Understanding Magnetisation Losses of Roebel Cables with Striated REBCO Strands

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***Abstract*—High current superconducting cables are essential for past and future accelerator and fusion magnets. The low temperature superconducting (LTS) cables for the LHC and ITER machine owe their success to the effective minimisation of the magnetisation in the LTS wires by incorporating twisted fine filaments. In contrast, the magnetisation of REBCO tapes remains significant in assembled strands of Roebel cables and twisted stacks cables. The quantitative details the magnetisation loss have not been sufficiently elaborated due the 3D nature of the strand assembling and/or twisting. Although full 3D modelling of Roebel cables has been made, the separation of loss components is less straightforward due to the complexity of their interplay. By using simplified 1D models based on conceptual reasoning, it was shown in our previous studies that (a) Roebel cables with $(2m+1)$ REBCO strands of critical current I_c are essentially two side-by-side stacks of m transposed strands and each stack is effectively a single Norris' strip of $\sim m \times I_c$ but also magnetically coupled to the other via the strong demagnetisation effect in the narrow gap in between, and (b) full decoupling into isolate tapes is only achieved in the single strand in transposition "flights" from one stack to another. Consequently, the magnetisation of Norris' strip can be extended straightforwardly for loss calculations in simple algebra forms to achieve satisfactory agreement with experimental results. On the other hand, the ac losses measured on Roebel cables with *striated* REBCO exhibited significant differences which are yet to be fully understood. Using qualitative arguments together with *1D* analytical results as well as numerical modelling, this work show the "filaments" in a striated strand are also magnetically coupled hence behave considerably differently from a set of isolated filaments of Norris' strips. It then explains that small random misalignments among the striated strands when assembled into a Roebel cable would alter significantly magnetic coupling within the stacks and result in the ac loss behaviour observed in experiments.**

***Index Terms*—REBCO 2G conductor, striation, Roebel cable, ac losses, modelling**

I. Introduction

HIGH current cables are essential for some superconducting devices such as accelerator and fusion magnets, superconducting magnetic storage coils and superconducting fault current limiters. Such cables are required to consist of several transposed superconducting strands to ensure uniform current distribution for the field quality and cryogenic stability. While the sustained research and development of 2G REBCO superconducting tapes have led to impressive critical current performances in high magnetic fields, the flat geometry of these tape conductors poses significant challenges to the assembling of fully transposed cables. One of the few possibilities is that of a Roebel bar [6], [7], [3], [2] which was originally invented more than a hundred years ago for reducing the eddy current losses in high current cables/busbars for conventional machines .

With the growing availability of 2G REBCO tapes in long length, several laboratories [7], [3] have been producing prototype Roebel cables with punched or laser-cut strands for the important studies on the critical current performance and manufacturing optimization. In addition, there have also been studies [5], [11], [4], [14] on the magnetization and ac losses, which inform on both the effectiveness of the Roebel transposition in homogenizing the current distribution and the complex magnetic interactions among the strands.

The hysteresis loss in superconductors is most effectively reduced by subdivision into fine filaments. In addition these filaments must be twisted at a sufficiently short pitch in order to ensure that they are magnetically uncoupled under desired ac conditions. Although striated parallel filaments can be made successfully by laser scribing to reduce ac losses in short samples [1], it is topologically challenging to twist them for uncoupling over long length. The strand transposition provides a longitudinally alternating magnetic disposition, which might be an effective block [11]against the long length coupling of the striated filaments. Although promising loss reduction in Roebel cables with striated strands has been reported [10], [15], the observed loss characteristics are quite unexpected and understood. The present work examines in detail the magnetic coupling among the filaments in and the stacks of striated strands offers insights for deeper understanding of the magnetisation of striated strands both isolated and in Roebel cables.

II. Methods

A. Experimental data

The experimental data of ac losses in Roebel cables shown in the present work were presented in previous publications[14], [15] where the details of the conductor strands, striation, and Roebel cable characteristics can be found. The data shown within this work are from measurement at 5 Hz hence dominated by magnetisation losses with negligible contributions from coupling currents. The data exhibits a consistent scaling of the magnetisation loss with the strands' critical current $I_c(T)$ over a wide range of temperatures between 5 K and 85 K and hence pointed a temperature independence of the underlying loss mechanism.

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B. Understanding Roebel cable magnetisation and ac losses in terms of magnetic coupling

a) The transposition of Roebel strand: A full strand-decoupling in Roebel cables is only realised during the transposition "flight" of a strand from one stack of tapes on one side to the other stack while the transposition alternates periodically among the $(2m+1)$ strands along the length. A decoupled strand in transposition acts as an isolated Norris' strip with the corresponding ac loss Q_S and loss factor factor Γ_S as a function of the reduced field $\beta_S = H_a/H_{PS}$:

$$\Gamma_S(\beta_S) = \frac{Q_S}{2\mu_0 H_a^2 S_S} = \frac{Q_S}{2\mu_0 H_a^2(2at)} = \frac{2a\pi}{5t\beta_S}\left(\frac{4}{5\beta_S}\ln\left(\cosh\left(\frac{5\beta_S}{2}\right)\right) - \tanh\left(\frac{5\beta_S}{2}\right)\right)$$

which peaks at $\beta_S = 1$ with the applied field H_a at the peak field $H_{PS} = 5\sigma_c/2\pi$. The subscript "S" denotes a single strand of width $2a$ and thickness t for a cross-section $S_S = 2at$. For a strand critical current I_c, $\sigma_c = I_c/2a$ is the linear critical current density per unit width.

b) Magnetic coupling between two side-by-side Norris' strips: As shown previously[13], the magnetic coupling between two isolated superconducting strips can be calculated efficiently using 1D $J-A$ (current density - magnet vector potential) or $T-H$ (electric vector potential - magnetic field) formulations to yield a *coupling factor* $\alpha(d/a)$ which depends the gap d between two in-line strips relative to the tape half-width a. Note $\alpha = 2$ corresponds to full magnetic coupling with a vanishing gap while $\alpha = 1$ for fully uncoupled when far apart. It was found that $\alpha(0.3) \sim \sqrt{2}$ which is in agreement[14], [13] with the experimental results for typical Roebel cables with a strand width $2a = 5$mm and a gap $d \sim [0.5-1.0]$mm $\sim 0.3a$. The combined loss factor of two magnetically coupled Norris' strips is $\Gamma_{2\times S} = \alpha(a/d)\Gamma_S(\beta_S)$.

c) Losses of two side-by-side stacks of m tapes in a Roebel cable with $(2m+1)$ strands: Apart from the strand in transposition, the $2m$ strands are divided into two side-by-side stacks of m tapes. As the tapes are very thin so that $mt \ll a$, e.g. for a strand thickness $t \lesssim 0.1$mm $< 0.05a$, the m strands *within* a stack behave collectively as a single Norris' strip but with a reduced stack critical current $I_{c,m} = \gamma m I_c$ where the factor $\gamma(t/a, m) < 1$, e.g. $\gamma \sim 0.65$ for $t = 0.1$mm, $a = 2$mm and $m = 7$ of a 15-strand Roebel cable[14]. For practical loss calculations, as long as the stacks still behave as a single Norris' strip, their magnetisation loss can be readily obtained as a function of applied field $\mu_0 H_a$ with a closed form expression of a Norris' strip of $I_{c,m} = \gamma m I_c$, i.e. the losses of an *isolated* stack is given by $Q_{mS} = \Gamma_S(\beta_S/\gamma m)2\mu_0 H_a^2 S_S$.

d) Roebel cable as magnetically coupled two side-by-side stacks of m strands plus an isolated strand in transposition: Combining the loss $Q_{2\times mS} = 2\alpha Q_{mS}$ of the two magnetically coupled side-by-side stacks with the loss Q_S of the alternating single transposition strand leads to the total loss of the $(2m+1)$-strand Roebel cable

$$\begin{aligned} Q_{2m+1} &= Q_S + \alpha Q_{2\times mS} \\ &= 2\mu_0 H_a^2 S_S\left(\Gamma_S(\beta_S) + 2\alpha\Gamma_S(\beta_S/\gamma m)\right) \\ &= \frac{2\mu_0 H_a^2 S_{2m+1}}{2m+1}\left(\Gamma_S(\beta_S) + 2\alpha\Gamma_S(\beta_S/\gamma m)\right) \end{aligned}$$

and the corresponding loss factor

$$\Gamma_{2m+1}(\beta_S) = \frac{\Gamma_S(\beta_S)}{2m+1} + \alpha\frac{\Gamma_S(\beta_S/\gamma m)}{m+1/2} \tag{1}$$

Figure 1. shows the loss factor $\Gamma_{2m+1}(\beta_S)$ of a 15-strand $(m=7)$ Roebel cable measured as a function of reduced field $\beta_S = H_a/H_{PS}(T)$ at different temperatures T between 5 K and 85 K. The thick red line is given by (1) and the dotted and dashed lines corresponds to the first and second terms of (1) respectively. While the agreement between (1) and the data is quite satisfactory, it's equally important to note that the only parameters are the two coupling factors γ and α which are expected not to vary significantly for Roebel cables with a modest number of strands.

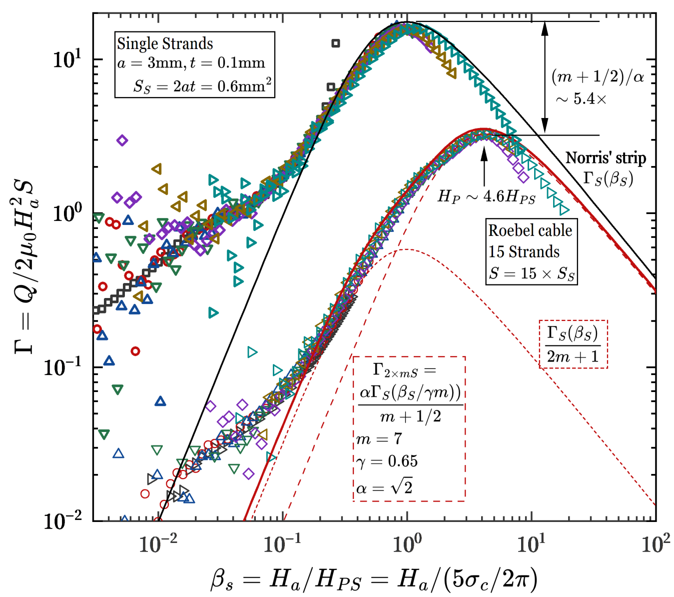

Fig. 1. Loss factor of a Roebel cable with 15 REBCO strands measured between 5 K and 85 K as a function of normalized field β_s with reference to the strand saturation field H_{Ps}. The dashed and dotted lines are calculated loss factor for the side-by-side stacks of 7 strands and the single strand in transposition. The thicker solid red line is the combined loss factor given by (1). The measured loss factor of a single strand is shown in thicker symbols for reference.

III. Magnetisation and AC Losses of Striated REBCO Strands

A. Loss reduction by uncoupling filaments

While there exists a considerable body of work on striated REBCO strands in the published literature (e.g. [12], [9] and reference therein), the main focus has been mostly on the time constant and losses of the coupling current among the filaments. The magnetisation of striated strands has been largely considered as a collection of fully uncoupled filaments of Norris' strips. For a striated tape of n_f filaments of width $2a_f$ without significant degradation in the linear critical current caused by striation, i.e. $\sigma_{c,f} = I_{c,f}/2a_f = \sigma_c$, the loss factor of an isolated filament is $\Gamma_f(\beta_f) = (a_f/a)^2\Gamma_S(\beta_S)$ with $\beta_f = \beta_S$ as $H_{Pf} = H_{PS} = 5\sigma_c/2\pi$. Correspondingly a collection of n_f such isolated filaments separated by a gap d has a loss factor $\Gamma_{nf} = n_f\Gamma_f = n_f(a_f/a)^2\Gamma_S(\beta_S) \sim n_f^{-1}\Gamma_S(\beta_S)$ with $n_f = a/(a_f+d)$, i.e., the loss factor of a striated strand is lower by a factor of n_f compared to the non-striated.

A closer examination of experimental results, as exampled in Fig. 2 for a 20 filaments tape, reveals that the loss factor peaks actually move to a lower field at $H_P \sim 0.46H_{PS}$ instead of remaining unchanged at H_{PS}. Compared to the corresponding non-striated tape (solid black line), the loss factor is reduced only by a factor of 6.6, which is about a 1/3 of the expected factor of $n_f = 20$ (solid red line), until the applied field is well beyond $H_{PS}$where the magnetic coupling among fully saturated filaments diminishes. It's worth noting that the loss factor peak is significantly broadened in the striated tape as shown more clearly in the inset in log-log scale.

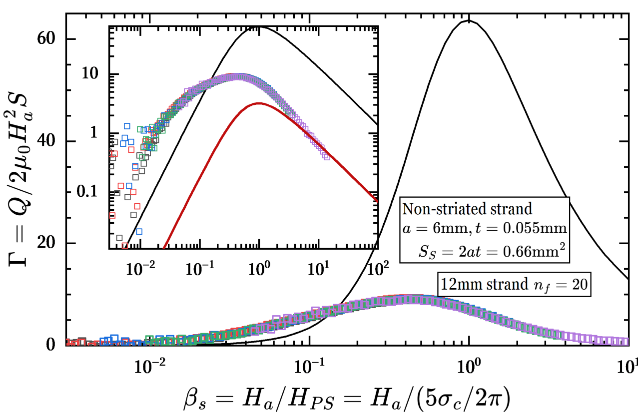

Fig. 2. Magnetisation Loss factor as a function of reduced field $\beta_S = H_a/H_{PS}$ for a striated REBCO tape 12mm wide, 0.055mm thick and with 20 filaments measured at temperatures between 5K and 85K. The loss factor of the corresponding non-striated tape is shown by the black solid line and the red solid line corresponds to 20 fully uncoupled filaments.

B. Magnetic coupling among the striated filaments

The kind of magnetic coupling between the side-by-side stacks in Roebel cables should be inevitable among the filaments in a striated tape. An infinite periodical array of in-line strips, where the analytical solution [8] is available, is a useful limiting case for $n_f \gg 1$. With the closed form expressions for the periodical distributions of field $b(x)$ and current $\sigma(x)$ given in [8], the hysteretic loss in each strip is obtained with $Q_f(H_a) = 8\int_0^{a_f}\phi(x|H_a)|\sigma(x|H_a)|dx$ where the flux $\phi(x) = \int_0^x b(\xi)d\xi'$. Fig. 3a shows that, as the magnetic coupling increases with a decreasing gap d between the strips with the loss factor per strip $\Gamma_{\infty f}$ in an infinite array moving to a *higher* and *broader* peak at *lower* peak field H_{Pf} than $H_{PS} = 5\sigma_c/\pi$ of an isolated single strip. The magnetic coupling factor $\alpha(d/a_f) = \Gamma_{\infty f}(d/a_f)/\Gamma_S > 1$

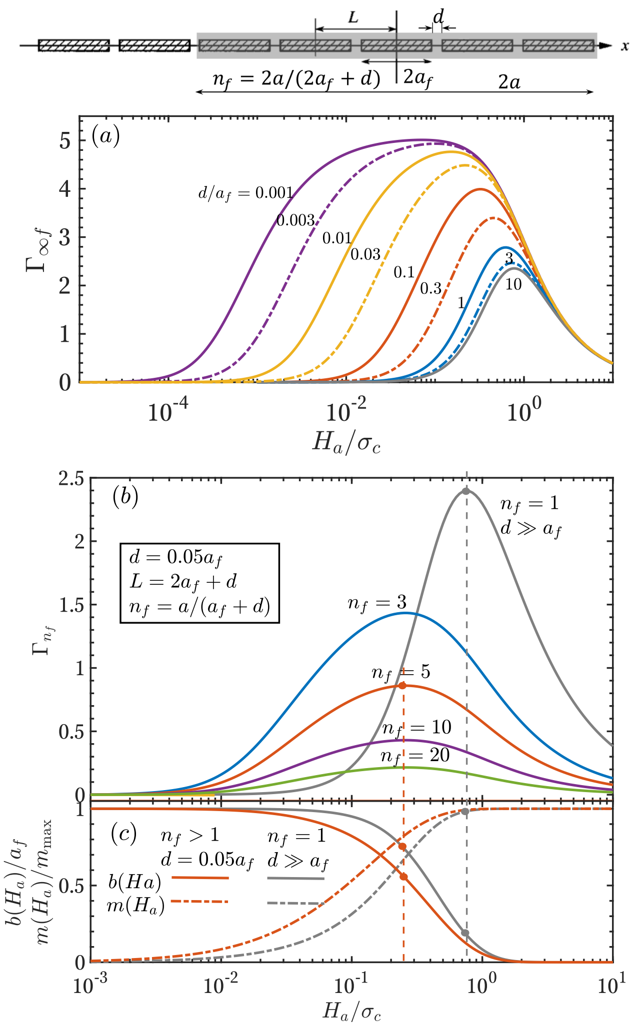

Fig. 3. Top: schematics of an infinite periodical array of in-line strips and approximate finite number of filaments $n_f$in a strand of width $2a$. (a) Loss factor $\Gamma_{\infty f}$ per single strip in an infinite array as a function of β_S for different gaps d between the filaments; (b) Loss factor of an approximate striated strand with diffrent number of filaments; (c) flux front and relative magnetisation for striated and non-straited strands.

for any finite d and increase to ~ 2.2 at $d = 0$ where $\Gamma_{\infty f}(d/a_f = \infty) = \Gamma_S$, i.e. the loss factor of an isolated strand.

Since the ac loss of a strip in an infinite in-line array is proportional to square of the spatial period L [8], subdividing a strand of width $2a$ to $n_f = 2a/(2a_f + d)$ filaments of width a_f is equivalent to reducing L from $2a$ to $L = 2a_f + d$. The collective loss factor of n_f filaments of $2a_f$ over $2a$ is

$$\Gamma_{n_f} = n_f\left((L^2/(2a)^2\Gamma_{\infty f}\right) = \frac{\Gamma_{\infty f}}{n_f}$$
$$= \alpha(d/a_f)\frac{\Gamma_S}{n_f}$$

i.e., the loss reduction by a factor of filament number n_f is only achieved over a magnetically coupled non-filamentary strand in an infinite array but offset by the magnetic coupling factor $\alpha(d/a_f)$ over an isolated strand. The loss factor Γ_{nf} for different n_f at a constant relative gap $d/a_f = 0.05$ is presented in Fig. 3b which shows that the peak loss factor reduces with increasing n_f while the peaked shifted to a lower $H_P \sim 0.25\sigma_c \sim 0.3H_{PS}$, which is even lower than the peak field observed experimentally for the striated strand in Fig. 2. It's important to note (Fig. 3c) that the filaments are far from saturation at peak Γ_{nf} with the corresponding flux front [8] at $b(H_P/\sigma_c) = 0.6a_f$ and the magnetisation [8] at $m(H_a/\sigma_c) = 0.8m_{\max}$. In contrast, an *isolated* non-striated strand is 84% penetrated with $b(H_{PS}) = 0.16a_f$ and nearly 100% saturated at $m(H_{PS}) = 0.99m_{\max}$.

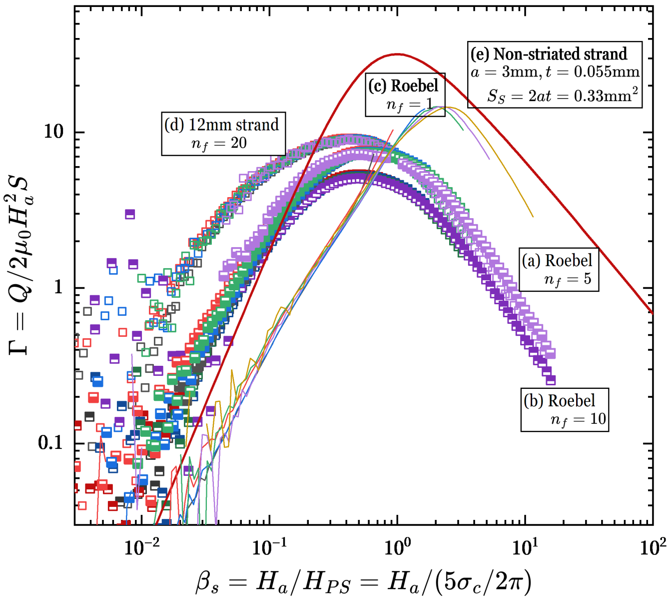

Fig. 4. Loss per unit length as a function of ac field amplitude H_a measured at temperatures between 10 K and 85 K for 9 strands Roebel cables with strands of (a) $1.0\mathrm{mm}/n_f = 5$ filaments, (b) $0.5\mathrm{mm}/n_f = 10$ filaments, and (c) no filaments. The losses of the three cables are shown together with the losses of (d) a striated strand with $0.5\mathrm{mm}/n_f = 20$ and (e) a non-striated strand.

IV. Magnetisation and AC Losses in Roebel Cables with Striated REBCO Strands

While the behaviour of a striated strand can be explained qualitatively by approximation as a part of an infinite array of Norris' strips, it is not obvious that the two side-by-side stacks of striated strands can also be similarly simplified while allow an enhanced critical current of $I_{c,m} = \gamma m I_c$. Indeed the experimental results (Fig. 4) on Roebel cables with 9 ($m = 4$) striated strands of $n_f = 10$ (upper-half filled symbols) indicate almost no movements of the loss factor peak positions from that of the $12\mathrm{mm}/n_f = 20$ single strand which is equivalent to the 6mmwide Roebel strand with $n_f = 10$. The peak position for the Roebel cable of $n_f = 5$ strands (lower-half filled symbols) is only slightly higher but remains below H_{PS}. In contrast, the Roebel cable with 9 *non-striated* strands, shown in the group of thin solid lines in Fig. 4 under legend (c), exhibits the expected higher peak field $H_P \sim 2.6H_{PS}$ for $m = 4$, i.e., $\gamma = 0.65$. For practical applications at high field well above H_P, it is striking that the striated Roebel strands behave as a collection of *uncoupled* filaments with significantly lower losses as the magnetic coupling among both the filaments and the stacked strands appears to vanish completely. In contrast, the non-striated strands with the stacks remain coupled at high field. The thick solid red line shows the much higher loss factor of a single 6mm non-striated strand, highlighting the loss reduction achieved by the Roebel cables.

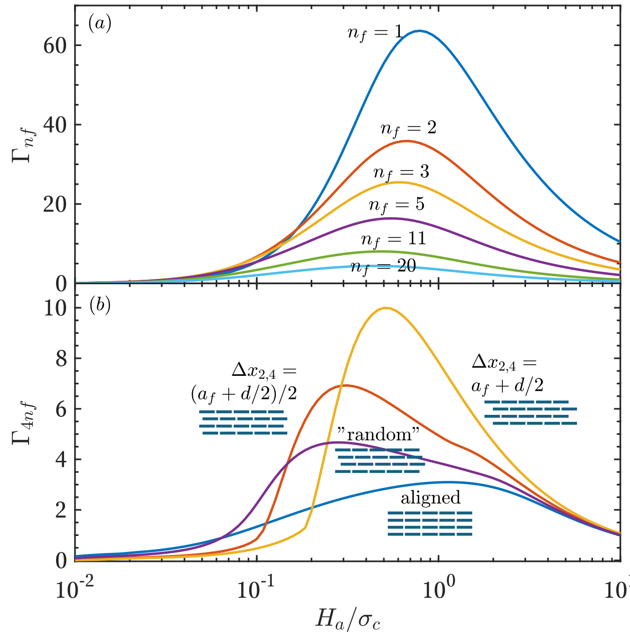

Fig. 5. Numerical results of loss factor as a function of reduced field $\beta = H_a/H_{PS}$ on (a) 12mm wide and 55μm thick striated strand with $n_f = 1, 2, 3, 5, 11, 20$ and (b) a stack of $m = 4$ striated strands of 6mm width and $n_f = 5$ filaments at various lateral displacements relative to each other, as indicated by the corresponding legends and schematic representations.

Quantitative explanations were sought by numerical solution for a *finite* array of striated filaments using 1D $T_z - H$ formulation [13] and Fig. 5(a) shows the loss factor obtained for a $2a = 12\mathrm{mm}$ wide striated strand with $n_f = 1, 2, 3, 5, 11, 20$. For $n_f = 20$, the loss reduction by a factor of 12 for $n_f = 20$ is still much higher than a factor of 6.6 found experimentally and the peak loss factor occurs at $H_P \sim 0.47\sigma_c \sim 0.59H_{PS}$ which is also higher than both the experimental result of $H_P \sim 0.46H_{PS}$ (Fig. 2) and $H_p \sim 0.3H_{PS}$ as a part of an infinite array (Fig.3b). It should be noted that the numerical models assume a field-independent critical current which is more or less expected for ac fields less than 0.2T and especially at low temperatures where the Roebel cables are more appropriate.

The modelling results for striated strands seem to give sufficiently reasons for applying the numerical method to stacks of striated strands in an attempt to explore the mechanisms for the lack of increase in the linear critical current density in Roebel cables with striated strands. The results for a stack of $m = 4$ striated strands 6mm wide with $n_f = 5$ filaments are shown in Fig. 5b. When the strands in a stack are perfect aligned, as shown by the blue line in Fig. 5b, it behaves as expected with a peak loss factor at $H_P \sim 1.36\sigma_c = 1.7H_{PS}$ which almost *triples* the peak field $H_P \sim 0.44\sigma_c = 0.55H_{PS}$ of a singe strand with 5 filaments, i.e., the linear critical current of a fully aligned stack indeed increases almost proportionally with $\gamma \sim 0.75$ with the number striated strands.

Since the flux penetration and associated losses are mostly due to the strong demagnetising field in the gaps between the filaments, it is reasonable to expect significant changes if the gaps within one strand is covered by the filaments in the strands above or below. The yellow and red lines in Fig. 5 correspond to the loss factor for displacing stands #2 and #4 by $a_f + d/2$ and $(a_f + d/2)/2$ respectively. In the former case where the gaps in strands #1 and #3 become symmetrically covered by the filaments in strands #2 and #4, the loss factor increases significantly with a peak shifted to a $lower$ field at $H_P \sim 0.5\sigma_c = 0.63 H_{PS}$. In the latter case with the gaps asymmetrically covered, the loss factor and its peak position are further lowered with $H_P \sim 0.3\sigma_c = 0.38 H_{PS}$. An example of random displacements of strands #2-#4 within $(a_f + d/2)/2$ appear to produce even more changes, as the loss factor for the specific random values (purple line) is decreased by another 1/3 with a peak at $H_P \sim 0.25\sigma_c = 0.31 H_{PS}$. Such a strong dependence of the losses on the relative displacement among the strands suggests that the stacks of striated strands in practical Roebel cables are unlikely to behave as the perfectly aligned ones which has the lowest losses but the highest peak field.

V. Conclusions

While a reasonable quantitative loss calculation in Roebel cables with non-striated REBCO strand can be obtained with a simple model of magnetic coupling between the two side-by-side stacks plus an isolated strand for the transposition between the stacks, the magnetisation loss of Roebel cables with striated strands remains less well understood. The present work makes a few not insignificant advances related to the magnetic coupling among the striated filaments. Unlike fully uncoupled filaments, the magnetic coupling not only offsets the expected loss reduction significantly but also leads to the loss factors reaching the maximum when the filaments' magnetisation is far from saturated. Furthermore, the losses in a stack of striated strands are shown to be very sensitive to the relative displacements among the strands, leading to higher losses than in perfect alignment. On the other hand, it remains unexplained how the filaments in a stack of striated strands become fully uncoupled with the desired loss reduction when become saturated at high field. The experimental and numerical results presented in this work not only show the potential for loss reduction by striated REBCO strands in assembled cables but also highlight that a quantitative understanding of their loss behaviour is still some way off. Further detailed studies should follow, the present work might point to the right direction.

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