORC) with helically wound striated layers around a cylindrical former [20–23] were discussed as an effective way for decreasing the CLs. Another property, limiting the practical application of superconductors, is their stability against any perturbation, caused by local changing of the parameters (critical current, critical temperature, spatial inhomogeneities in geometrical parameters, local stress, conductor movement) or some electromagnetic perturbation. Current sharing between the superconductors should be enabled to avoid the local transition of the superconductor and eventually of the whole design into normal state. If needed, the excess current can then be taken “away” from the “critical” region by neighboring superconductors. This is the necessary condition to get long samples with high enough critical currents. However, facilitating the current transfer to neighboring filaments or strands can be a real problem for structures with high electric resistance between the superconductors, like the CORC and Roebel structures, as well as some BSCCO wires and even for very fine filamentary NbTi superconductors with CuNi or CuMnNi insulating layers on them [24]. The balance between the requirement of low total AC loss and stability is not always easy to find [24,25].

Coating the striated CC tapes resulted in increase of the CLs, therefore the necessity of twisting was declared for enduring the CLs at an acceptable level [26–32]. Although these are smaller than for the non-striated samples, the additional losses are by far not negligible [31]. The partial coating with periodically placed normal metal (NM) [33,34] could be a solution also for the untwisted tapes, where the required full periodicity of the plates can be achieved by short-cutting the tapes at the ends of the design or adopting the method of “internal twist” [35–37].

As we show in this paper, this procedure can generally be a promising solution of the stability problem also for twisted structure with nearly insulated filaments, stripes, layers or strands. The CORC con-

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figuration [20,22] is an example where the NM plates [32,33] can very effectively enable the necessary current sharing. The results may be easily adapted to classical low temperature, as well as other high T_c cables (BSCCO samples with nearly insulated filaments [38–40], Roebel samples [17–19,41]). In all these conductors, the current sharing between the filaments or strands is eminently important for the stability of longer superconducting cables or wires.

2. Losses due to currents between the stripes

At first, we calculate the coupling losses in the "twisted" striated tapes, like the CORC tapes [23]. In the following, W means always losses per cycle. The principles of the stripe configuration with "twist length" $2L$ and cable width b are sketched in Fig. 1. The applied AC magnetic field of amplitude B_m and circular frequency $\omega = 2\pi f$ is applied in the direction *perpendicular* to the wide side of the striated tape just at the position $x = L/2$. The spatial field change is approximately sinusoidal (like for simple twisting) or quadratic (probably closer to the Roebel structure).

As the flux change induces currents of opposite sign on the left and right side from the point $x = L/2$, the induced voltage U is evidently zero there. For other positions $x = x_0$, one has

$$U = \dot{B}F_0 \equiv F_0 \partial B/\partial t, \tag{1}$$

where F_0 is the area between two opposite stripes with the distance y_0 from the tape center. Then

$$U(x_0) = 2\dot{B}\int_{x_0}^{L/2} y dx, \tag{2}$$

with

$$y = \left\{ \begin{array}{c} y_0 \sin\frac{\pi x_0}{L} \\ 4y_0 \frac{x_0}{L}\left(1-\frac{x_0}{L}\right) \end{array} \right\} \tag{3}$$

for the sinusoidal and quadratic change of the applied magnetic field, respectively. Here, y is the line described by the individual stripes with maximum distance y_0 from the central line (actually, the axis of the cable) and $0 \leqslant x_0 \leqslant L$.

Introducing the relative coordinate $\xi = x_0/L$, the electric field $E = U/2y_0$ is then changing with the position as

$$E = \left\{ \begin{array}{c} \frac{\dot{B}L}{\pi}\cos(\pi\xi) \\ \frac{\dot{B}L}{3}(1-6\xi^2+4\xi^3) \end{array} \right\}. \tag{4}$$

As it should be, this formula leads to $E = 0$ at $\xi = 1/2$ ($x_0 = L/2$). After integrating the loss density E^2/ρ, one obtains the CLs per length and cycle as (in units of VA s/m)

$$\frac{W}{fL} = H\int_{-b/2}^{b/2} dy_0 \int_0^L \frac{E^2}{f\rho}dx_0 = \frac{\dot{B}^2 bL^2 H}{Af\rho}, \tag{5}$$

where H is the thickness of the normal region where the currents are flowing. The factor A equals $2\pi^2$ and 18.5, respectively. It is not surprising that both values are not very different, as the sinusoidal and quadratic areas differ not too much. In the following, we take $A = 20$ for simplicity.

3. Comparing with hysteresis losses in cables

As mentioned, the "original" CLs through the substrate in some striated samples in the form of cables can be made very low, if interconnections between the stripes are absent [23,27–29,42,43]. We calculate now, how large should be the resistivity between the stripes, to have lower coupling losses than the hysteresis losses.

The hysteresis losses per unit length and cycle for the striated samples above the penetration field [44] are given (as in (5), in units of VA s/m) by [42]

$$\frac{W_h}{fl} = Nw^2 J_c B_m \approx wI_c B_m, \tag{6}$$

where N is the number of stripes, w their width, and the sheath critical current is $J_c = I_c/Nw$. The overall critical current I_c can be in the best samples above 100 A [9–11]. Using the values for $I_c = 140$ A, $w = 0.8$ mm and $B_m = 0.1$ T, one obtains for the hysteresis losses per cycle and unit length $W_h/lf = 1.12 \times 10^{-2}$, which is in rough accordance with the measured value [23]. For the wound tape, one has to take however into account a reduction factor 1/2 due to the changing value of the perpendicular component of the magnetic field. For the sinusoidal form, this is just the result of integrating the function $\sin^2(\pi x_0/L)$ over the period length L, which leads to the factor 1/2. This factor can be clearly seen by comparing the original and wound cable [23].

Comparing (5) and (6), one obtains

$$\frac{W}{W_h} = \frac{8\pi^2 f B_m b L^2 H}{A\rho w I_c}. \tag{7}$$

With the parameters given above, and $f = 144$ Hz, $L = 25$ mm, $b = 4$ mm and $H = 2$ µm, one obtains $W/W_h = 2.5 \times 10^{-7}/\rho$ (ρ in Ω m). For having the coupling losses of the same order as the hysteresis losses, one should have the resistivity of the material between the stripes $\rho \approx 2.5 \times 10^{-7}$ Ω m. This means that for having the CLs about one order of magnitude smaller than the hysteresis losses, it would be sufficient to have the matrix resistivity between the stripes about three orders of magnitude larger than that of pure copper.

4. Inserting a normal plate on the stripes

Now, let us add a thin normal plate connecting the stripes in the cable [33,34]. Due to the contact with the stripes, additional

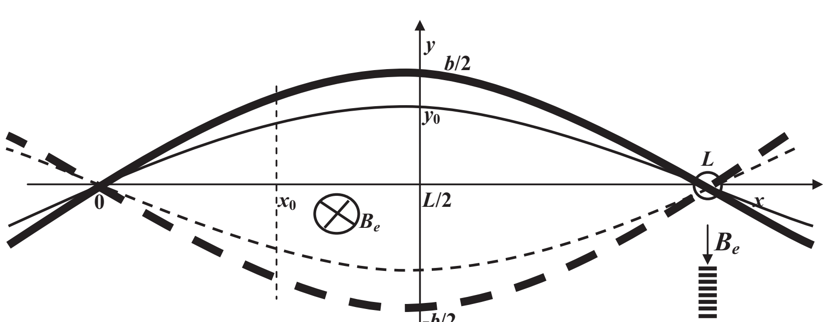

Fig. 1. The principles of the "wound" stripe configuration with "twist length" $2L$ cable width b. The applied AC magnetic field is assumed to be *perpendicular* to the wide side of the striated tape at $x = L/2$. The field change is assumed as sinusoidal like for simple twisting or quadratic (probably closer to the Roebel structure). The coordinate y describes the curve of the individual stripes with maximum distance y_0 from the center. At $x = L$, the magnetic field is parallel to the tape surface.