Overcurrent Characteristics of 1 m Long Superconducting Model Cable using YBCO Coated Conductors

H. Ueda1, X. Wang1, A. Ishiyama1, S. Mukoyama2, M. Yagi2, N. Kashima3, S. Nagaya1 and Y. Shiohara4

1. Introduction

YBCO coated conductors are expected to be used in future high-temperature superconductor applications because they have better $J_C$ characteristics at high temperatures and in high magnetic fields. In applications to power transmission cables, as shown in figure 1, a number of YBCO tapes would be assembled and wound spirally on a Cu former. The YBCO tapes and the Cu former would be connected in parallel and could be subjected to short-circuit fault currents 10 to 30 times the operating current. The fault currents would drive the YBCO tapes into the normal state and thus generate Joule heating for the duration of the fault. Therefore, in order to examine the stability and feasibility of YBCO power transmission cables, it is important to demonstrate the redistribution of the transport current and the electromagnetic coupling between the YBCO tapes and the Cu former during a short-circuit fault current. We constructed a 1 m long superconducting model cable and subjected it to an overcurrent with a peak of 31.5 kA for a duration of 2.0 s, as established by JEC (Japanese Electrotechnical Committee). We examined the redistribution of the transport current between the YBCO sample tapes and the Cu former by using Hall probes. In addition, we developed a novel computer code based on the finite element method and an equivalent circuit in order to clarify the characteristics of the redistribution of the transport current and the thermal behaviour within the cable. Finally, we designed a 10 m long cable that would reach the degradation temperature of the YBCO tape due to the fault currents.

Abstract. In applications to power transmission cables, a number of YBCO tapes would be assembled and wound spirally on a Cu former. The YBCO tapes and the Cu former would be connected in parallel and could be subjected to short-circuit fault currents 10 to 30 times the operating current. The fault currents would drive the YBCO tapes into the normal state and thus generate Joule heating for the duration of the fault. Therefore, in order to examine the stability and feasibility of YBCO power transmission cables, it is important to demonstrate the redistribution of the transport current and the electromagnetic coupling between the YBCO tapes and the Cu former during a short-circuit fault current. We constructed a 1 m long superconducting model cable and subjected it to an overcurrent with a peak of 31.5 kA for a duration of 2.0 s, as established by JEC (Japanese Electrotechnical Committee). We examined the redistribution of the transport current between the YBCO sample tapes and the Cu former by using Hall probes. In addition, we developed a novel computer code based on the finite element method and an equivalent circuit in order to clarify the characteristics of the redistribution of the transport current and the thermal behaviour within the cable. Finally, we designed a 10 m long cable that would reach the degradation temperature of the YBCO tape due to the fault currents.
and 2) parallel-connected YBCO tapes, focusing on the redistribution of the transport current caused by an overcurrent pulse [1].

In this paper, we report that 1) a 1 m long superconducting model cable was constructed; 2) an overcurrent of 31.5 kA_{rms} was applied for 2.0 s to the constructed cable in a liquid nitrogen bath and the redistribution of the transport current between the YBCO tapes and the Cu former was examined by using Hall probes; 3) numerical simulations were carried out by using a newly developed computer code based on the three-dimensional finite element method (3D FEM) and an equivalent circuit in order to clarify the characteristics of the redistribution of transport current and thermal behaviour in the cable; and 4) a 10 m long cable was designed that would reach the degradation temperature of the YBCO tape due to the fault currents.

2. Overcurrent test of 1 m long model cable

2.1. Structure of 1 m long model cable

We constructed a model cable consisting of a one-phase, 1 m long cable using YBCO tapes and performed an overcurrent test. Figure 2 shows a photograph of the cable. Table 1 shows the specifications of the YBCO tapes which were selected for the cable. The cable conductor was composed of five straight YBCO tapes wound onto a Cu former made from Cu stranded wires. The YBCO tapes were not wind spirally. This cable had no shield layer. The cross-sectional area of Cu former was designed such that the temperature did not reach 300 K (room temperature) when carrying an overcurrent of 31.5 kA_{rms} for 2.0 s. The dielectric insulation was based on lapped polypropylene laminated paper (PPLP) impregnated with liquid nitrogen (LN2). The $I_C$ of the cable was measured to be 360 A at 77 K.

2.2. Experimental results

Figure 3 shows the experimental results of the overcurrent test with a fault current of 31.5 kA_{rms} (maximum of 44.5 kA) at 60 Hz for 2.0 s. The waveforms of the currents were calculated by using the values obtained with Hall probes. As shown in figure 3(a), the peak current in the Cu former was 41 kA, and the total current through the YBCO tapes was 6 kA. Phase differences were observed among the current in the YBCO tapes, that in the Cu former and the total current. As shown in figure 3(b), we observed a delay in the temperature rises because the temperatures were measured by using Pt thermometers located over the PPLP which had a thickness of 0.25 mm on the surface of YBCO tapes and Cu former. The temperatures of the YBCO tapes and Cu former were 200 K and 250 K, respectively. From these results, it was found that the Cu former is the main source of heat during the fault event. It took 40 min to decrease the temperatures of the YBCO tapes and Cu former to 77 K. The critical current of the YBCO tapes was measured after the fault current tests and no $I_C$ degradation was observed.
### Table 1. Specifications of 1 m long model cable.

| Component       | Specification                  |
|-----------------|--------------------------------|
| Former (Cu stranded wire) | Outer diameter 14.8 mm          |
|                 | Outer diameter of each strand 2.3 mm |
|                 | Number of strands 37            |
|                 | Section area 150 mm²            |
| Spacer (PPLP)   | Outer diameter 27.8 mm          |
| YBCO tape       | Length 900 mm                   |
|                 | Width 10.0 mm                   |
|                 | Thickness of Cu stabilizer 100 μm |
|                 | Thickness of Ag stabilizer 10 μm |
|                 | Thickness of YBCO (MOCVD) 0.8 μm |
|                 | Thickness of buffer (PLD-CeO₂, IBAD-GZO) 2.0–2.4 μm |
|                 | Thickness of Hastelloy 100 μm   |
| Insulator (PPLP)| Outer diameter 45.0 mm          |

### Figure 3. Experimental results of overcurrent test.
- $I₁–I₅$ and $I_{total}$ are the currents of the YBCO tapes, the current of the Cu former and the transport current, respectively.
- $T₁–T₅$ are the temperatures of the YBCO tapes and $T_f$, that of the Cu former.

### 3. Numerical simulation

#### 3.1. Model and formulation

To model and design a superconducting cable, we developed a numerical code based on the 3D FEM and an equivalent circuit, as shown in figure 4. Each layer in the cable was formulated by using the 3D FEM to perform thermal analysis and estimate the distribution of heat. The equivalent circuit was used to represent the magnetic coupling among the Cu former, conductor layers and shield layers. The governing equations of the current distribution in the cable are as follows.

$$\nabla \cdot (\sigma \nabla \phi) = 0
$$

$$
\begin{bmatrix}
R_{cond} & 0 \\
0 & R_{shield}
\end{bmatrix}
\begin{bmatrix}
I_{cond} \\
I_{shield}
\end{bmatrix}
+ 
\begin{bmatrix}
L_{cond} & M \\
M & L_{shield}
\end{bmatrix}
\frac{d}{dt}
\begin{bmatrix}
I_{cond} \\
I_{shield}
\end{bmatrix}
+ 
\begin{bmatrix}
V_{cond} \\
V_{shield}
\end{bmatrix}
= 
\begin{bmatrix}
E_{cond} \\
0
\end{bmatrix}
$$

where, in equation (1), $\phi$ and $\sigma$ are the scalar potential and the electrical conductivity, respectively. Equation (1) was formulated by the 3D FEM. The power law, referred to as the ‘$n$-value model’, was used as an approximation of the $I–V$ relation of the YBCO tape.

In equation (2), $I_{cond}$ and $I_{shield}$ are the currents of the conductor part (consisting of the YBCO tape and Cu former) and the shield layers, respectively. $R_{cond}$ and $R_{shield}$ are contact resistances of the conductor layers and shield layers, respectively. $L_{cond}$ is a matrix consisting of the self and mutual
inductances of the conductor layers, and $L_{\text{cond}}$ is that of the shield layers. $M$ is a matrix consisting of the mutual inductance between the conductor part and shield layers. $V_{\text{cond}}$ and $V_{\text{shield}}$ are the resistive voltage drops across the conductor part and shield layers, respectively, derived from equation (1). $E_{\text{cond}}$ is the voltage drop across the conductor part.

In the thermal analysis, we consider the heat transfer of LN$_2$ on the surface of the cable.

3.2. Numerical results
The results of the numerical simulation are shown in figure 5. The waveforms of the current and temperature were reproduced. However, the currents of the YBCO tapes in the numerical simulation, as shown in figure 5(a), were lower than those measured in the experiment, as shown in figure 3(a). This reason for this may be ascribed to inaccuracies in the estimation of the impedance of the cable, including the contact resistance and inductance.

The developed numerical code is useful in the thermal design of the superconducting cable such as in estimating the required thickness of the Cu stabilizer and the cross-sectional area of the Cu former.

Figure 4. Numerical model for calculation of current distribution.

Figure 5. Numerical results of overcurrent test. $I_1$–$I_5$, $I_f$ and $I_{\text{total}}$ are the currents of the YBCO tapes, the current of Cu-former and the transport current, respectively. $T_1$–$T_5$ are the temperatures of the YBCO tapes and $T_f$ that of the Cu-former.
4. Thermal stability of 10 m long model cable against overcurrent

We focus on the thermal stability of the cable, particularly that of the Cu former and the shield layer, by using the developed numerical code. Table 2 shows the specifications of a 10 m long model cable that would reach the degradation temperature of the YBCO tape due to fault currents of 31.5 kA_{rms} applied for durations of 2.0 s. The dielectric insulation is based on lapped PPLP impregnated with LN2.

**Table 2. Specifications of 10 m long model cable.**

| Component          | Specifications                                      |
|--------------------|-----------------------------------------------------|
| Cu former          | 19 mm\(\phi\), 200 mm\(^2\)                       |
| HTS conductor layer| 2 layers, 5 tapes/layer, YBCO tape with Cu stabilizer of 0.1 mm\(^1\) soldered, spiral |
| Cu conductor layer | 0.2 mm\(^1\)                                       |
| Insulator          | PPLP 6.5mm\(^1\)                                   |
| HTS shield layer   | 1 layer, 10 tapes, YBCO tape with Cu stabilizer of 0.1 mm\(^1\) soldered, spiral |
| Cu shield layer    | 0.8 mm\(^1\)                                       |

**4.1. Cu former and Cu stabilizer**

The electrical insulation between the conductor part and shield layers also acts as thermal insulation. Under fault conditions, the current will be transferred to the Cu former and the temperature increase will be mitigated by the thermal inertia of the Cu former. Thus, the cross-sectional area of Cu former must be determined in the cryogenic design. Figure 6 shows the relationship between the cross-sectional area of the Cu former and the maximum temperature for an overcurrent of 31.5 kA_{rms} applied for 2.0 s. As the number of YBCO tapes increases, the soldered Cu stabilizer must increase, and as a result, we can reduce the cross-sectional area of the Cu former. With 10 YBCO tapes forming the conductor layer and the cross-sectional area of Cu former set to 200 mm\(^2\), the temperature rises to 140 K.

**Figure 6. Cross-sectional area of Cu former vs. maximum temperature.**

**4.2. Shield layer**

The shield layer consists of YBCO tapes for normal operation and a Cu layer for short-circuit events. The currents in the shield layer and in the conductor layer are equal in magnitude but opposite in direction. As a consequence, the cable will not generate any significant external magnetic field and will demonstrate very low impedance. The Cu shield layer is wrapped over the superconducting shield to reduce the temperature rise in the shield conductor under fault-current conditions. Figure 7 shows the numerical results of the currents of the conductor part and shield layer for an overcurrent of 31.5 kA_{rms} applied for 2.0 s. The current in the shield layer has the same magnitude as that in the conductor part but is in the opposite direction, as shown in figure 7(a). As time advances, the current in the shield layer decreases because of the temperature rise, as shown in figure 7(b). The temperatures of the conductor and shield are shown in figure 8. We calculated the temperature for different thicknesses of the Cu shield layer. In a previous study, we performed preliminary experiments on the damage caused by overcurrent pulse drives, focusing on the limitation of the temperature rise without degradation; in that study, the first signs of degradation in the YBCO tapes were observed at around 600 K [2].
Therefore, a Cu shield layer with a thickness of 0.8 mm or greater is required to prevent degradation of the YBCO tapes.

![Current traces of conductor and shield while carrying an overcurrent.](image1)

**Figure 7.** Current traces of conductor and shield while carrying an overcurrent.

![Temperatures of conductor and shield while carrying an overcurrent.](image2)

**Figure 8.** Temperatures of conductor and shield while carrying an overcurrent.

Thickness of Cu layer in shield is (a) 0.4 mm and (b) 0.8 mm.

5. **Conclusion**
A 1 m long superconducting model cable was constructed. An overcurrent with a peak of 31.5 kA_{rms} and duration of 2.0 s was applied to this cable in a LN₂ bath, and the redistribution of the transport current between the YBCO tapes and the Cu former was examined by using Hall probes. Numerical simulations were carried out by using a newly developed computer code based on the finite element method and an equivalent circuit in order to clarify the characteristics of the redistribution of the transport current as well as the thermal behaviour within the cable. Finally, a Cu former and shield layer for a 10 m long model cable were designed to withstand an overcurrent of 31.5 kA_{rms} for 2.0 s.

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