Development of Low AC Loss Windings for Superconducting Traction Transformer

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Abstract. We have been developing a light weight and high efficiency superconducting traction transformer for railway rolling stock. We designed and fabricated a prototype superconducting traction transformer of a floor-mount type for Shinkansen rolling stock in 2004. We performed the type-test, the system-test, and the vibration-test. Consequently, we could verify that the transformer satisfied the requirement almost exactly as initially planned. However, there have been raised some problems to be solved to put superconducting traction transformer into practical use such that AC loss of the superconducting tape must be lower and the capacity of the refrigerator must be larger. Especially it is the most important to reduce the AC loss of superconducting windings for lightweight and high efficiency. The AC loss must be reduced near the theoretical value of superconducting tape with multifilament. In this study, we fabricated and evaluated the Bi2223 tapes as introduced various measures to reduce the AC loss. We confirmed that the AC loss of the narrow type of Bi2223 tapes with twist of filaments is lower, and we fabricated windings of this tape for use in superconducting traction transformer.

1. Introduction
We have been developing a light weight and high efficiency superconducting traction transformer for railway rolling stock [1],[2]. We have designed and fabricated a prototype superconducting traction transformer of a floor-mount type for Shinkansen rolling stock in 2004 [3]. The transformer of a core-type design is equipped with a primary winding, four secondary-windings, and a tertiary winding. All the windings are wound of Bi2223 superconducting tapes, and cooled by sub-cooled liquid nitrogen at 66-K. The outer dimensions are approximately 1.2 m (width) x 0.7 m (depth) x 1.9 m (height) excluding the compressor. Its weight is 1.71 ton excluding those of refrigerator and compressor. We have performed the type-test, the system-test, and the vibration-test [4]. As a result, we could verify that the transformer complied with the requirement almost exactly as initially planned. However, there were some problem areas encountered to be solved to incorporate the superconducting traction transformer into practical use such that the AC loss of the superconducting tape must be lesser, and the capacity of the refrigerator must be larger. Especially it is essential to decrease the AC loss of superconducting windings for lightweight and high efficiency. The AC loss must be reduced nearly to the theoretical value of the superconducting tape with multifilament.
In this study, we fabricated and evaluated the Bi2223 tapes, which introduced various measures to reduce the AC loss, and we fabricated windings of a low AC loss Bi2223 tape for use in the superconducting traction transformer.

2. Measures to reduce AC loss
The standard technical specifications of the conventional Bi2223 superconducting tapes which were used in the superconducting traction transformer fabricated previously in 2004 are multifilament structure without having a twist and a barrier in the width approximately 4.2 mm and the thickness of approximately 0.2 mm.

We assumed the following measures to reduce the AC loss in the Bi2223 superconducting tapes:
- A) The width shall be narrow
- B) The superconducting filaments shall be twisted
- C) A barrier shall be introduced around superconducting filaments

In this study, we investigated the effect of A) and B) measures. We fabricated and evaluated many Bi2223 superconducting tape specimens of various features including dimensions of the width, thickness and aspect ratio, and structures such as a twist pitch and the number of filament were modified as evident in table 1. Figure 1 is shown examples of the superconducting tapes.

| Parameter       | Value       |
|-----------------|-------------|
| Width (mm)      | 0.9 - 4.6   |
| Thickness (mm)  | 0.11 - 1.05 |
| Aspect ratio    | 1.7 - 20    |
| Number of filament | 19, 37, 55 |
| Twist pitch (mm) | 2 - 17, ∞ |

Figure 1. Fabricated superconducting tapes.

2.1. Dimension and cross section
We measured the width and thickness of the fabricating Bi2223 superconducting tape specimens continuously with the optical-type measurement. The cross and longitudinal vertical section was visible to confirm the superconducting filament condition, and measurement of the twist pitch. Figure 2 shows the longitudinal vertical section of specimens with or without the twist of superconducting filaments.
2.2. Critical current

We measured the critical current of specimens by a four-terminal pair method in saturated liquid nitrogen at 77 K and self-magnetic field.

Figure 3 shows the characteristics of critical current density as a function of the width, thickness, and aspect ratio of the specimens. The critical current density tended to be proportional to the width and inversely proportional to the thickness of specimens. There are high critical current density specimens, such as those that are more than 10 kA/mm², when the width is more than 2 mm and the thickness is less than 0.3 mm. This tendency becomes clear when unit of the horizontal axis is the aspect ratio. The critical current density is proportional to the aspect ratio. When the aspect ratio is lower, the critical current density is also lower. When the aspect ratio became more than about 14, the critical current density became higher. Therefore, we must keep the high aspect ratio for higher critical current density.

2.3. AC loss

We measured the AC loss in fabricated Bi2223 superconducting tape specimens by magnetization method using a saddle-shaped pick-up coil in saturated liquid nitrogen at 77 K [5]. We applied an AC sinusoidal magnetic field at the frequency of 50 Hz in the parallel and the perpendicular directions to the wide surface of the superconducting tape. The magnetic field was applied to 0.2 T, which are assumable in superconducting windings at rating driving. The length of the specimens is 80 mm.

Figures 4 and 5 show the characteristics of AC loss in the parallel and perpendicular magnetic fields at the amplitude of 0.2 T. In these figures, the AC loss of the vertical axis estimated as per unit volume, per cycle and divided by critical current density. In the parallel magnetic field, the AC loss tends to decrease in proportion to thickness and is not influenced by the width. On the contrary, in the perpendicular magnetic field, the AC loss tends to decrease in proportion to width and is not influenced by the thickness. Therefore, it is effective to a narrow width and a thin thickness to reduce the AC loss.

The superconducting tape made of a narrow width and a thin thickness therefore they can be twisted in a short pitch as shown in figure 2. In such fabrication, it is possible to twist to the shortest of 2 mm pitch. There was slight decrease of the critical current density, and its reduced effect of the AC loss by superconducting filaments twisted.
Figure 3. Characteristics of critical current density as a function of (a) the width, (b) the thickness, and (c) the aspect ratio of the specimens at 77 K and self-magnetic field.

Figure 4. Characteristics of AC loss in parallel magnetic field which is 0.2 T and 50 Hz as a function of (a) the width and (b) the thickness of the specimens at 77K.
Figure 5. Characteristics of AC loss in perpendicular magnetic field which is 0.2 T and 50 Hz as a function of (a) the width and (b) the thickness of the specimens at 77K.

3. Low AC loss Bi2223 superconducting tape

Based on the results of fabrication and evaluation in Chapter 2, we developed the low AC loss Bi2223 superconducting tapes according to the practical specifications for superconducting traction transformer as shown in Table 2. There is a reduced effect for AC loss and high critical current density, furthermore, a mechanical characteristic fall is less, and an effect on windings is less.

Figure 6 shows the characteristics of AC loss of the developed low AC loss Bi2223 superconducting tape was visible in sub-cooled liquid nitrogen at 66 K and the frequency range from 0.2 Hz to 60 Hz. The AC loss of developed superconducting tape decreased less than that of a conventional type superconducting tape, which was previously applicable in 2004, since the superconducting tape became narrower, thinner, and added twist of the superconducting filaments. However, in the perpendicular magnetic field, the AC loss has remarkable frequency dependence in a region of larger amplitude of the magnetic field to compare with an equivalent penetration field [5].

Moreover, the critical current of the low AC loss type superconducting tape become lower than that of conventional type superconducting tape, since the superconducting tape became narrower and thinner.

Table 2. Specifications of low AC loss superconducting tapes (Standard value).

| Parameter                        | Conventional type | Primary and tertiary | Secondary winding |
|----------------------------------|-------------------|----------------------|-------------------|
| Width (mm)                       | 4.2               | 2.6                  | 2.3               |
| Thickness (mm)                   | 0.25              | 0.18                 | 0.18              |
| Number of filament               | 61                | 19                   | 37                |
| Twist pitch (mm)                 | -                 | 8                    | 8                 |
| Critical current (A) @77K, Self-magnetic field | 110 – 120 | 47                   | 48                |
Figure 6. Characteristics of AC loss in the (a) parallel and (b) perpendicular magnetic field of the developed low AC loss Bi2223 superconducting tape in subcooled liquid nitrogen at 66 K. The dot lines are the characteristics of AC loss of conventional type superconducting tape which is used previously in 2004.

4. Low AC loss superconducting windings for superconducting traction transformer

We designed superconducting windings for superconducting traction transformer with the low AC loss superconducting tape. Table 3 shows the technical specifications of the windings. These specifications are identical to that of transformer as fabricated previously in 2004 such as rating capacity, voltage, current, number of the turns, dimensions et.al. The windings shall be composed a number of superconducting tapes in parallel and pile to secure current capacity because the critical current of low AC loss superconducting tapes is lower than that of conventional type superconducting tape. The primary winding must be composed of three superconducting tapes in a pile from a single one. The secondary windings must be composed of twenty-four superconducting tapes. In these windings, there is a problem area attributable by the conventional winding method such that the structure becomes complicated, the increased number of the transpositions among the superconducting tapes and other pertinent factors. Therefore, we have studied on the constitution and transposition methods in every winding. In addition, we fabricated four windings of the low AC loss superconducting tape, each one of which consisted of inner secondary, tertiary, primary and outer secondary windings for one leg minute of a core-type transformer, which has two legs. Figure 7 shows the primary winding. These windings maintain about the same dimensions and specifications as that of transformer fabricated previously in 2004, and assembled in a cryostat is made of GFRP.

We measured the voltage-current curves and estimated the critical current as listed on table 4 at cooled by saturated liquid nitrogen at 77 K. The critical current of every winding is of an appropriate value as evaluated by the voltage-current curve of short specimens at 77 K. There was a problem neither in the winding structure nor in deterioration during the fabrications.

We measured the characteristics of AC loss in the case of assembled transformer by the electrical method in 60 Hz AC operation at cooled by sub-cooled liquid nitrogen at 66 K. When the inner and outer secondary windings were connected in series and the primary winding is short-circuited; the characteristic of AC loss is as shown in figure 8. We confirmed that the AC loss became lower than half of that of the transformer fabricated previously in 2004. Moreover, the secondary winding can be kept superconductivity at 750 A, which is a rated current of the design, below which there was none of extreme increase in the loss.
Table 3. Specifications of superconducting windings.

| Parameter       | Primary winding | Secondary winding | Tertiary winding |
|-----------------|-----------------|-------------------|-----------------|
|                 |                 | Inner             | Outer           |                 |
| Voltage         | 25 kV           | 1.2 kV            | 1.2 kV          | 440 V           |
| Current         | 80 A/coil       | 750 A             | 750 A           | 454.5 A/coil    |
| Number of turn  | 200 turns x 10 layers = 2,000 turns | 96 turns x 1 layer = 96 turns | 96 turns x 1 layer = 96 turns | 35 turns x 1 layer = 35 turns |
| (125 turns x 16 layers = 2,000 turns) |                 |                   |                 |
| Number of parallel | 3 piles (Single) | 12 piles x 2 parallels (8 piles) | 12 piles x 2 parallels (8 piles) | 4 piles x 2 parallels x 2 streaks (3 piles x 2 parallels) |
| Structure       | Multi-strand multi-layer solenoid coil (Single-strand multi-layer solenoid coil) | Multi-strand single-layer solenoid coil | Multi-strand single-layer solenoid coil | Multi-strand single-layer solenoid coil |

*( ) : Values of the superconducting traction transformer fabricated previously in 2004

Figure 7. Fabricated primary winding.

Figure 8. Characteristic of AC loss in the case of assembled transformer by the electrical method in 60 Hz AC operation at cooled by sub-cooled liquid nitrogen at 66 K. When the inner and outer secondary windings were connected in series and the primary winding is short-circuited.

Table 4. Critical current at cooled by saturated liquid nitrogen at 77-K.

| Winding       | Measurement (A) | Evaluated by short specimens (A) |
|---------------|-----------------|----------------------------------|
| Primary winding | 54              | 48                               |
| Secondary windings | Inner 502          | 504                                 |
|                | Outer 509         | 504                                 |
| Tertiary winding | 542              | 480                                |
5. Conclusions
We developed a low AC loss Bi2223 superconducting tape that is a narrow type with a twist of filaments, and we fabricated windings of this tape for use in superconducting traction transformer. The AC loss of these windings became lower than half of that of transformer fabricated previously in 2004; however, the AC loss of the superconducting tape must be more reduced to one-third or a quarter for practical use.

We will fabricate and evaluate the superconducting traction transformer which will be assembled using low AC loss Bi2223 superconducting windings developed in this study and a cooling system with a high capacity pulse-tube refrigerator.

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