Fabrication of Superconducting Traction Transformer for Railway Rolling Stock

H Kamijo, H Hata, H Fujimoto, A Inoue, K Nagashima, K Ikeda, H Yamada, Y Sanuki, A Tomioka, K Uwamori, S Yoshida, M Iwakuma and K Funaki

1Railway Technical Research Institute, Kokubunji-shi, Tokyo 185-8540, Japan
2Fuji Electric Systems, Shinagawa-ku, Tokyo 141-0032, Japan
3Fuji Electric Advanced Technology, Hino-shi, Tokyo 191-5802, Japan
4Taiyo Nippon Sanso, Shinagawa-ku, Tokyo 142-8558, Japan
5Kyushu University, Higashi-ku, Fukuoka 812-8581, Japan

E-mail: hiroki@rtri.or.jp

Abstract. We designed a floor type single-phase 4 MVA superconducting traction transformer for Shinkansen rolling stock. In this study, we fabricated a prototype superconducting traction transformer based on this design. This transformer of the core-type design has a primary winding, four secondary windings and a tertiary winding. The windings are wound by Bi2223 superconducting tapes and cooled by subcooled liquid nitrogen. The core is kept at room temperature. The cryostat is made of GFRP with two holes to pass core legs through. The outer dimensions are about 1.2m x 0.7m x 1.9m excluding the compressor. Its weight is 1.71t excluding that of refrigerator and compressor. The transformer was tested according to Japanese Industrial Standards (JIS)-E5007. We confirmed that the performance of transformer has been achieved almost exactly as planned. The rated capacity is equivalent to 3.5MVA in the superconducting state.

1. Introduction
We are developing a light weight and high efficiency superconducting traction transformer for railway rolling stock [1]. A traction transformer that is on-board equipment of rolling stock requires lightweight. We performed a conceptual design for optimization, fabricated and tested high-Tc superconducting coils that simulate windings, and investigated a cooling system and other components [2]. We then designed a floor type single-phase 4 MVA superconducting traction transformer for Shinkansen rolling stock [1]. In this study, we fabricated a prototype superconducting traction transformer based on this design.

2. Superconducting traction transformer
We have performed design study of 4MVA superconducting traction transformer for Shinkansen type rolling stock such as shown in Table 1 [1]. All windings are wound by Bi2223 superconducting tapes. The superconducting windings are cooled by subcooled liquid nitrogen at 66K. From the viewpoint of reducing ac loss, we have accepted core-type design. We chose the floor type at the first development stage because we expected additional problems to be cleared in order to realize an underfloor type.
The electric characteristics such as the percent impedance and reactance matrix are ensured to be the same as those of conventional transformer.

The superconducting traction transformer was optimized adopting 1-turn voltage and winding dimension as parameters. As a result, when a present Bi2223 superconducting tape is used, although the efficiency will be improved a little, the weight does not decrease because the ac loss is larger. But if ac loss of the superconducting tape is reduced to one fifth compared with the present one, the weight will be reduced, too. The weight is 2.4t and the efficiency is more than 99%. A one turn voltage is 12.5V/turn which is half that of the conventional traction transformer at this time.

**Table 1. Specifications of 4-MVA superconducting traction transformer for rolling stock.**

| Specification                  | Value                              |
|--------------------------------|------------------------------------|
| Primary winding                | 4 MVA, 25 kV, 160 A                |
| Secondary winding              | 3.6 MVA, 1.2 kV, 750 A X 4 windings |
| Tertiary winding               | 400 kVA, 440 V, 909 A              |
| Percent impedance              | Same as conventional one (Approx. 20%) |
| Reactance matrix               | Same as conventional one           |
| Test method                    | Tested by JIS-E5007 (Test Methods for Traction transformers of Railway Rolling Stock). A short circuit time at secondary windings is 0.1 second. |
| Installation place             | Upper floor                        |

3. Fabrication

We fabricated a floor type single-phase superconducting traction transformer based on the design that could lighten the weight when the ac loss of superconducting tape will be reduced.

3.1. Superconducting tape and windings

We presumed a superconducting tape of high performance in the design. Its critical current is about 130A at 77K and 210A at 66K in the self-magnetic field. At the time of the manufacturing, we were not able to get this tape. The critical current was lower and was about 110A in the self-magnetic field at 77K and the width of tape was wider than that at design. And ac loss could not be achieved to be lower. The specifications of the superconducting tape are shown in Table 2. The rate of silver is 1.6.

The superconducting traction transformer has a primary winding, four secondary windings and a tertiary winding. The primary and tertiary winding coils are placed around each of the two legs evenly and connected in parallel. Two secondary windings are placed around each of two legs. At each leg, the inner secondary winding, tertiary winding, primary winding and outer secondary winding are arranged in this order from inside to outside. The specifications of windings are shown in Table 2 [2].

3.2. Cooling system

A cryostat is made of GFRP which is non-magnetic material, and has a complicated structure because it has two holes to pass two legs of core through and eddy current loss must be avoided. It is a race track outer form and has two cylinders which are laid on to pass core legs through.

In this fabrication, the superconducting tapes could not decrease ac loss. Therefore, ac loss became larger and was anticipated to be over 6kW. It is necessary to reduce ac loss to a theoretical level. However the refrigerator of 1kW will be required for that transformer. This time we had no time to develop a lightweight 1kW refrigerator and the conventional GM type refrigerator with 200W at 80K was installed. At the tests, the windings were cooled to 66K by decompression of liquid nitrogen.

3.3. Dimension and weight

The completed superconducting transformer is shown in Fig. 1. The outer dimensions are about 1.2m (width) x 0.7m (depth) x 1.9m (height) excluding the compressor. Its weight is 1.71t excluding that of refrigerator and compressor. We assumed the weight of the 1kW refrigerator and compressor as about 0.61t. Total weight is 2.32t, almost the same as that of the design study. This weight is 20% lighter than that of conventional one. A break down of the weight is shown in Fig. 2.
**Table 2. Specifications of superconducting tape and winding**

| Tape | Primary | Secondary | Tertiary |
|------|---------|-----------|----------|
| Material | Bi2223 Ag/Mn alloy sheathed | | |
| Cross section | Within 4.5mm x 0.27mm | Within 4.3mm x 0.27mm | |
| Insulation | Polyimide tape | PVF | |
| Number of parallels | 1 | 8 piles | 2 parallels x 3 piles |
| Rated voltage | 25kV | 1.2kV | 440V |
| Rated current at design | 160A (Two coils are connected parallel) | 750A x 4 windings | 909A (Two coils are connected parallel) |
| Number of turns | 125turn x 16layer = 2000turn | 96turn x 1layer = 96turn | 35turn x 1layer = 35turn |
| Structure | Single-strand multi-layer solenoid coil | Multi-strand single-layer solenoid coil. 15 times transpositions. | Multi-strand single-layer solenoid coil. 5 times transpositions. |

4. Tests
The superconducting traction transformer was tested according to type tests of JIS-E5007 (Test Methods for Traction transformers of Railway Rolling Stock). We added test items for superconducting apparatus such as resistance measurement at 77K. A part of the items and matters were modified because the characteristics of superconducting tape were inferior to those of the design, one of the secondary winding was not wound by a new type superconducting tape and the cooling power of the refrigerator was lower.

4.1. Resistance measurement
A resistance of the windings was measured at room temperature and at 77K. The critical current of all windings was of appropriate value as evaluated by short samples from the voltage-current characteristic at 77K. There was no problem in winding structure and no deterioration during the manufacturing. Furthermore, we re-measured the voltage-current characteristic after all tests. The results were almost the same as those before the tests. The windings degradation was not found.

4.2. No load test
Four secondary windings were connected in series. The primary and tertiary windings were opened. The test was excited from secondary winding at 66K. The no load loss was 0.71kW when 25kV of rated voltage was induced in the primary winding.
4.3. Load test
The load loss of transformer with plural windings is measured by each winding and the total loss is the sum of each loss at each winding. But this method can't be applied to the superconducting transformer because the magnetic field imposed to each winding from other windings affects the loss considerably. Therefore, we performed a loss analysis together with measurement. The loss was measured by the electrical method in 60Hz ac operation at 66K.

When the inner and outer secondary windings of one leg wound by a new type superconducting tape were connected in series and the primary winding is short circuited, the loss characteristic is shown in Fig.3. We found that the maximum current keeping superconductivity for the secondary winding is 650A, below which there was no extreme increase in the loss. This value is appropriate from the performance of used superconducting tape. Increasing the current at 750A which is a rated current of the design, the loss increased greatly by a joule loss but it could be confirmed that current could be supplied for a short time. The total output of this transformer to keep superconductivity corresponds to 3.5MVA when the current of the secondary windings is 650A and the current of the tertiary winding is 909A of design rated value. Ac loss was calculated 6.2kW at 3.5MVA by analysis and the efficiency was 96.8% as shown in Table 3.

4.4. Withstand voltage test
The power-frequency withstand voltage test, induced voltage test (42kV) and impulse voltage test (150kV) were enforced when the transformer was cooled by subcooled liquid nitrogen at 66K. The transformer has cleared all the test conditions established as the JIS withstand voltage tests.

![Loss characteristic in 60Hz at 66K](image)

**Table 3. AC loss at 3.5MVA**

| Winding  | Capacity (MVA) | Current (Arms) | AC loss (kW) |
|----------|----------------|----------------|--------------|
| Primary  | 3.52           | 140.8          | 3.06         |
| Secondary| 3.12           | 650 x 4        | 2.63         |
| Tertiary | 0.40           | 909            | 0.47         |

5. Conclusions
The superconducting traction transformer has been manufactured almost exactly as planned. The outer dimensions and weight are almost equal to the design. The withstand voltage test performed successfully. The rated capacity is equivalent to 3.5MVA in the superconducting state, which is lower than the designed value, because we could not use high performance superconducting tapes that were presumed at the design stage. Ac loss has been calculated as 6.2 kW at 3.5 MVA. It is important to reduce ac losses.

References
[1] Hata H, Kamijo H and Fujimoto H 2001 *International Conference Railway Traction Systems Proceedings* 2 87
[2] Kamijo H, Hata H, Fujimoto H, Bouno T, Sakaki K, Yamada H, Iwakuma M and Funaki K 2004 *Transactions of the International Cryogenic Materials Conference-ICMC* 50B 871

Acknowledgments
The Ministry of Land, Infrastructure and Transportation funded this R&D.