Critical current measurement for design of HTS DC power cables

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Abstract. Critical currents of HTS DC power cables were calculated. In the calculation a relationship between critical current density and magnetic flux density proposed by Gömöry et al. [1] was used and the parameters used in the relationship were obtained by the critical current measurements with respect to the external magnetic field for a sample of the HTS tape. Numerical models of cables were composed and their critical currents were calculated, which showed the strong dependence on the arrangement of the HTS tapes in the cable. Critical current measurements of model cables assembled based on the calculations showed that the measured critical currents also depended on the arrangement of the HTS tapes strongly. The calculated results were compared with the experimental results, which showed that the experimental results agreed well with the calculated results.

1. Introduction
Superconducting direct current (DC) power transmission can reduce the loss of transmission by the use of the superconductivity of zero electric resistance. It has been developed around the world and, recently, has been used for actual transmission and distribution systems [2, 3, 4, 5]. High temperature superconducting (HTS) DC power cables with higher critical current are demanded to reduce the cost of the transmission systems, in particular, for a long distance. We have studied the arrangements of the HTS tapes in cables to improve their critical current characteristics [6, 7]. It was found that the critical current could be significantly increased by adjusting the magnetic field around the cables by making small gaps between the HTS tapes in the cables.

The critical currents of cables with gaps between HTS tapes were calculated in this study. Since the magnetic field around an HTS tape affects the critical current of the HTS tape, the relationship between these have to be known. The formula proposed by Gömöry et al. [1] was adopted to reveal this relationship in this study, which was a phenomenological relationship between the magnetic flux density and the critical current density of an HTS tape based on the Kim formula [8] expressing the magnetic field dependence of the critical current density. The four parameters are used in the formula proposed by Gömöry et al. [1], which were also obtained based on the method proposed by Gömöry et al. [9]. The critical currents of a single HTS tape were measured with respect to the magnetic field applied externally to the HTS tape from different directions. The four parameters were determined so that the calculated results agreed with the experimental results in an iterative procedure. Numerical models of cables with different gap width between the HTS tapes were composed and their critical currents were
calculated. Model cables were assembled based on the numerical models and the critical currents were measured. By the comparison between the calculated and measured results the calculation procedure to design HTS DC power cables was evaluated.

2. Calculation method
The critical current of an HTS tape is calculated by an iterative procedure in the program based on the method proposed by Gömöry et al. [1]. In the program, a model of an HTS tape is divided into small elements as shown in Fig. 1. It is supposed that the critical current density along an element depends on the magnetic flux density at the element. The magnetic flux density is calculated by the Biot-Savart law. The magnetic flux density at the element $j$ produced by the current at the element $i$ is written as

$$dB_{i,j} = \mu j_{ci} dxdy / 2\pi r_{i,j}$$

where $\mu$ is the magnetic permeability, $j_{ci}$ is the critical current density at the element $i$, $r_{i,j}$ is the distance from the element $i$ to the element $j$, and $dx$ and $dy$ are the width and the height of the element. The magnetic flux density at the element $j$ is the sum of $dB_{i,j}$ over all the elements and can be written as

$$B_j = \sum_i dB_{i,j}$$

The relationship between the critical current density and the magnetic flux density is required to close the loop for iteration. Here, a phenomenological expression between the critical current density and the magnetic flux density proposed by Gömöry et al. [1] is adopted, which is

$$j_{cj} = j_{c0} / \left(1 + \sqrt{k^2 B_{\parallel j}^2 + B_{\perp j}^2 / B_0}\right)^{\beta}$$

where $j_{cj}$ is the critical current density at the element $j$, $B_{\parallel j}$ and $B_{\perp j}$ are the parallel and perpendicular components of $B_j$ with respect to the HTS tape surface, respectively, and the four parameters of $j_{c0}$, $k$, $B_0$ and $\beta$ are the values determined from experiments. $j_{cj}$ can be obtained by iterative calculations from eq. (1) to eq. (3).

3. Critical current against the external magnetic field
To obtain the four parameters in eq. (3) the method also proposed by Gömöry et al. [9] was followed. Critical currents of a single HTS tape, $I_{cex,i}$ were measured with respect to the magnetic flux densities and the angles of the external magnetic field. The four parameters in
eq. (3) were determined by iterative calculations so that the calculated critical currents, $I_{cc,i}$, for each data minimized

$$\Delta I_c = \frac{1}{N} \sum_{i=1}^{N} (I_{cc,i} - I_{cc,i})^2.$$  (4)

Once the four parameters are obtained for a single HTS tape, the critical current of any configurations, such as cables, can be calculated by the iterative procedure.

The sample of the HTS tape was 160 A class DI-BSCCO type HT-CA. The HTS tape was rotated around the current direction axis in a uniform magnetic field. The range of the angle was from 3 to 90° measured from the line perpendicular to the current direction on the HTS tape surface, $\theta$, as shown in Fig. 1. 90° denotes that the magnetic field was applied perpendicularly to the surface. 0° denotes that the magnetic field was applied in parallel to the surface and perpendicularly to the current direction. The range of the magnetic flux density was from 0 to 100 mT. The critical current was measured in the liquid nitrogen. The voltage difference between two positions on the HTS tape surface along the current direction was measured with respect to the applied current and the critical current was determined by the $1 \mu A/cm$ criterion. The results of the critical currents are shown in Fig. 2. From the results the four parameters were determined by the procedure explained above as; $j_{c0} = 173.3$ A/mm$^2$, $B_0 = 0.0318$ T, $k = 0$, and $\beta = 0.69533$. The calculated results based on these parameters are also shown on the figure. These parameters reproduced the experimental results quite well.

4. Numerical model of cables and calculations

Examples of the numerical model of cables are shown in Fig. 3. The size of a model HTS tape is supposed to be 4.5×0.26 mm, which corresponds to the size of the HTS area in the HTS tape used in the experiments, and the node number of an HTS tape is 10×5. The model cable has two layers and each layer has six HTS tapes. The HTS tapes in the outer layer are placed between and on the tapes in the inner layer. The calculations were performed with respect to the inner layer radius ($R$) defined as the distance from the cable axis to the center of an HTS tape in the inner layer and with respect to the deviation of the outer layer radius from its minimum at which the HTS tapes in the outer layer touch those in the inner layer ($d$). The models in Fig. 3 are for the cases of $R = 4.18$ and $R = 8.08$ mm with $d = 0$ and $d = 0.5$ mm.

The currents of all the HTS tapes are supposed to flow by the same amount in the same direction. By the preliminary experiments and calculations it was found that the critical current
of the inner layer became much higher than that of the outer layer. Due to the limited number of the power supply, all the HTS tapes were connected in series and the same amount of the current was fed in them in the experiments. Therefore, in the calculations the current of the inner layer was set to the same amount with that of the outer layer and was supposed to distribute uniformly in the HTS tape in each iteration step to make the condition of the calculations the same with that of the experiments.

5. Critical current measurements of model cables
Two different model cables were assembled. The configurations of the HTS tapes of the model cables were the same as those shown in Fig. 3, which had two layers and each layer had six HTS tapes. The inner layer radii were \( R = 4.18 \) mm and \( R = 8.08 \) mm. The HTS tapes of the outer layer were attached to the HTS tapes in the inner layer like Fig. 3. The HTS tapes were the 160 A class DI-BSCCO type HT-CA, which was taken from the same lot of the HTS tape used in the experiment explained in the section 3. The size of the HTS tape was \( 4.5 \times 0.26 \) mm excluding the thicknesses of Cu laminations and Kapton tapes for insulation. Due to the Cu laminations and the Kapton tapes it was difficult to determine \( d \) precisely. All the HTS tapes were connected in series as shown schematically in Fig. 4. The voltage differences on the HTS tape surfaces along
the current direction were measured in the liquid nitrogen with respect to the applied current for some of the HTS tapes in the model cables. From the measured $I-E$ characteristics of the HTS tapes, the critical currents were obtained.

6. Results and discussions
The results of $I-E$ curves of the model cables are shown in Fig. 5 for $R = 4.18$ mm and in Fig. 6 for $R = 8.08$ mm. For $R = 4.18$ mm, the measurements were performed for two tapes in the inner layer and four tapes in the outer layer and, for $R = 8.08$ mm, performed for one tape in the inner layer and six tapes in the outer layer. Due to the precision of the assembly of the model cables, the $I-E$ curves in each layer were slightly different from each other, though they should be the same. The critical currents were determined by the $1 \mu A/cm$ criterion. As seen in the figure, the critical currents of the HTS tapes in the inner layer are larger than those in the outer layer.

The calculated results are shown in Fig. 7 together with the experimental results. The calculated results were for $d = 0, 0.5, 1$ mm. A result for the single HTS tape measured in a self-magnetic field is shown as a horizontal line in the figure, for reference. The experimental results are averages of the measured results. The calculated results become larger with the increase of
Figure 7. The calculated results for $R = 0-10$ mm and $d = 0, 0.5, 1$ mm, and the experimental results for $R = 4.18$ and $8.08$ mm are shown. A result for a single HTS tape in the self-magnetic fields also shown for reference.

$R$ and take a maximum, while they sharply decrease with the increase of $d$. The arrangement of the HTS tapes near the maximum of the critical current is almost the same as the figure for $R = 8.08$ mm in Fig. 3, in which the edges of the HTS tapes in the inner layer are wrapped by those in the outer layer.

The experimental results were also depend on the arrangement of the HTS tapes strongly. In the case of $R = 4.18$ mm, the result is even smaller than the the result obtained for the case of the single HTS tape in the self-magnetic field. By the change from $R = 4.18$ to $8.08$ mm, the critical current increased about 10%. This tendency was expected not only from the present calculations, but also the previous measurements [6, 7].

The calculated results are compared with the experimental results. For the experimental results, it is difficult to specify the $d$ value. Other than the superconducting material, there were Cu laminations with 0.05 mm thickness and Kapton tapes with approximately 0.07 mm thickness on each HTS tape. Therefore $d$ should be at least 0.24 mm. If the precision of the assembly was considered, it is probable that $d$ would be the order of 0.5 mm. If this fact is considered, it can be said that the experimental results agreed well with the calculated results and it is considered that the program for the calculation of the critical currents of the cables works well.

7. Conclusion

Computer program to calculate critical currents of cables for the HTS DC power transmission was developed. The relationship between critical current density and magnetic flux density, which was required for the program, was obtained by the formula proposed by Gömöry et al. [1]. In the equation, four parameters which should be determined by experiments were required and were obtained by the measurements of the critical currents with respect to the external magnetic field. Numerical models of the cables were composed and their critical currents were calculated, which showed the strong dependence of the calculated results on the arrangement of the HTS tapes in the cable. Based on the calculations model cables were assembled. The measured critical currents also depended on the arrangement of the HTS tapes strongly. The calculated results were compared with the experimental results. The experimental results agreed well with the calculated results, which shows that the program works well.
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