Design and evaluation of 10-kA class superconducting DC power cable based on longitudinal magnetic field effect

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Abstract. In this study, we designed a power cable based on the longitudinal magnetic field (LMF) effect using an iterative approximation method. An evaluation of the cable shows that it is more efficient than conventional-design power cables. A cable with four inner layers and four shield layers and a maximum winding angle of 30° had a current capacity of more than 10 kA. Based on calculation results, we fabricated a 2-m-long LMF power cable and a conventional-design power cable. Experimental results show that the proposed power cable can carry more current (8.8% more current per tape and 18% more current overall) than a conventional-design power cable due to the LMF effect. These results well agree with the theoretical calculation results.

1. Introduction
Superconductors are expected to be applicable to power transmission cables because their resistance is zero in the superconducting state. Conventional power transmission cables have a transmission loss of about 5%. Superconducting power cables can reduce this loss, enabling the transmission of high-capacity power. Generally, when current flows through a superconductor, a magnetic field is generated, decreasing the critical current density. Most formerly developed superconducting cables with a conventional design thus have a structure that suppresses the influence of magnetic fields. The present study proposes a superconducting cable based on the longitudinal magnetic field (LMF) effect [1-3]. In an LMF, the magnetic field and current point in nearly the same direction [4-7], which increases the critical current density [8-11]. The proposed cable consists of inner layers and shield layers. The winding angle of each layer is gradually adjusted to create a magnetic field that is parallel to the current. It is expected that the generated magnetic field can suppress the decrease in the critical current density, since the Lorentz force is suppressed [1-3].

In this study, we confirm the superiority of the LMF power cable over a conventional-design power cable. The LMF power cable is designed using an iterative approximation method. Based on the calculation results, we fabricated a 2-m-long 10-kA power cable and measured its critical current properties. The critical current properties for a conventional-design power cable were measured for comparison. The superiority of the proposed power cable is discussed.

2. Calculation Methods
In this study, we calculated the current flowing through the entire cable based on the magnetic field dependence of the critical current density (Jc-B) properties of REBCO (REBa2Cu3O7−δ, RE: rare earth)
coated tape. Both conventional-design and longitudinal magnetic field (LMF) cables with a current capacity of over 10 kA were evaluated.

The angular dependence of $J_c$ can be approximated from experimental data as [2]

$$J_c(\phi) = \frac{1}{2}(J_{cm} + J_{cm}) + \frac{1}{2}(J_{cm} - J_{cm}) \cos 2\phi,$$

where $J_{cm}$ is the critical current in an LMF for which the current and magnetic field directions are the same, $J_{cm}$ is the critical current density in the transverse configuration for which the current is normal to the magnetic field and the magnetic field is in the $ab$ plane, and $\phi$ is the angle between the current and the magnetic field directions. The critical current is given by

$$I_i = 2\pi a_i J_{ci} t,$$

where $a_i$ is the radius of the $i$-th superconducting layer from the inner side, $t$ is the thickness of the REBCO layer in the tape, and $J_{ci}$ is the critical current density for the tape. In this case, the LMF in the $i$-th layer generated by the outer layer is given by

$$B_{li} = \sum_{k=i+1}^{n} \mu_0 l_k \sin^2 \theta_k \frac{2\pi a_k \cos \theta_k}{2\pi a_i} + B_e,$$

where $\theta_k$ is the winding angle ($\theta_k = 0$ means that the long direction of the tape is along the cable axis) and $B_e$ is the LMF created by the outer shield layers. The transverse magnetic field in the $i$-th layer generated by the inner layers is given by

$$B_{li} = \sum_{k=1}^{i-1} \mu_0 l_k \cos \theta_k \frac{2\pi a_i}{2\pi a_i}.$$

The strength of the magnetic field is given by

$$B_i = (B_{li}^2 + B_{li}^2)^{1/2},$$

and the angle from the tape direction is given by

$$\phi_i = \theta_i - \tan^{-1} \frac{B_{ii}}{B_{il}}.$$
3. Experimental Methods
Based on the theoretical calculation, we designed an LMF power cable and a conventional-design power cable. For the LMF power cable, 89 YBCO (YBa$_2$Cu$_3$O$_{7−δ}$) tapes were used for the inner layers and 95 YBCO tapes were used for the shield layers. Each layer was wound at the calculated angle so that the outermost layers of both the inner and shield layers had a 30° winding angle. Table 2 shows the common specifications of the proposed LMF and conventional-design power cables.


Table 2. Common specifications of proposed LMF and conventional-design DC power cables.

| Type    | Lamination | Critical current [A] (77 K, s.f.) | Width [mm] | Thickness [mm] |
|---------|------------|-----------------------------------|------------|----------------|
| YBCO    | Copper     | > 160 [A]                         | 4.8 ± 0.1  | 0.23 ± 0.02    |

The conventional-design power cable was fabricated using the same superconducting tape with different tape angles in each layer to evaluate the performance of the LMF power cable. The angle of the layers was alternated between ±θ_{max} (i.e., S- and Z-winding in alternate layers).

For the conventional-design power cable, 82 and 87 tapes were used for the inner and shield layers, respectively. In the LMF cable, because some layers had a smaller tape winding angle than that in the conventional-design cable, more tape was needed to create the same layer. This means that the number of tapes in each layer was different. The comparison was thus based on the current value for the entire cable and the current value per tape.

Fig. 2 shows a photograph of fabricated power cable samples. The length of the superconducting part of the cable is 2.0 m and the total length of the cable including the terminals is about 2.6 m. A DC current was applied through the terminals and the total current and voltage were measured. Here, the voltage taps were located directly on the superconducting tape just inside the metal connectors to avoid the influence of the normal conductors. For both types of cable, we measured the critical current using the 4-probe method, where the current flows (i) through only the inner layers and (ii) through the inner and shield layers in series.

Figure 2. Photograph of power cable samples. Upper is the conventional-design power cable and lower is the LMF power cable.

4. Results and discussion

Fig. 3(a) shows the θ_{max} dependence of the total current I. The total current is higher than 10 kA at θ_{max} = 0°. Here, the former diameter is 35 mm. The cable has three inner layers and three shield layers.
Figure 3. $\theta_{\text{max}}$ dependence of total current for (a) 3 layers in inner and shield layers, and (b) 4 layers in inner and shield layers.

In Fig. 3, the solid and dashed lines are the critical current for the LMF power cable and the conventional-design power cable, respectively. At 0°, the current values are the same because there is no structural difference between the two types of power cables. As the maximum angle increases, an LMF effect appears, and thus the current for the LMF power cable is larger than that for the conventional-design power cable. In the conventional-design power cable, the critical current is decreased by the effect of the self-magnetic field. In the LMF power cable, although the total current decreases, the decrease is suppressed by the LMF effect. The LMF cable thus outperforms the conventional-design power cable. For the conventional-design power cable, the total current decreases slowly up to about 20° and then decreases almost linearly towards 0 A. For the LMF power cable, the decrease is more gradual than that for the conventional-design power cable up to around 30°, and is almost linear above 30°. The rate of decrease is smaller than that for the conventional-design power cable. In other words, the rate of increase of the total current for the LMF power cable compared to that for the conventional-design power cable increases with increasing angle. The current for the LMF power cable is about 18% higher than that for the conventional-design power cable at an angle of about 30°, at which the cable is easy to bend. Because the total current is less than 10 kA at 30° for the case of three inner layers and three shield layers, a higher total current is required.

To achieve a total current higher than 10 kA at 30°, the numbers of inner layers and shield layers were increased. Fig. 3(b) shows the results of the calculation for a cable with four inner layers and four shield layers. The current for the LMF power cable is about 19% higher than that for the conventional-design cable. This increase is higher than that for the cables with three inner layers and three shield layers, which shows that the LMF effect is stronger for a higher number of layers. The increase in the current in the shield layers is considered to be due to a stronger LMF, and thus the difference in the total current between the two types of power cables increases.

Based on these calculations, 10-kA class 2-m-long LMF and the conventional-design power cables with four inner layers and four shield layers were fabricated and their total current was measured. Table 3 shows the experimental and theoretical results of $I_c$ for the inner layers.
Table 3. Comparison of experimental and theoretical results for $I_{c}$ in inner layers.

| Cable type                  | Measurement type               | Experiment $I_{c}$ [A] | $I_{c}$ per tape [A] | Theoretical calculation $I_{c}$ [A] | $I_{c}$ per tape [A] |
|-----------------------------|--------------------------------|------------------------|----------------------|------------------------------------|----------------------|
| LMF power cable             | Only inner layers              | 12799                  | 143.8                | 13057                              | 146.7                |
|                             | Inner and shield layers in     |                        |                      |                                    |                      |
|                             | series connection              |                        |                      |                                    |                      |
| Conventional design power   | Only inner layers              | 11251                  | 137.2                | 11110                              | 135.5                |
| cable                       | Inner and shield layers in     |                        |                      |                                    |                      |
|                             | series connection              | 11139                  | 135.8                | 11110                              | 135.5                |

The experimental results for both types of power cables are similar to the theoretical results, indicating the validity of this experiment and the design of the power cables. The difference in $I_{c}$ per tape between the experiments and theoretical calculation is less than 2%. For the LMF power cable, the currents per tape for only the inner layers and the inner and shield layers in series are 143.8 and 147.7 A, respectively. The cable with the inner and shield layers has about 2.7% higher current per tape than the cable with only the inner layers. The shield layers produce the LMF effect, which increases the current flowing in the inner layers. The current in the cable with the inner and shield layers is about 1.2% smaller than that in the cable with only the inner layers for the conventional-design power cable. The $I_{c}$ values per tape are 137.2 and 135.8 A, respectively. This decrease indicates that the magnetic field in the shield layers affects the inner layers and thus decreases the critical current density. The current in the LMF power cable is 147.7 A per tape and that in the conventional-design power cable is 135.8 A per tape. The current in the LMF power cable is thus about 8.8% higher. In terms of the total current in the entire cable, the current for the LMF power cable is about 18% higher than that for the conventional-design power cable. These experimental results are consistent with the theoretical results.

In order to fabricate a cable with better performance, a higher current flow is required. Thinner superconducting layers lead to a higher LMF effect and higher $I_{c}$ [12]. Since the power cable operates in a low magnetic field, superconducting tape does not require artificial pinning centers for high-magnetic-field applications. Artificial pinning centers disturb uniform current flow and thus suppress the LMF effect. Therefore, superconducting tape suitable for the LMF effect is desired for a high-performance cable because it will increase the total $I_{c}$.

5. Conclusion
In this study, we compared the current properties of an LMF power cable and a conventional-design power cable using calculations and experiments. The theoretical results show that the cable with the LMF effect carries higher current than the conventional-design power cable with a four-layer structure and an outmost winding angle of 30°. The experimental results show that the LMF power cable can carry 8.8% more current per tape and 18% more current overall compared to the conventional-design power cable. The experimental results agree well with the theoretical calculations. Thinner tape allows more current to flow and increases $I_{c}$.

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