

Analysis of critical current reduction in self- field in stacked twisted 2G HTS tapes

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Abstract. Twisted stacked-tape cable (TSTC) is one of the methods to produce flexible current carrying elements (CCE) with high current density made of 2G coated conductors. The critical current of CCE in self-field is less than the sum of critical currents of all tapes used to make CCE. This critical current reduction is attributed to self-field influence of critical currents of tapes. To describe the current reduction accurately in TSTC it is necessary to take into account current and field distribution in a stack cross-section using dependencies of critical current on magnetic field for each tape. In other words one has to make self-consistent calculations of current and magnetic field distribution in a stack. In this paper we present the self-consistent analysis of magnetic field and current distribution in TSTC with different number of tapes using the generalized Kim model. We also measured current degradation in TSTC made of from two to ten 2G tapes and compared it with calculations. We found good coincidence of calculated and measured current degradation that confirm the validity of our approach.

1. Introduction

The common way to create HTS current carrying element consists of tapes laid in helix on round core (CORCC) [1] or in making ROEBEL element [2]. Both technologies have advantages such as uniform current distributions between tapes, but also have significant limitations, such as low current density for CORCC and high tapes outgoings for ROEBEL.

One more way to create high current density carrying element is a twisted stack of HTS tapes (TSTC) [3]. TSTC have a high potential for the introduction to DC applications with high current densities, for example for degaussing of ships or for low voltage DC cables for data centers [4]. This technology provides compactness, high current density and negligible tapes outgoings. On the other hand, undesirable feature of twisted stacked tapes is critical current reduction due to self-field effect as it was observed in [3] and [5]. Advanced study of this effect is needed if low field application of TSTC is considered. In this paper we summarize our detailed analysis of current reduction in self-field both numerically and experimentally.

2. Critical currents of TSTC

2.1. Method of calculation of magnetic field in TSTC

In order to calculate magnetic field at arbitrary point (x,y), produced by twisted tape, one can note, that in limit $\text{twist pitch} \gg \text{tape width } (w) \gg \text{tape thickness}$, Biot–Savart law for straight tape is a fine approach:



$$\vec{b}(x, y, \eta) = \frac{\mu_0}{2\pi} \int_{-w/2}^{w/2} \frac{-\vec{e}_x(y-\eta) + \vec{e}_y(x-\xi)}{(x-\xi)^2 + (y-\eta)^2} J(\xi) d\xi \quad (1)$$

where are: (ξ, η) - coordinates of tape, $J(\xi)$ - current density.

Each tape in stack is located in external magnetic field, produced by all another tapes of stack. Thus, for k -th tape in stack, corresponding external magnetic field will be expressed as:

$$\vec{B}_k(x) = \sum_{i \neq k} \vec{b}(x, \eta_k, \eta_i) \quad (2)$$

In HTS layers for $j_c(B)$ Kim's model [6] is used

$$j_c = \frac{j_{c0}}{\left(1 + \frac{\sqrt{k^2 B_x^2 + B_y^2}}{B_0}\right)^\beta} \quad (3)$$

with parameters, which measured at VNIKP at temperature 77 K for the used in work SuperPower SCS4050 [7] HTS tape: $k = 0.5, \beta = 0.7, B_0 = 0.11 \text{ T}$.

Then, modified critical current density allows to recalculate magnetic field distributions, therefore looping the calculations. This iterative process runs until consistent magnetic field \Leftrightarrow critical current density distributions will be found. It should be noted that process converges very fast – for only several iterations steps.

2.2. Measurements tools

Measurements of each tape critical current reduction in stack for various numbers of tapes in stack and various gaps between tapes was performed on insert (figure 1) at temperature 77 K. Set of shunts (10 long copper strips for each tape) provides very uniform current distribution between tapes (0.5% accuracy) and serves as handy current sensor of each tape. Single tape critical current measurements and calibration of shunts were made preliminarily. Tapes are laying in stack on a length $\sim 50 \text{ cm}$. Each tape has its own voltage taps pair.

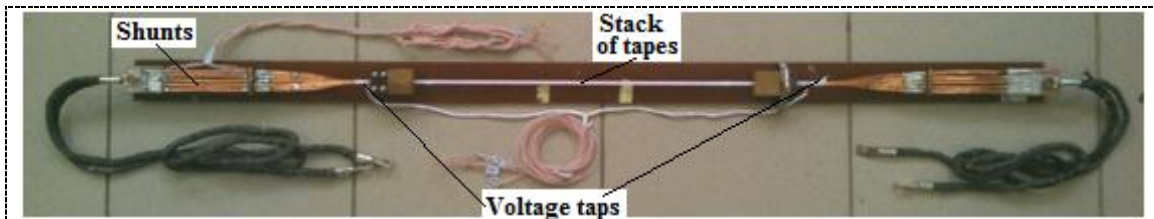


Figure 1. Optimal configurations of stacks with cross section $4 \times 4 \text{ mm}^2$.

2.3. Experimental and calculated results

Results of each tape's critical current reduction measurements in tight stack of ($n=2 \dots 10$) tapes are represented in figure 2 (number of tapes in stack in graph's legend).

By averaging this data over tapes in stack, one can find average critical current degradation:

$$\text{degr}(n, \Delta) = \frac{\sum_{i=1}^n I_{c_i}(n, \Delta)}{\sum_{i=1}^n I_{c_{i0}}} \quad (4)$$

where are: n – number of tapes in stack, I_{c0} – single tape critical current, Δ - gap between tapes in stack.

Both numerical and experimental results for tight ($\Delta=0$) stack of I_c reduction $\text{degr}(n,0)$ function are shown in figure 3. There is good agreement with numerical results. Some deviations can be explained by difference in critical currents of single tapes (ignored in calculations).

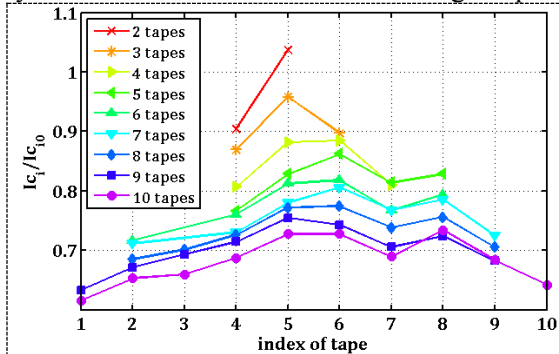


Figure 2. Each tape critical current reduction in tight stack.

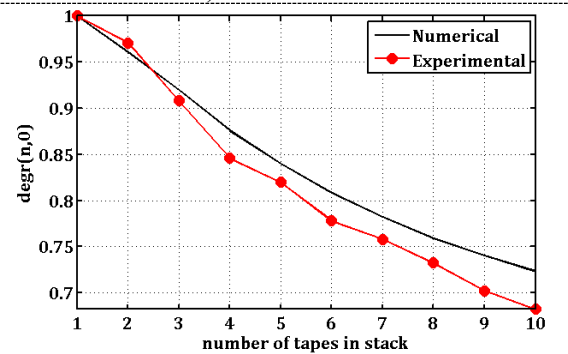


Figure 3. Average critical current reduction as a function of number of tapes in tight stack.

Next part of the experimental work was study influence on critical current reduction of gaps between tapes in a stack. This was done for stack of 7 tapes by inserting of electrical insulating paper between tapes. Thickness of paper is 120 μm , which allows to check multiple gap values: 120, 240, 360, 480 and 600 μm for stack of 7 tapes. Results of measurements are shown in figure 4.

Critical current reduction of each tape averaged over 7-tapes of stack and numerical values of $\text{degr}(7,\Delta)$ function are compared in figure 5.

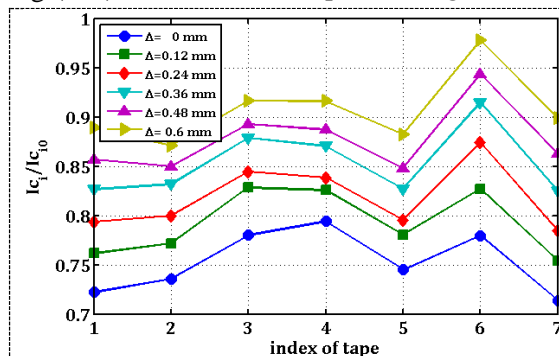


Figure 4. Critical current reduction of each tape in stack of 7 tapes.

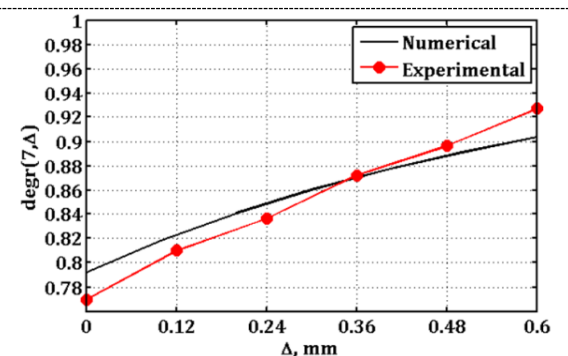


Figure 5. Average critical current reduction as a function of a gap between tapes.

Thus, numerical method was confirmed experimentally. Additional attention should be paid while choosing $j_c(B)$ models (or interpolation data) for numerical evaluation, which plays central role in all calculations.

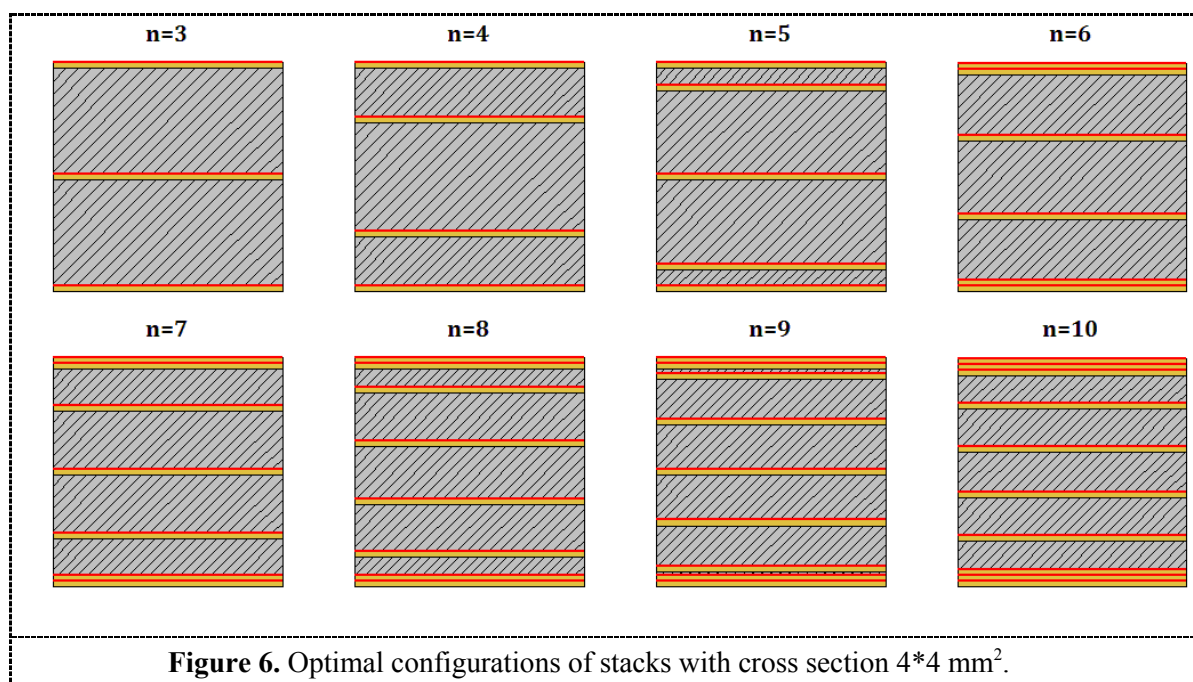
3. Optimization of tape location (tapes configuration) in a stack with fixed cross-section

With implemented numerical model of mutual tapes influence in stack one can solve optimization problem – find N-tapes positions in a stack with fixed cross-section, corresponding to maximal current density. Chosen cross section configuration for this problem is $4 \times 4 \text{ mm}^2$. This cross-section is filled by N tapes (width-4 mm, thickness-0.1 mm). The remaining space of cross section is filled by additional layers (insulating, stabilizing, etc.). In general, N-tapes problem have N-1 independent parameters of optimization (gaps between tapes). For clarity, there is a simplification about each tape's critical current – all of them are set to be of the same value. This simplification reduces the number of parameters in two times (because of horizontal symmetry of the problem). For example, for stack of 4 tapes only 1 parameter of optimization is needed: if gap Δ between 1 and 2 tape is chosen, then gap between 3 and 4 tape is the same (due to symmetry), and gap between 2 and 3 tape will be equal to $4 - 4 * 0.1 - 2 * \Delta$.

Finally, optimization problem solutions against number of tapes in stack from 3 to 10 are given in table 1 and illustrated in figure 6.

Table 1. Optimal values of gap.

Number of tapes in stack	3	4	5	6	7	8	9	10
gaps, μm	1850, 1850	850, 1900, 850	290,1460, 1460, 290	0, 1060, 1280, 1060, 0	0, 630, 1020, 1020, 630, 0	0, 320, 830, 900, 830, 320, 0	0, 70, 700, 780, 780, 700, 70, 0	0, 0, 500, 650, 700, 650, 500, 0, 0



4. Conclusion

TSTCs in self-field conditions were experimentally and numerically evaluated. Calculation method of mutual HTS tapes influence in stacked twisted tapes was proposed. This method was confirmed by experimental measurements. Thus, it can be used for analysis of more complicated problems. Solution for stack optimization problem, based on calculation method of this work, was given also.

References

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