

# Current-carrying capacity of HTS DC cables with the reduced Lorentz force

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**Abstract.** The structure of superconducting DC cable made with high temperature superconducting tapes is designed to improve the current-carrying capacity by reducing the Lorentz force acting on flux lines. For this purpose an axial magnetic field is produced by the outer shield conductor. The analysis was performed for the optimum structure for various superconducting tapes with different  $J_c(B, \theta)$  characteristics. It is found that the current-carrying capacity increases appreciably when the difference in the critical current density of the tape is large enough between normal and parallel magnetic fields.

## 1. Introduction

It is known that the critical current density dramatically increases when a metallic superconductor is placed in a parallel magnetic field. This is the longitudinal magnetic field effect. However, the critical current density does not appreciably increase in a parallel magnetic field in high temperature superconductors (HTS) due to weak links at boundaries of inhomogeneous distribution of tilted grains. Nevertheless, the critical current of HTS tapes in the parallel magnetic field is higher than that in the normal magnetic field [1-4].

Then, we proposed to use this superior property in a parallel magnetic field for superconductivity DC cables [5]. The optimum structure was investigated based on the critical current property of a typical superconducting tape. However, the optimum structure is different from tape to tape. In this paper we calculated the current-carrying capacity of the cable made with some commercial HTS tapes to investigate the influence of superconducting properties of HTS tapes.

The layout of the tapes in the inner conductor of the cable is shown in Fig.1 [6]. The outermost layer of the cable has the maximal inclination of the superconducting tapes. The axial magnetic field produced by the outer layers makes the magnetic field at the inner layers more axial, resulting in a smaller Lorentz force acting on the flux lines [3]. The current-carrying capacity was calculated by the iteration method similarly to the previous analysis [6].

## 2. Method of calculation

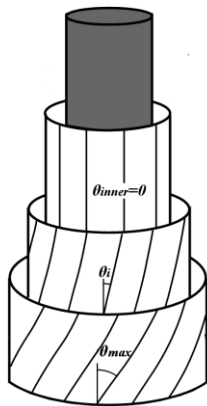
It is assumed that the external axial magnetic field  $B_{ext}$  is applied to the inner conductor of the cable by the current flowing back the outer shield layer. For the estimation of the total current-carrying capacity, the critical current density of each layer, which depends on the local magnetic field, must be determined. That is, the critical current density  $J_{ci}$  of  $i$ -th layer is formally given by

$$J_{ci} = f(B_i, \theta_i), \quad (1)$$



where  $B_i$  is the strength and  $\theta_i$  is the angle of the magnetic field from the current direction on the  $i$ -th layer. These variables,  $B_i$  and  $\theta_i$ , are functions of the current flowing in each layer. Thus, these must be solved consistently. For this purpose, the iteration method was used for the set of equations (1). The details of the analysis are given in [6].

One of the parameters of the cable is the angle  $\theta_{max}$ , the maximal inclination of the superconducting outermost layer. The innermost layer is approximated to be parallel to the cable axis, for simplicity. The distribution of the angle  $\theta_i$  is assumed to be linear in the region between the two layers. It is found that any variation from this linear dependence leads to a decrease in the current-carrying capacity. It means that the linear dependence is optimal.



**Figure 1.** The layout of superconducting tapes in the cable with reduced Lorentz force.

### 3. Calculated results

We examined 3 superconducting tapes, the critical current properties of which are shown in the leftmost column in Fig.2. Sample C shows a gradual increase in  $J_c$  with increasing parallel magnetic field, while  $J_c$ 's in samples A and B decrease monotonically. The middle and right columns show the calculated current-carrying capacity ( $I_c$ ) as a function of  $\theta_{max}$  under various external magnetic fields  $B_{ext}$  for the cable of 40mm diameter with 6 and 13 layers, respectively.

In the case of 6-layer cable made with sample A, for example,  $I_c$  of the cable increases with increasing  $\theta_{max}$ , because the external layers create the axial magnetic field for inner layers. When  $\theta_{max}$  becomes too large,  $I_c$  decreases because of a worse efficiency of the transport current, resulting in some maximum capacity at a medium value of  $\theta_{max}$ . The peak value of the capacity tends to increase with increasing  $B_{ext}$  first, and then decreases. The first increase is caused by the increase in the critical current density of the tape due to the change in the field direction, and the latter decrease comes from the decrease in the critical current density in a higher magnetic field. If we compare the graphs in the middle column to the corresponding graphs in the rightmost column, it is found that  $I_c$  of the cable enhances when the number of the layers is increased. It can be also shown that the ratio of the current-carrying capacity of the present cable to that of the conventional cable increases with increasing layer number.

### 4. Discussion

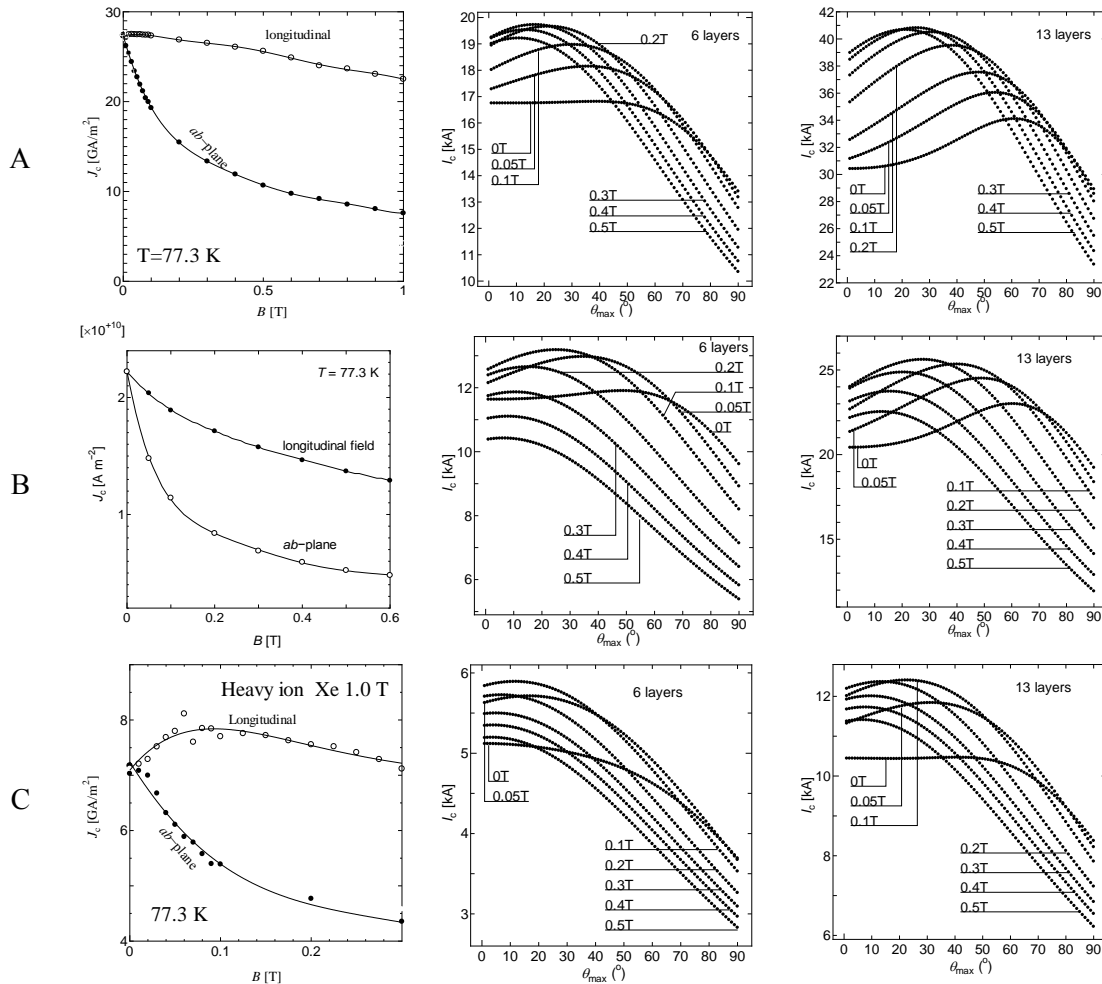
The performance of the proposed cable was also investigated for superconductors with different critical current densities. We focus sample C, because its critical current density increases with increasing parallel magnetic field. Hence sample C seems to be suitable for application to the present cable. Nevertheless, the obtained  $I_c$  is not so large. In particular,  $I_c$  for this sample decreases with increasing  $\theta_{max}$  for  $B_{ext} = 0$ , while those for other samples increase. We want to clarify the reason for this. For this purpose, we approximate  $J_c(B)$  characteristics by lines as in Fig. 3:

$$J_{cLon}(B) = 7.173 \times 10^9 + a \times 1.232 \times 10^{10} \times B \quad \text{A/m}^2 \quad (3),$$

$$J_{cAB}(B) = 7.173 \times 10^9 - b \times 2.132 \times 10^9 \times B \quad \text{A/m}^2 \quad (4),$$

where  $J_{cLon}(B)$  and  $J_{cAB}(B)$  are the critical current densities in a parallel and normal magnetic field  $B$ . The coefficients  $a$  and  $b$  are the multiplication factor, and  $a=b=1$  represents the observed results. We

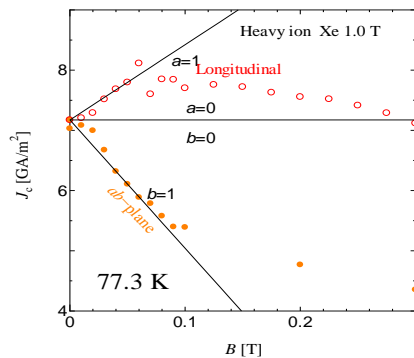
assume a cable with 7 layers. Then, the magnetic field inside the cable does not exceed 0.1T under the condition of  $B_{ext} = 0$ , and the linear approximation holds safely.



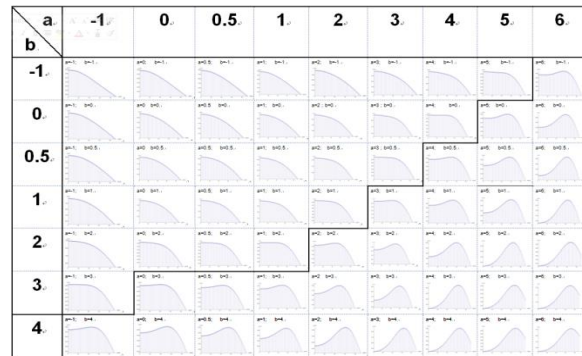
**Figure 2.** Calculated results of current-carrying capacity ( $I_c$ ) of the reduced Lorentz force cable using the various superconducting tapes. Left column -  $J_c$  vs. parallel (upper line) and normal (lower line) field. Middle and right columns - the current-carrying capacity vs. angle  $\theta_{max}$  for 6 and 13 layers cable in an external axial magnetic field of 0T-0.5T

It is possible to obtain different characteristics for other samples by changing  $a$  and  $b$ . Figure 4 shows  $I_c$  vs.  $\theta_{max}$  under  $B_{ext} = 0$  for various values of  $a$  and  $b$ . In Fig. 4 the boundary is also shown between the areas showing positive and negative variation rate of  $I_c$  with respect to  $\theta_{max}$  at small values of  $\theta_{max}$ . It is found from Fig. 4 that the positive variation rate, a more efficient property, is obtained when the sum of  $a$  and  $b$  is greater than some value about 4. When this sum becomes large, i.e., when the difference in the two  $J_c(B)$ 's become large, the variation rate increases appreciably. When  $a$  is sufficiently large, the axial magnetic field produced by helical windings sufficiently increases the critical current density of the tape, resulting the positive variation rate. When  $b$  is sufficiently large, the magnetic azimuthal field produced by the inner layers decreases. If the outer layer is twisted, the field angle at outer layer decreases, and the critical current increases. As a result, the variation rate becomes positive. Thus,  $I_c$  vs.  $\theta_{max}$  property  $B_{ext} = 0$  is not simply determined only by the  $J_{cLon}(B)$ . In sample C, although  $a$  is not large,  $b$  is not large. Thus, the variation rate is not positive in sample C.

In a practical cable the optimal structure must be sought under the avail magnetic field  $B_{ext}$ .



**Figure 3.** The Fig. 2c dependence with interpolating lines for low magnetic field. The parameters  $a$  and  $b$ , the increments of  $\Delta J_c/\Delta B$  of parallel and normal application of magnetic field will be modified.



**Figure 4.** Influence of the inclination of the dependence  $J_c(B)$  (parameters  $a$  and  $b$ ) for the efficiency of the cable with reduced Lorentz force.

## 5. Conclusion

In the present work the new design of HTS cable is investigated. It is demonstrated that  $I_c$  of the cable gradually increases with increasing layer number and external magnetic field, and takes a maximum at some external magnetic field. It was found that the characteristics of a cable made with superconducting tape with  $J_c$  that increases with parallel magnetic field are not good under the condition of  $B_{ext} = 0$ . It was shown that the difference of  $J_c$  between parallel and normal magnetic fields must be sufficiently large to get good characteristics of current-carrying capacity. In the next investigation the optimum condition including the axial magnetic field  $B_{ext}$  must be sought.

## 6. Acknowledgements

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