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Optimization of wire construction from several 2G HTS tapes

D.R. Kumarov[a], D. Sotnikov[a], V.I. Scherbakov[a], A. Mankevich[b], A. Molodyk[*, b], Kideok Sim[c], and Soon Hwang[c]

[a] *CJSC SuperOx, Moscow, Russia*
[b] *S-Innovations LLC, Moscow, Russia*
[c] *SuperGenics Co., Ltd, Changwon, 51542, Korea*

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Abstract

Despite the second generation HTS tapes (2G HTS tape) have limits in critical current value, scientific and electric devices require more current density day after day. These requirements are realized by using different superconducting wires that consist of 2G HTS tapes designed in various combinations. Authors of this paper have developed the numerical model for estimation of total critical current in the superconducting wire and critical current in each 2G HTS tape placed in this superconducting wire. The current drop in six 2G HTS tapes having different constructions was analyzed. The result of this research is the decrease of critical current up to 25 % for the stack of tapes and up to 5 % for the parallel tapes in the same plane. In addition, what was also made is the estimation of the current distribution by length for six 25 m 2G HTS tapes in different constructions and determination of current deviation by length of the wire.

Keywords: HTS, coated conductor, critical current, cable

1. INTRODUCTION

The necessity of applying devices with high current density leads to the usage of superconductors in different areas of applied physics and energy systems: from implementation of cables and fault current limiters [1] to magnets of accelerators [2] and fusion energy [3]. Modern devices require the increase of current-carrying properties of conductors, and consumers induce new ways for the production of superconducting wires. Superconducting wire is a current carrying element that consists of one or several 2G HTS tapes. One of the ways to produce such high-current superconducting wire is the use of several parallel 2G HTS tapes. This method makes possible to produce superconducting wires for such low-field devices as superconducting fault current limiters (SFCL), cables and other devices with high current density, which operate both on direct and alternating current.

2G HTS tapes contribute to improvement of traditional technologies due to small size and high current (for example, 12-mm width tape with thickness 120 μm and critical current 500 A), and they also replace low temperature superconductors due to operation in cheap and safety liquid nitrogen. Combinations designed using 2G HTS tapes are not only compact and flexible, but also have high current density. That means that products, which are made from 2G HTS tapes, use the smaller cryogenic vessels, operate at higher temperatures (77 K) and need cheaper equipment for keeping the required temperature.

2G HTS tapes have several technical species that cause difficulties for production of combined wires of varies constructions:

1) influence of magnetic field decreases the current-carrying properties of 2G HTS tapes;
2) 2G HTS tapes have deviation of critical current by length of tape.

Superconducting tape with transport current is the source of magnetic field that can decrease the critical current in neighboring tapes. It is necessary to estimate the influence of magnetic field from each tape in the construction in order to obtain the total critical current of the wire. Moreover, the critical current is different by length of the 2G HTS tape regarding the quality of production of this type of superconductor. Therefore, it is necessary to have the deviation of critical current by all length of the wire in order to assess the possibility of using particular wire in the device.

The paper describes the method of assessing the critical current distribution between 2G HTS tapes for different combinations of the position of the tapes in the wire (for example, several tapes in parallel in the same plane, or a stack of tapes, etc.). This calculation is based on the self-field of each 2G HTS tape in combination and the total magnetic field of all tapes, which affects the critical current of each tape in the wire. Computation of the combination of 2G HTS tapes provides the critical current of the final wire and allows choosing the best combination for applying in the developed device.

2. NUMERICAL MODELLING

The modelling of the magnetic field of 2G HTS tapes was developed using Matlab software.

Possibilities of the developed model can be demonstrated

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[*] Corresponding author: a.molodyk@superox.ru

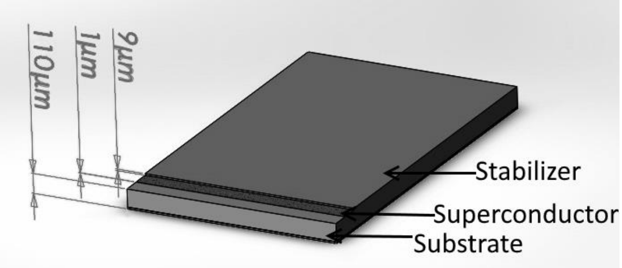

Fig. 1. Main geometry of the 2G HTS tape.

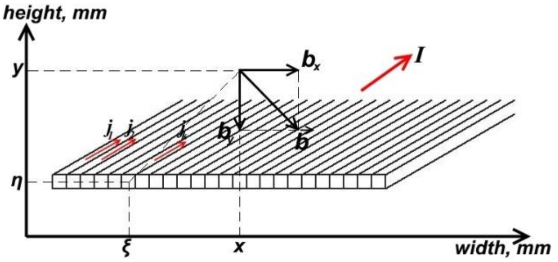

Fig. 2. Dividing superconducting layer of the 2G HTS tape on strips.

using the following geometry of the 2G HTS tape: width of the tape is 12 mm, the thickness of the substrate is 110 µm (including stabilization in bottom), the thickness of the REBCO layer is 1 µm, and the thickness of the stabilization layer on the top of the tape is 9 µm (Fig. 1). The shown geometry is very close to real layers of the 2G HTS tape [4]; also, the shown sizes can be revised considering real layers by initial requirements.

The geometry of layers of each 2G HTS tape gives us information about position of superconducting layers in all configuration. We can divide superconducting layer as a set of parallel strips with current in each [5] and calculate the magnetic field of each strip by Biot-Savart law (Fig. 2). In this case, the magnetic field is a sum of magnetic fields from all strips, so we can use the equations from [6] for this calculation:

$$b_x = -\frac{\mu}{2\pi}\frac{j\,(y-\eta)}{\{(x-\xi)^2+(y-\eta)^2\}}d\xi d\eta$$
$$b_y = \frac{\mu}{2\pi}\frac{j\,(x-\xi)}{\{(x-\xi)^2+(y-\eta)^2\}}d\xi d\eta \qquad (1)$$

where x, y – coordinates of measured field point; ξ, η – coordinates of strip of the 2G HTS tape with current density j. These calculations are made for the 2G HTS tape with very thin superconducting layer, so we can take the change η of strip by as 0 in (1), and use dη equals to 1 µm – the thickness of superconducting layer. It provides accurate results and makes calculations much easier.

The next unknown parameter is the current distribution in the tape. Brandt's model [7] describes the current distribution for width of 2G HTS tapes with various transport currents and applied fields. However, the critical current density is distributed uniformly by width of the 2G HTS tape [7] including the case when the superconductor is placed in external magnetic field. We need the maximum current value that can be applied to each tape in the wire for model in this paper. The maximum applied current corresponds to critical current of 2G HTS tapes. Therefore, we can take the uniform distribution of current density in all tapes.

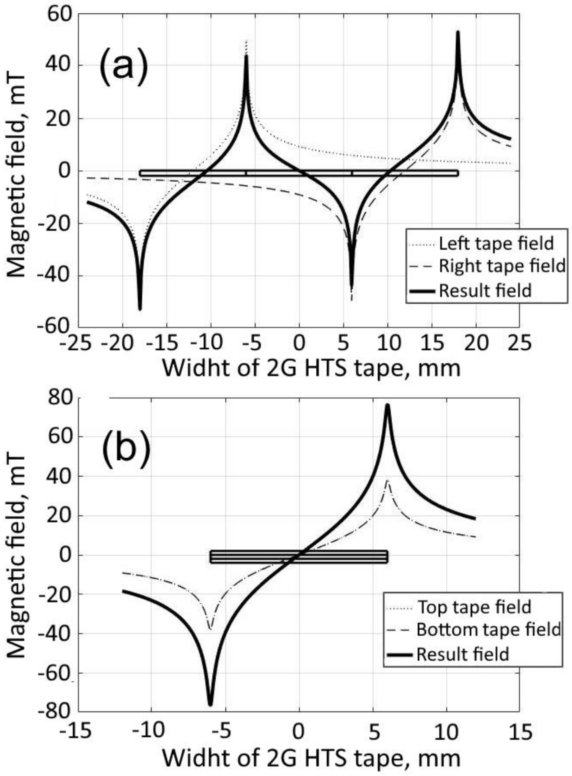

Fig. 3. Influence of magnetic field of neighboring 2G HTS tapes to middle tape for configurations of (a) three parallel tapes in same plane and (b) three parallel tapes in stack.

Using the equation (1) and the assumption of uniform current distribution by width of 2G HTS tapes, we can compute the magnetic field distribution on the 2G HTS tape from neighboring tapes. This calculation is developed for 2 cases of construction: a) for three parallel 2G HTS tapes that are placed in the same plane (Fig. 3(a)) for three parallel 2G HTS tapes in stack (Fig. 3(b)). The case of tapes in the same plane shows that the resulting field on the middle tape (solid line in Fig. 3a) is less than the magnetic fields of neighboring tapes (dotted and dashed lines). The tapes-in-plane construction results in decreasing of field influence on the middle tape. The case of stack of three tapes shows that magnetic field of the top tape (dotted line) and the bottom tape (dashed line) are almost the same. The resulting magnetic field is a sum of top and bottom tapes' magnetic fields, which is twice bigger.

The next step is the estimation of influence of the magnetic field on the critical current of the tape. The best way to assess the influence of magnetic field on critical current is to measure it directly and make approximation of the gained data. If it causes difficulties, it is possible to use I_c (B) from already published results of alike measurement such as in [8]. Our team usually uses SuperOx 2G HTS tape, so the parameters corresponds to the measured SuperOx tape:

$$I_c(\theta,B) = I_{c0}\left(1+\varepsilon_0\left(B/B_0\right)^{\alpha}\right)^{-\beta} \qquad (2)$$

where $\varepsilon_0 = \sqrt{(\sin(\theta)^2 \gamma^2 + \cos(\theta)^2)}$, B_0 = 53.26 mT, α = 1.59, β = 0.36, γ^2 = 3.34 for the SuperOx tape. The influence of magnetic field of neighboring tapes is less than 100 mT usually [9]. For example, we obtain 100 mT magnetic field for configuration in Fig 3(b) with the critical current of about 3550 A in each 12-mm 2G HTS tape, what is impossible for current level of technology. As we know, parallel magnetic field does not decrease critical current of 2G HTS tapes in fields less than 100 mT, so we can use only perpendicular field in following calculations. It means, that θ = 0 and the (2) equation can be re-written as the following:

$$I_c(0,B) = I_{c0}(1+\left({}^{B}/_{B_0}\right)^{\alpha})^{-\beta} \tag{3}$$

The measurements of magnetic fields influence are usually provided in uniform external magnetic field. However, the magnetic field is strongly non-uniform in practical devices. We considered that both directions of the perpendicular field decrease the critical current value, and we calculated the applied external magnetic field as the average value of applied field of absolute values of the magnetic field. Therefore, the final field distribution is obtained by summarizing the external fields of all tapes in combination, that allows to find the average value of absolute values of the field.

Based on aforesaid, the modelling of the critical current distribution in combination starts with magnetic fields calculation for case, when all tapes are under critical current in self-field. It provides the maximal magnetic fields that could be gained in this construction. After that, we computed the critical currents of the tapes by (3) that corresponds to applied magnetic fields, and calculated new magnetic fields based on a new current distribution in combination. Then step-by-step we found steady-state condition, when all critical currents in the tapes correspond to the applied magnetic field. It is the final step of the calculation of the current distribution resulting in the critical current distribution in tapes in construction.

3. COMPARISON OF CONSTRUCTIONS OF 2G HTS WIRES

The main purpose of construction of 2G HTS tapes in one wire is the increase of critical current. Further this wire can be used in different devices (transformers, current leads, SFCL, etc.), that require the current higher than 500 A. The developed model can be applied for estimation of degradation of critical current of several 2G HTS tapes that are combined in one wire.

We used the model for comparison of the current distribution of six 2G HTS tapes in the following constructions (the superconducting layer of all tapes is placed in the top part of the tape):

1) all 6 tapes are placed in the same plane (configuration 1x6) (Fig. 4(a));

2) three stacks of double tapes are placed parallel in the same plane (configuration 2x3) (Fig. 4(b));

3) two stacks from triple tapes are placed parallel in the same plane (configuration 3x2) (Fig. 4(c));

4) all 6 tapes are placed in the stack (configuration 6x1) (Fig. 4(d)).

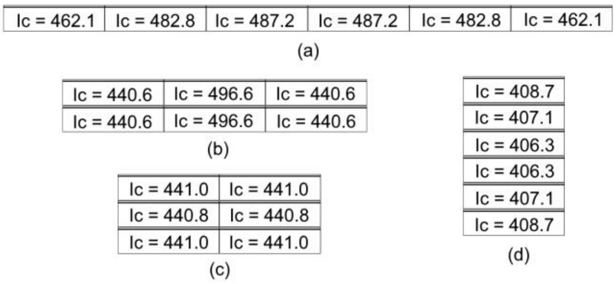

Fig. 4. Critical current in 2G HTS tapes in wires of 4 configurations: (a) 1x6; (b) 2x3; (c) 3x2; (d) 6x1.

TABLE I

RESULTS OF TYPES OF CONSTRUCTION OF 2G HTS TAPES.

Configuration	1x6	2x3	3x2	6x1
Total Ic, A	2864	2755	2645	2444
Sizes, WxH (mm)	72x0.12	36x0.24	24x0.36	12x0.72

Demonstrative result can be obtained by usage of the same critical current equals to 500 A in self-field in all 6 tapes. The geometry of tapes corresponds to Fig. 1 with standard width 12 mm. The computation of 4 constructions of the wires provided the results, that are presented in Fig. 4.

The most obvious result is the total critical current that was gained by this calculation (Table 1). We obtained the biggest critical current at construction 1x6 (all-tapes-in-plane). The more layers of tapes in stacks there are, the lower total critical current is. It is shown in Fig. 3 - when the total magnetic field on the middle tape in stack from 3 tapes was twice more than self-fields on neighboring tapes.

The gained results can be applied for development of new devices. For example, construction type 1x6 provides the maximal advantage and minimal using of high-cost 2G HTS tapes. This type of wire can be applied in transformer, current leads or SFCL. At the same time, the combination 6x1 is more compact, and it can be more actual to use one tape more in stack to make more current density.

For better understanding of already implemented designs of cables, let us estimate the decrease of total current in comparison with self-field in popular wires: twisted stacked-tape cable (TSTC) and Roebel cable.

3.1. TSTC.

TSTC cable is the most preferable type of superconducting wire that is planned to be used in innovative superconducting devices [10]. This wire is produced from several 2G HTS tapes designed in stacks and twisted (Fig. 5). By estimation of producers, this cable should have uniform degradation of critical current by influence of the magnetic field on all length. Moreover, TSTC is very compact cable with very high current density.

Fig. 5. Twisted stacked-tape cable [10].

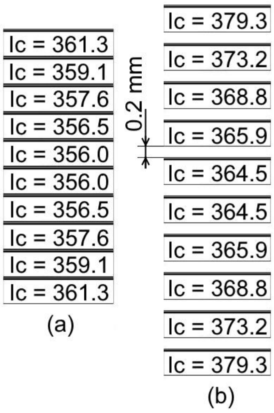

Fig. 6. Critical current distribution in the stack of 10 2G HTS tapes for (a) compact stack and for (b) distance 0.2 mm between tapes in stack.

TSTC is the vertical stack of several 2G HTS tapes in cross-section.

We estimated the critical current of each tape in stack by using our model for standard 10 tapes (500 A, 12 mm width, geometry is presented in fig. 1). As it is shown, the minimal degradation of critical current presents in the tapes on edge of the stack (top and bottom tape) (Fig. 6(a)), but degradation is almost the same for all tapes in the stack. The total critical current of the stack is equal to 3580 A that is just 72% from total current of tapes in self-field (5000 A). When modeling stacks consisting of 4, 6, 8, 10 and 20 tapes in stacks, we get degradation to 89%, 81%, 76%, 72% and 59% of the critical current, respectively.

If the distance between tapes in stack is 0.2 mm (it can be achieved by adding of non-magnetic stabilizers), the total critical current is 3703 A (Fig. 6(b)), that is 120 A more than critical current of the compact construction (without distance between tapes). Therefore, the critical current of the wire vary by changing the distance between tapes. It is actual for optimization of using 2G HTS tapes for tasks with known geometry for the wire intended to be used.

3.2. Roebel.

Another popular type of superconducting cable with low AC-losses is a Roebel cable [11]. It has compact construction and low influence from external magnetic field (Fig. 7).

Fig. 7. Roebel cable [10].

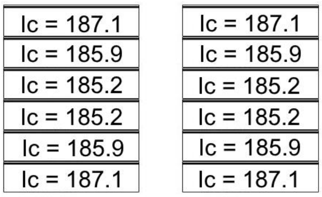

Fig. 8. Current distribution in 2G HTS tapes in cross-section of Roebel cable.

Usually this type of cable is gained by cutting 2G HTS tapes in serpentine shaped strands, after that winded in cable that looks like two parallel stacks of tapes in cross-section. The critical current of tapes in Roebel cable is less than critical current of initial 12-mm width tapes because of width of the obtained tapes. In rough estimation we can use the critical current of each tape as 5.5 mm / 12 mm x 500 A ≈ 230 A for tapes of 5.5 mm of width. The distance between stacks in cross-section will be 1 mm (12 mm of initial tape minus 2 x 5.5 mm of cut tapes). In this case, we will get the distribution of critical current in 12 tapes in the Roebel cable presented in Fig. 8.

We gained the critical current that is equal to 2232 A in comparison with critical current of tapes in self-field that is equal to 2760 A. The total critical current in the Roebel cable of 12 tapes with width 5.5 mm shows almost 20 % degradation when tapes are designed in the construction. The Roebel type cable is a low ac-losses type of superconducting cable that can be used in innovative areas of applying superconductivity, for instance aircrafting [11].

4. LONG-LENGTH WIRES CALCULATION

As we know, 2G HTS tapes have big deviation of critical current by length of the tape. During construction of those tapes in one wire, we can estimate roughly the resulting critical current distribution by length. The developed model allows to calculate the current distribution of wires of varies construction with using initial data of tapes, which can be obtained by TapeStar analysis [12].

Six 12-mm width 2G HTS tapes are took for applying them in the high-current device. The initial scans of critical currents in self-field are presented in Fig. 9. We used one 150 m 2G HTS tape of SuperOx' production with uniform current distribution by length, and divided it in six 25-m tapes to check different combinations in the wire.

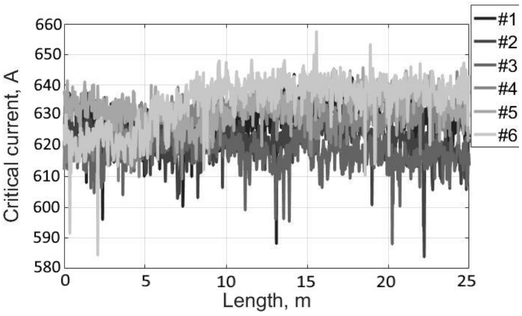

Fig. 9. Critical current distribution of six 2G HTS tapes produced by SuperOx.

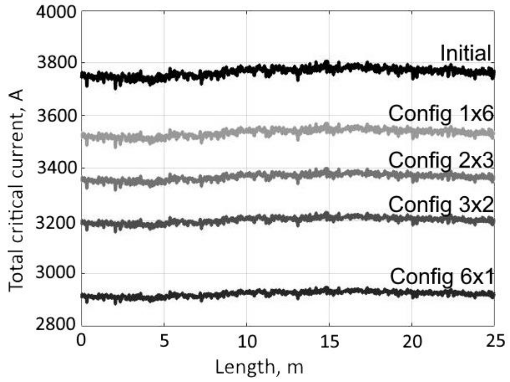

Fig. 10. Critical current distributions by length for a sum of six 2G HTS tapes and four constructions from six tapes: 6x1, 3x2, 2x3, and 1x6.

The first step is interpolation of the data for all six tapes so that all coordinates by length are equal for all tapes. The next step is choosing the construction of the wire. Six tapes allow making four compact constructions, which were already used in chapter 4: 1x6, 2x3, 3x2 and 6x1 configurations. Using our model, we substituted the values of the critical current for each point by length of the tapes. Finally, we gained the distributions that are presented in Fig. 10.

The total current of the gained wires is less than the total current in self-field down to 76 % for case of stack (config. 6x1) (3800 A for self-field tapes and 2900 A for stack). The lowest change of the total current is seen in 1x6 configuration, it was predicted by previous calculations. Usage of the developed model shows the critical current distribution by all length of the wire. It provides us with information about the minimum current of the wire and change of the current by length. This information is crucial for determination the possibility of using the wire in the device. For example, the deviation of critical current in 6x1 construction is 64 A in comparison to 94 A for 1x6 construction. The difference of uniformity will be more obvious if wires include initial tapes with more deviation of critical currents by length. It means that 6x1 construction is more applicable for high fields and for lower temperatures.

5. CONCLUSION

The developed numerical model allows to estimate the critical current distribution in 2G HTS tapes in wires of various combinations. It allows knowing the total critical current of the wire and critical current of each layer. Usage of this model helped to calculate the critical current distribution in the wires of various combination consisted of six parallel 2G HTS tapes. It allows making a choice for quantity of tapes in the wire and can predicate the degradation of current-carrying properties. We found, that the lowest critical current presents in stacks of 2G HTS tapes (up to 25 % of degradation for six tapes in stack), and the highest critical current corresponds to the configuration of all-tapes-in-plane (the degradation is up to just 5 % for six tape in plane).

In addition, this model was applied for long-length wires, and it gave the current distribution of wires with various combinations by length. Achieved distribution estimates usage of the wire in the device and shows weak points that the produced wire may have.

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