The influence of winding direction of two-layer HTS DC cable on the critical current

V S Vyatkin¹, K Kashiwagi², Y V Ivanov¹, E S Otabe² and S Yamaguchi¹
¹Chubu University, Japan, ²Kyushu Institute of Technology, Japan

(vyatkin@isc.chubu.ac.jp)

Abstract. The design of twist pitch and direction of winding in multilayer HTS coaxial cable is important. For HTS AC transmitting cables, the main condition of twist pitch is the balance of inductances of each layer for providing the current balance between layers. In this work, the finite element method analysis for the coaxial cables with both same and opposite directions winding is used to calculate magnetic field distribution, and critical current of the cable is estimated. It was found that the critical current of the cable with same direction winding is about 10 percent higher than that in the case of the cable with the opposite direction winding.

1. Introduction
Optimization of coaxial cable winding is necessary for HTS cable designing. For example, the force-free configuration of DC coaxial cable [1, 2] enhances the current-carrying capacity. However, the inductance of different layers is not the same. The same inductance of layers is important to provide the same transport current in each layer for AC cables. In conventional coaxial two-layer cable, each layer has different winding directions [3]. However, it is considered that the perpendicular (c-axis) component of magnetic field to the superconducting tape is large in the opposite winding direction, resulting in low critical current property due to the large perpendicular component of magnetic field. Therefore, same winding direction in two-layer cable is considered to be suitable to reduce the perpendicular component of magnetic field and critical current of the cable will be improved.

In the present work, the two-layer HTS cable with same and opposite winding directions in each layer for providing the same layer inductance are used, and the magnetic field distribution around the cable is calculated by finite element method (FEM). The advantageous and disadvantageous of same and opposite directions of winding from the view point of the current carrying capacity of the cable are discussed. The same direction winding provides also longitudinal magnetic field effect. However, it is possible to obtain increasing of the critical current without using the longitudinal magnetic field effect, when critical current of HTS tape higher in the parallel magnetic field. Therefore, this work uses only perpendicular magnetic field dependence of critical current, and the longitudinal magnetic field effect is omitted.

2. Calculation model
The model for calculating the magnetic field distribution and current carrying capacity was the coaxial two-layer cable which inner layer radius was 12 mm and outer layer radius was 13 mm. The specification of parameters of the cables given in the Table 1.
Table 1. The specification of the samples for calculation.

| Sample of HTS cable          | Number of HTS tapes of inner/outer wire | Diameter of inner/outer layer, [mm] | Twist pitch of inner/outer layer, [mm] |
|------------------------------|----------------------------------------|------------------------------------|----------------------------------------|
| Same direction winding       | 12/12                                  | 12/13                              | 100/100                                |
| Opposite direction winding   | 12/12                                  | 12/13                              | 100/100                                |

The calculation performed with program JMAG [4] for finite element method analysis. The layers are not connected electrically and wound in the same or opposite directions. The cross section is shown in figure 1. The twist pitch of the superconducting tape layer is 100 mm, and $z$-axis is the longitudinal direction of the cable as shown in figures 2 and 3.

The value of magnetic field at the tape surface determines the value of critical current. First, it is necessary to calculate the value of magnetic field acting on the tape surface when the transport current flow to the both layers in case of same and opposite winding directions.

![Opposite direction Model](image1.png) ![Same direction Model](image2.png)

**Figure 1.** The cross section of two-layer cable with winding on the opposite and same directions.

![Image 3](image3.png) ![Image 4](image4.png)

**Figure 2.** The calculation model with opposite direction winding (left) and same direction winding (right).

Figure 4 shows the calculated result of position dependence of perpendicular ($c$-axis) component of magnetic field to the tape surface for the cases when superconducting tape layers wound in the same and opposite directions. It is found that the value of perpendicular component of magnetic field is less in the case of superconducting tape layers wound in the same direction. It means that the value of critical current is higher for the case of same winding direction.
For the case when the winding performs in opposite direction, the value of magnetic field on the surface of HTS tape changes as a function of $z$-axis, and it takes minimum value as same as the case of the same direction winding at $z = 6.25$ mm. The value of magnetic field takes maximum value and is two times larger than that in the minimum case.

Figure 5 shows the position dependence of perpendicular ($c$-axis) component of magnetic field for various position of cable cross section for the case of opposite direction winding. The curve $0^\circ$ corresponds the cross section when the tapes of different layer touches each other as shown in figure 3 at $z = 0$ mm. The curve $7.5^\circ$ corresponds position $z = 6.25$ mm in figure 3. $360^\circ$ is corresponds to position of $z = 100$ mm. It is found that the position dependence of magnetic field changes periodically with the angle of $7.5^\circ$.

It is necessary to calculate the value of critical current in two-layer cable in case of winding in the same and opposite directions. For the case of winding in the same direction the distribution of magnetic field along the $z$-axis is homogeneous. The value of critical current is possible to determine through the average voltage on the cable according criterion of electrical field in the cable, $E_0 = 10^{-4} \text{ V/m}$.

The perpendicular magnetic field dependence of critical current density of the YBCO tape from the data of reference [5] and approximation function are shown in figure 6.

The critical current of straight tape in two-layer cable with winding in the same direction is possible to calculate from the figure 4 (lower curve, corresponding same direction winding) and figure 6. The distribution of normalized critical current in the width $J(B(x))$ is shown in figure 7 (upper curve). The important parameter is the average value of critical current density, and is 0.938. It means that the value of critical current is 0.938 from the maximum value in case of absence of magnetic field acting on the tapes.

The measurement of critical current of single tape and the cable with same length can give the different results because the length of the tape of the cable is longer compare with the straight tape. In our case, the cable is inclined with angle $\phi = 37^\circ$ (because twist pitch = 100 mm, circle length = $2 \cdot \pi \cdot R = 2 \cdot \pi \cdot 12$ mm = 75 mm). The length of tape for 1 m of the cable will be $\frac{1}{\tan(\phi)} = 1.327$ m.
The voltage on the cable for 1 m is $V = E_0 \left( \frac{I}{I_c} \right)^n$, where $I$ is transport current, $I_c$ is critical current which is determined when the electric field of the cable becomes $E_0 = 10^{-4}$ V/m, the coefficient $n$-value is $n = 10$ to $20$, respectively. The length of the cable increases $\frac{1}{\tan(\varphi)} = 1.327$ times. This is equal to the ratio of length of tape in the cable $l_{\text{tape in cable}}$ and that of single tape $l_{\text{tape alone}}$, $l_{\text{tape in cable}} \over l_{\text{tape alone}}$. Then the voltage taking into account the changing of length is

$$V = \frac{l_{\text{tape in cable}}}{l_{\text{tape alone}}} \cdot V_0 \left( \frac{I}{I_c} \right)^n,$$

(1)
where $V_0$ is the voltage for the case that tape length is cable length without twisting. The length of tapes is larger for the case of twisting, and the voltage is larger. To obtain the same voltage $V = V_0$, it is necessary to decrease current. In this case, the value of critical current of the cable in case of longer tape is:

$$I_{c\text{ cable}} = I_{c0} \cdot \sqrt[n]{\frac{I_{\text{tape in alone}}}{I_{\text{tape cable}}}} = I_{c0} \sqrt[n]{\cos \varphi} = I_{c0} \cdot \frac{10^{-20}}{0.8} = 0.98 \div 0.99 I_{c0}. \tag{2}$$

Therefore, there is no difference between single tape and cable from point of view critical current measurement in longer tape.

For the case of cable wounded in the opposite directions, the situation is more complicated, since the magnetic field along the tape is not homogeneous and there exists the underloaded and overloaded areas. Therefore, for simplicity, the current is assumed to flow parallel each other and total voltage of the tape can be obtained from the integral of voltage drop. Then, critical current is determined at the electric field reaches to the electric field criterion, $E_0 = 10^{-4}$ V/m. The total voltage is given by

$$V(x) = \int_{x=0}^{x=1000\text{mm}} \left( \frac{I(x)}{I_c(x, z)} \right)^n u_0 \cdot dz = V_0. \tag{3}$$

The value of local critical current depends on the coordinates from the edge of the tape ($x$) and coordinate of cross section ($z$). For each value of $x$ the voltage $V(x)$ was calculated and the transport current of each $x$ was taken to obtain the value $V(x) = V_0$.

The dependence of transport current as a function of $x$ is shown in figure 7 (lower curve). This is the position distribution of critical current in the tape. The average value of critical current is 0.854. It is about 10% less than for the case of same direction winding. Although the effects of longitudinal magnetic field are not taken into account, this effect make the profit of same direction winding.

It is possible to conclude that the same direction winding is more profitable from the view point of the critical current, since the perpendicular component of magnetic field is smaller in the case of same direction winding.

3. Conclusion

In the present study, the comparison of the critical current of same and opposite direction winding of two-layer cable with same twist pitch was performed. The calculation of the magnetic field distribution was made with finite element method. First, the distribution of magnetic field on the HTS tape was calculated. And then, the critical current was calculated in both cases. It is found that the same direction winding is at least 10% better than opposite direction winding for critical current of the cable. The future research will concern the experimental research with this type of cable.

References
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