AC loss characteristics of RE-123 superconducting cable

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Abstract. High temperature superconducting (HTS) cables with RE-123 coated conductors are expected to lower AC loss compared to that with BSCCO cable. Sumitomo Electric Industries, Ltd. (SEI) has been developing not only BSCCO wires but also RE-123 coated conductors. Recently, SEI has developed a RE-123 coated conductor with a new type of textured metal substrate (Clad-type). The clad-type substrate has lower magnetization loss and higher mechanical strength compared with a nickel alloy substrate. To clarify the potential of this novel substrate for AC cable application, a 2-layer cable conductor was manufactured. It shows good AC loss characteristics, and the measured AC loss was less than 0.1 W/m at 1 kArms and 60 Hz. The influence of the magnetism of the clad-type substrate on AC loss in the cable conductor is much smaller than that of nickel alloy substrate. The novel coated conductor with clad-type substrate is suitable for AC cable application.

1. Introduction

High temperature superconducting (HTS) cables achieve large power capacity and low-loss power transmission in a compact size, and have economical and environmental-friendly advantages such as energy saving, resource conservation, carbon-dioxide reduction and electromagnetic interference (EMI)-free performance. Due to these advantages, HTS cable demonstration projects and practical application studies are underway around the world [1]-[3].

There are two types of HTS wires, silver-sheathed Bi-2223 wires and RE-123 (RE = rare earth element) coated conductors. At present, Bi-2223 wires have reached to the mass production stage and have been put into commercial use through the world. On the other hand, RE-123 coated conductors are still at the research and development stage because of difficulties associated with their mass production technologies. However, it has advantages for HTS cable application. AC loss in RE-123 coated conductors subjected to a parallel magnetic field is extremely smaller compared with that in Bi-2223 wires because of the thin-film structure of the RE-123 superconducting layer.

Sumitomo Electric has been developing RE-123 coated conductors on textured metal substrates using a reel-to-reel pulsed laser deposition (PLD) system [4]-[6]. Recently, a 200-m-class RE-123 coated conductor was successfully fabricated [7]. A 10-m three-cores-in-one-cryostat type (“3-in-One”) HTS cable with the RE-123 coated conductors was manufactured and its over-current characteristics were inspected [8]. The basic structure of a “3-in-One” HTS cable is shown in Figure 1. A conducting layer is composed of RE-123 wires, which are wound onto a stranded copper wire former. The electrical insulation is composed of polypropylene laminated paper (PPLP) which is
Impregnated with liquid nitrogen. RE-123 wires are also used to form a shielding layer over the electrical insulation. Copper tapes are wrapped on the superconducting shield to reduce the temperature rise of the shield conductor under over-current conditions. The three cable cores are stranded, and inserted into a cryostat made of co-axial stainless steel corrugated pipes with thermal insulation. The space between the two corrugated pipes is evacuated and maintained in a vacuum state in order to reduce heat invasion from the surroundings into the low-temperature part of the cable. The space between the outside of the three cable cores and the inside of the cryostat is filled with liquid nitrogen. No Ic degradation was observed after exposure to over-currents with a maximum current of 31.5 kArms for 2 sec (120 cycles), which meets the requirements for 66 - 77 kV class power cables in Japan. However, since a textured Ni-alloy was used as the substrate, a hysteretic loss in the substrate increases the AC loss of the HTS cable. Furthermore, the magnetism of the substrate influences the AC loss generation in its superconducting layer.

Recently, Sumitomo Electric has developed a RE-123 coated conductor with a new type of textured metal substrate (Clad-type). The clad-type substrate has lower magnetization loss and higher mechanical strength compared with the Ni-alloy substrate. To clarify the potential of this novel substrate for AC cable application, we experimentally studied the AC loss characteristics of a cable conductor with RE-123 coated conductors with clad-type substrates.

Figure 1. Basic structure of “3-in-One” HTS cable.

2. RE-123 coated conductors

The developed RE-123 coated conductor (CC) is composed of a textured metal substrate, a buffer layer, a superconducting layer, and a stabilizing layer in ascending order, as shown in figure 2. In this paper, two types of CC wires (CC1 and CC2) were used. The specifications are listed in table 1.

CC1 was composed of a 100-μm-thick clad-type substrate and a GdBa2Cu3Cux (Gd-123) superconducting layer. A 10-mm wide tape was cut into 2-mm wide strips, and each strip was coated with 10-μm-thick copper by electroplating. CC2 was composed of a 90-μm-thick Ni-alloy substrate and a HoBa2Cu3Cux (Ho-123) superconducting layer. A 10-mm wide tape was cut into 4-mm wide strips, and each strip was also coated with 10-μm-thick copper by electroplating.

Figure 3 shows the measured magnetization of the clad-type and Ni-alloy substrates at 77.3 K. Table 2 shows the comparison of properties between the two substrates. Here, the magnetization losses were calculated from figure 3. The magnetization of the clad-type substrate as well as its hysteresis was much smaller than that of the Ni-alloy substrate. This result shows that the clad-type substrate is suitable for use in AC cable application.
Figure 2. Structure of RE-123 coated conductor.

Table 1. Specifications of RE-123 coated conductors.

| Name of coated conductor | CC1 (Clad-type)                  | CC2 (Ni-alloy)                  |
|--------------------------|---------------------------------|---------------------------------|
| Substrate                | Clad-type textured metal (100 μm) | Ni-alloy textured metal (90 μm) |
| Buffer layers            | CeO₂ / YSZ / CeO₂               | CeO₂ / YSZ / CeO₂               |
| Superconducting layer    | GdBCO                           | HoBCO                           |
| Protective layers        | Ag (DC sputting)                | Ag (DC sputting)                |
|                          | Cu (Electroplating)             | Cu (Electroplating)             |
| Width of conductor       | 2 mm                            | 4 mm                            |
| Thickness of conductor   | 150 μm                          | 150 μm                          |
| Critical current         | 46 – 52 A                       | 40 – 60 A                       |

Figure 3. Measured magnetization curves of clad-type and Ni-alloy substrates.
Table 2. Magnetization loss and mechanical strength of substrate.

| Name of substrate | Clad-type | Ni-alloy |
|-------------------|-----------|----------|
| Magnetization loss (Jm⁻³) | 52 | 1300 |
| Strength (MPa) | 500 | 200 |

3. Cable conductor configurations

To clarify the potential of this novel substrate for AC cable application, 2-layer cable conductors were manufactured. CC wires were assembled spirally on a FRP former with the superconducting layer side outwards. Specifications of two cable conductors are listed in table 3. C-1 is a 2-layer cable conductor with CC1 (Clad-type), and C-2 is that with CC2 (Ni-alloy). Figure 4 shows the measured I-V curves of the cable conductors at 77.3 K. The measured critical current value of C-1 and C-2 were 2440 A and 1340 A, respectively, which nearly matched with the estimated values from each critical current value of the CC wires.

Table 3. Specifications of cable conductors.

| Name of coated conductor | C-1 (Clad-type substrate) | C-2 (Ni-alloy substrate) |
|--------------------------|---------------------------|--------------------------|
| Diameter of FRP former   | 17.5 mm                   | 18.5 mm                  |
| HTS conductor            | CC1, 52 pcs, 2 layers     | CC2, 28 pcs, 2 layers    |
| Outer diameter           | 18.5 mm                   | 19.5 mm                  |
| Length                   | 1.5 m                     | 1.0 m                    |
| Critical current         | 2440 A                    | 1340 A                   |

Figure 4. Measured I-V curves of cable conductors.
4. AC loss measurement results

The AC current was supplied to the cable conductor, and the voltage between two voltage taps attached to the cable conductor was measured. Then, AC loss per unit length of the cable conductor was obtained as

\[ Q = \frac{I_t V_t}{d}, \]  

where \( d \) is the distance between the voltage taps; \( I_t \) is the root-mean-square of the transport current; \( V_t \) is the root-mean-square of the loss component of the tap voltage obtained using a lock-in amplifier. The frequency of the transport current was 60 Hz in this experiment.

Figure 5 shows the measured AC losses of the cable conductors (C-1 and C-2). The AC loss in C-1 (clad-type) was much smaller than that in C-2 (Ni-alloy). The measured AC loss in C-1 was less than 0.1 Wm\(^{-1}\) at 1 kArms and 60 Hz.

![Figure 5. Measured AC losses in cable conductors.](image)

Figure 6 shows the transport current \( I_t \) and the measured AC loss \( Q \) normalized by the critical current \( I_c \) of each cable conductor and its square, respectively. The horizontal axis indicates the load factor \( (I_p / I_c) \), and the vertical axis indicates the normalized AC loss \( (Q / I_c^2 / f) \), where \( I_p \) (\( = \sqrt{2} I_t \)) and \( f \) is the amplitude and frequency of the transport current, respectively. In this figure, Norris’s strip values \( Q_{NS} \) for C-1 and C-2 are also plotted with dashed lines as a reference. \( Q_{NS} \) is defined as

\[ Q_{NS} = \frac{\mu_0}{N \pi} \left\{ (1 - I_p / I_c) \ln(1 - I_p / I_c) + (1 + I_p / I_c) \ln(1 + I_p / I_c) - (I_p / I_c)^2 \right\}, \]  

where \( N \) is the number of the CC wires in the cable conductor [9].

The measured AC loss is larger than \( Q_{NS} \) particularly at the low-load region. This is because the magnetization loss in the substrate increases the total AC loss in the cable conductor. The sums of \( Q_{NS} \) and the magnetization loss in the substrate \( Q_{Sub} \) for C-1 and C-2 are also plotted with solid lines in figure 6, where \( Q_{Sub} \) was calculated from the magnetization curves at various magnetic fields (for example, figure 3) in consideration of the magnetic field distribution in the cable conductor. For C-1 (Clad-type), the influence of \( Q_{Sub, C-1} \) on the total loss \( (Q_{NS, C-1} + Q_{Sub, C-1}) \) decreases with increasing
load-factor, and the measured AC loss is nearly the same as $Q_{NS,C-1}$ at the high-load region. On the other hands, for C-2 (Ni-alloy), the total AC loss is mainly governed by the magnetization loss in the substrate. In addition, the difference between the measured loss and the estimated one ($Q_{NS,C-2} + Q_{Sub,C-2}$) increases with increasing load-factor. The reason is estimated that the magnetism of Ni-alloy substrate influences the magnetic flux distribution in the coated conductor and then influences the AC loss generation in its superconducting layer. This result shows that the novel coated conductor with clad-type substrate is suitable for AC cable application.

**Figure 6.** Normalized AC losses in cable conductors.

5. **Conclusions**
Sumitomo Electric has developed a RE-123 coated conductor with a new type of textured metal substrate (Clad-type). The clad-type substrate has lower magnetization loss and higher mechanical strength compared with the nickel alloy substrate. A 2-layer cable conductor assembled with the coated conductors using the clad-type substrate shows good AC loss characteristics, and the measured AC loss was less than 0.1 Wm\(^{-1}\) at 1 kArms and 60 Hz. The influence of the magnetism of the clad-type substrate on AC loss in the cable conductor is much smaller than that of nickel alloy substrate. The novel coated conductor with clad-type substrate is suitable for AC cable application.

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