The World's Largest 5 kA rms・ Extremely-Low- Loss High-Tc Yttrium(Y)-based Superconducting Power Cable

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Yttrium(Y)-based superconducting wires are expected to be adapted to the various superconducting applications. They have a high current density and show high performance in liquid nitrogen, which is much cheaper than liquid helium used for the conventional superconductors. In 1991, Fujikura succeeded in developing the key original technology to fabricate Y-based superconducting wires, which was named ion-beam-assisted deposition (IBAD) method. An 816.4 m long(L) wire with end-to-end critical current (Ic) of 572 A/cm-width at 77 K, self field (s.f.), corresponding to the world record Ic × L value of 466,981 Am/cm-width, was achieved by Fujikura. In this project, Y-based IBAD wires with high Ic=500 A class/cm-width (@77 K,s.f.) were applied to an HTS power cable for the first time in order to obtain the merits of large current capacity and extremely low loss. The current loading test of the cable proved that the measured AC loss of the cable was sufficiently less than the target value of 2 W/m/phase @5 kA rms at 77 K.

1. Introduction

Superconductivity is a phenomenon of exactly zero electrical resistance occurring below certain temperature (critical temperature: Tc), in certain materials called "superconductors" first discovered by Dutch physicist H.K.Onnes in 1911. Conventional superconductors, so-called low temperature superconductors (LTS), showed superconductivity just above the boiling point of liquid helium(4 K=−296 °C). On the other hand, several kinds of cuprate-perovskite ceramic materials discovered in 1987 showed superconductivities at unusually high critical temperatures far above the boiling point of liquid nitrogen (77 K=−196 °C). They were called high temperature superconductors (HTS).

Y-based superconducting wire was called as the second-generation HTS wire compared to the first one of Bismuth (Bi)-based superconducting wire. It has the strongest intrinsic superconducting properties among HTS materials. It was expected to show the highest current transport performances especially in magnetic field, and also high mechanical strength suitable for a wide range of applications. In 1991, Fujikura succeeded in developing a key original technology to fabricate tape-shaped Y-based superconducting wire , which was called as ion-beam-assisted deposition (IBAD) method. An 816.4 m long wire with end-to-end critical current (Ic) of 572 A/cm-width at 77 k, self field (s.f.), corresponding to the world record Ic×L value of 466,981 Am/cm, was achieved by Fujikura.

In parallel with development of high-performance Y-based superconducting wire, we have actively been developing superconducting magnet coil as another application. In 2012, we succeeded in developing " The World's Largest 5 T Y-based HTS Magnet with a 20-cm-diameter Room Temperature Bore"[1)].

As one of the most promising applications of the high Ic wires, a superconducting cable is expected to show superior performance with large current capacity and extremely low loss.

Also the superconducting power cable has some enviromental merits such as energy saving, CO_2 gas reduction and non-leakage of magnetic field. Superconducting wire has exactly zero electrical resistance for transporting direct current (DC), however, extremely small transmission loss occurs in the case of transporting alternating current (AC). AC loss depends on the ratio of operating current to critical current(Ic) of superconducting wires, hence it is expected to reduce AC loss by decreasing this ratio with using higher Ic Y-based superconducting wires. For materialization of this, an application to power cable has been studied actively as a part of the NEDO project, "Development of Y-based Superconducting Power Equipment".

In the final year (2012) of the NEDO project, Y-based IBAD wires with the world's highest Ic=500 A class/cm-width (@77 K,s.f.) were applied to an HTS power cable for the first time in order to verify the merits of large current capacity and extremely low loss, as reported in this paper.

1 Superconductor Business Development Department

2. Development of Y-based superconducting wire for practical use

2.1 Specifications of Y-based superconducting wire

The structure and photograph of Y-based superconducting wire produced by Fujikura are shown in Fig.1. Hastelloy TMC276 tapes (75 μm or 100 μm thick) are used as metal substrates. Several buffer layers, including biaxially textured layers, are deposited on the substrate by sputtering and IBAD method. A superconducting layer is deposited on the buffer layer by pulsed-laser-deposition (PLD) technique. An Ag layer is deposited on the superconducting layer by sputtering as a protection layer. In addition, a copper tape is laminated with solder on the Ag layer as a stabilizer and double polyimide tapes are wrapped as an insulation layer. A total thickness of the superconducting wire is approximately 150 – 300 μm.

Fujikura's product lineup of Y-based superconducting wire is shown in Table1. The specification of critical current (Ic) of the wire is over 500 A/cm- width at 77 K, self field (s. f.), namely 250 A/5mm- width.

2.2 Lengthening and enhancing performance of Y-based superconducting wire

Y-based superconducting material was discovered almost at the same time as other HTS materials. However, unfortunately there was difficulty to make the wire practically applicable. Since superconducting current was so easily interrupted at an interface between the crystals of superconductors, single-crystal like structures was desired along the whole length of Y-based superconducting wire. In 1991, Fujikura succeeded in developing the key original technology to fabricate tape-shaped Y-based superconducting wire, which was called as ion-beam-assisted deposition (IBAD) method [2]. By means of IBAD method, a functional thin buffer layer was deposited on the surface of polished metal tape. The crystalline axes of the buffer were biaxially controlled by irradiation with an Ar ion beam inclined at a certain degree to the substrate normal. Furthermore, Fujikura has employed PLD method to fabricate a superconducting layer on the buffer layer. In order that the performance of superconducting layer deposited by PLD method does not depend largely on the temperature, we have developed the unique large PLD system with hot-wall heating, it is called "hot-wall PLD". As a result, we have succeeded in developing fabrication of long-length superconducting layer with high performance at high rate of 40 nm/s. Fig.2 shows progress of wire development in Fujikura. In 2011, an 816.4 m long wire with end-to-end measured Ic of 572 A/cm-width was successfully fabri-

Table 1. Product lineup of typical Y-based superconducting wires.

Products	Width (mm)	Thick-ness (mm)	Sub-strate (μm)	Stabilizer (μm)	Critical Current (A) (@77K, s.f.)
YSC-SC05	5	0.16	75	75	> 250
		0.21	100	100	> 250
FYSC-SC10	10	0.16	75	75	> 500
		0.21	100	100	> 500

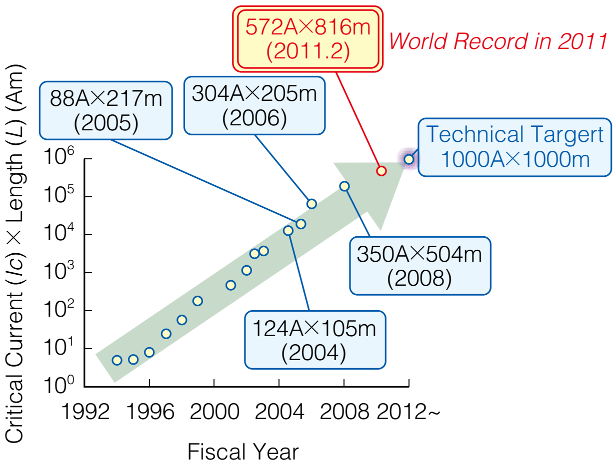

Fig. 2. Progress of I_c×L value of Y-based superconducting wires in Fujikura.

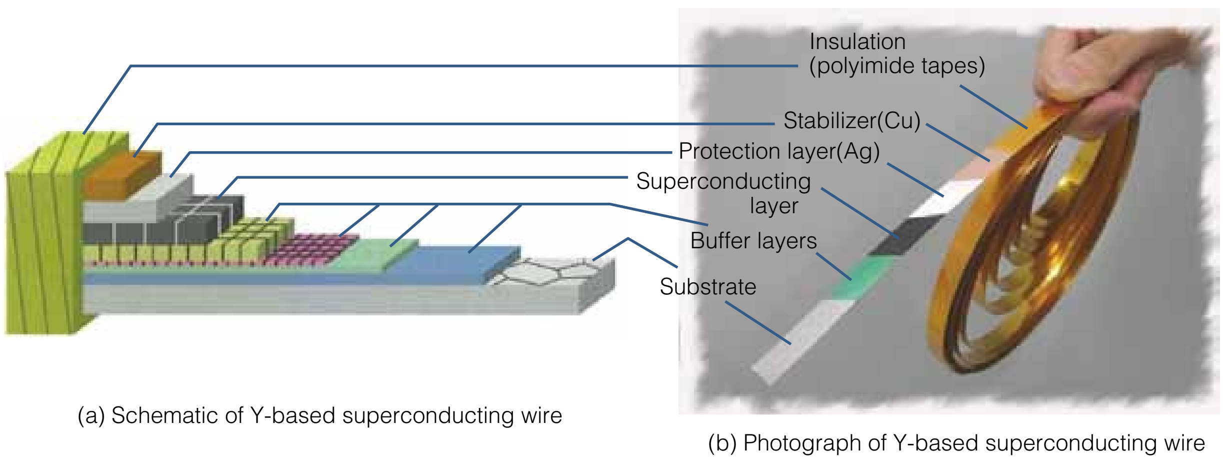

Fig. 1. Schematic of the structure and photograph of yttrium(Y)-based superconducting wires.

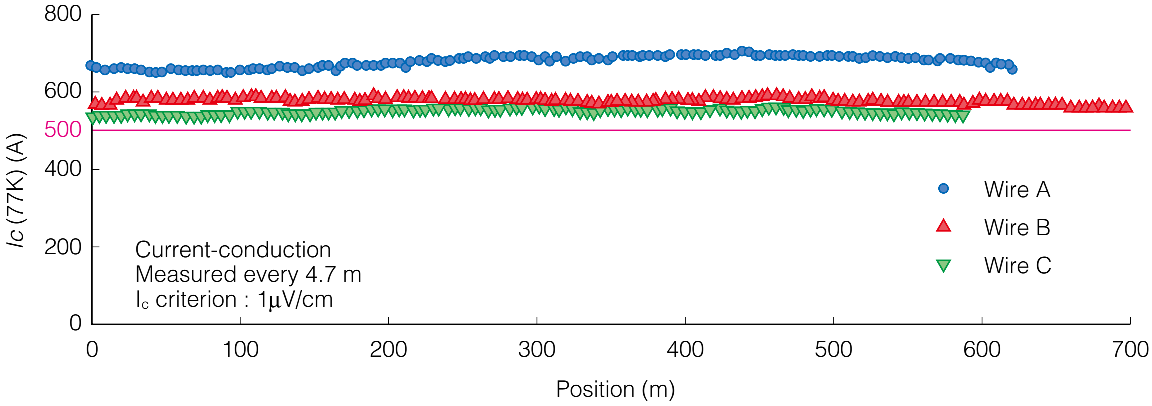

Fig. 3. Longitudinal I_c distribution t of production wires (typical examples).

cated. Its Ic x L value updated the world record of 466,981 Am/cm- width. As a result of these developments, quite uniform Ic over 500 A/cm- width with length over 500-m is routinely obtained as shown in Fig.3.

3. Design and fabrication of the Y-based superconducting power cable with large current capacity and low AC loss

A 20 m long 66kV HTS cable with a rated current of 5 kA rms was fabricated by applying IBAD-PLD wire mentioned above with high Ic=600 A/cm-width (@77 K,s.f.). The verification system was constructed, which includes the 20 m cable, a combined terminal vessel, and a cooling system. The current-loading characteristics of the HTS cable with the high Ic wire were verified.

3.1 Specifications and fabrication of the cable

In designing cable core, the target is as follows,

- Rated capacity : 66 kV - 5 kA rms class
- Object : one core of the three-core cable
- AC loss of conductor and shield : less than 2.0 W/m at 5 kA rms
- Outer diameter of cable core : one core of the three-core cable applicable to 150 mmϕ duct

The 20 m long HTS cable manufactured by Fujikura Ltd. was shown in Fig. 4, 5. The structure of the HTS cable was designed in accordance with the results [3] of the NEDO project “Development of Y-based Superconducting Power Equipment”. The specifications of the HTS cable are shown in Table 2. The cable core consists of a former made of stranded copper wires, an HTS conducting layer, an electric insulation layer, an HTS shielding layer, a copper shielding layer and a core protection. The cryostat pipe has an adiabatic multilayer applied between two stainless-steel corrugated pipes. The HTS conducting and shielding layers are consisted of 4 mm wide wires with a 0.1-mm-thick substrate and a 0.02 mm thick copper stabilizer. Critical current at 77 K, s.f., which is defined with 1μ V/cm is more than 240 A per 4 mm in width.

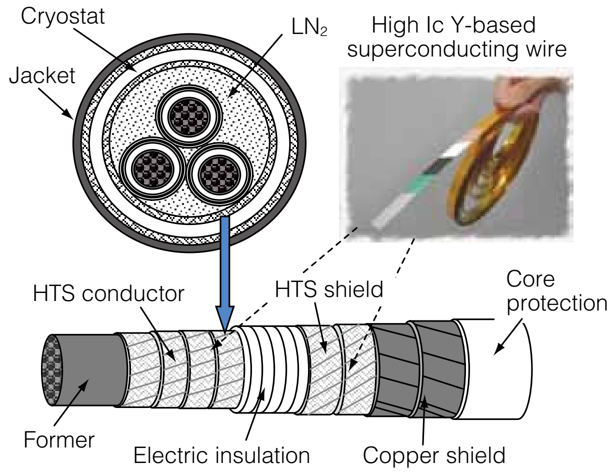

Fig. 4. Structure of high I_c Y-based HTS cable (Three-core cable).

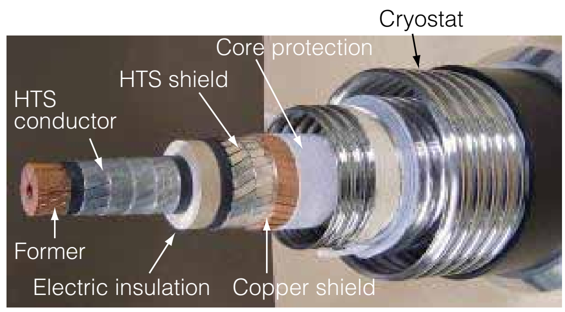

Fig. 5. Photograph of Y-based HTS cable (One-core cable).

Table 2. Specifications of the HTS cable.

Items	Specifications
Former	Stranded copper wires (140 mm2) 20 mmϕ
HTS conductor	4 layers, All 4 mm-width tapes (I_c = 14 kA) I_c = 240 A/4 mm-width (77 K, s.f.)
Electric insulation	Craft papers (6 mm-thickness)
HTS shield	2 layers, All 4 mm-width tapes (I_c = 12.7 kA) I_c = 240 A/4 mm-width (77 K, s.f.)
Copper shield	Copper tapes (100 mm^2)
Core protection	Nonwoven tapes 45 mmϕ
Cryostat	Double corrugated SUS pipes Vacuum thermal insulation
Jacket	Polyethylene 114 mmϕ

Fig. 6 shows measurement results of total Ic of all Y-based superconducting wires before and after the fabrication of the cable core. It shows almost the same values before and after fabrication. In addition, the designed load factors of the HTS conductor and shield were approximately 50 % and 55 %, respectively.

3.2 Preliminary evaluation with short sample of the cable

By measuring frequency dependence of the current distributoin with a short spare cable, it was confirmed that current distribution among layers of conductor and shield is uniform for 20 m long current loading test line. In addition, AC loss at 77 K was measured as less than 2.0 W/m at 5 kA rms as shown in Fig.12.

4. Verification of AC current loading characteristics

4.1 Structure of verification system

The verification system was constructed at Sakura plant in Fujikura Ltd. in January 2013. The system included the 20 m long HTS cable, a combined terminal vessel, and a cooling system. Schematic and photograph of the current loading test line are shown in Fig. 7 and 8 respectivly. Both ends of the cable were connected in one terminal vessel in order to shorten the connecting wire to suppress its impedance (resistance and inductance), while in case of two isolated terminal vessels the connecting wire would have become lon-

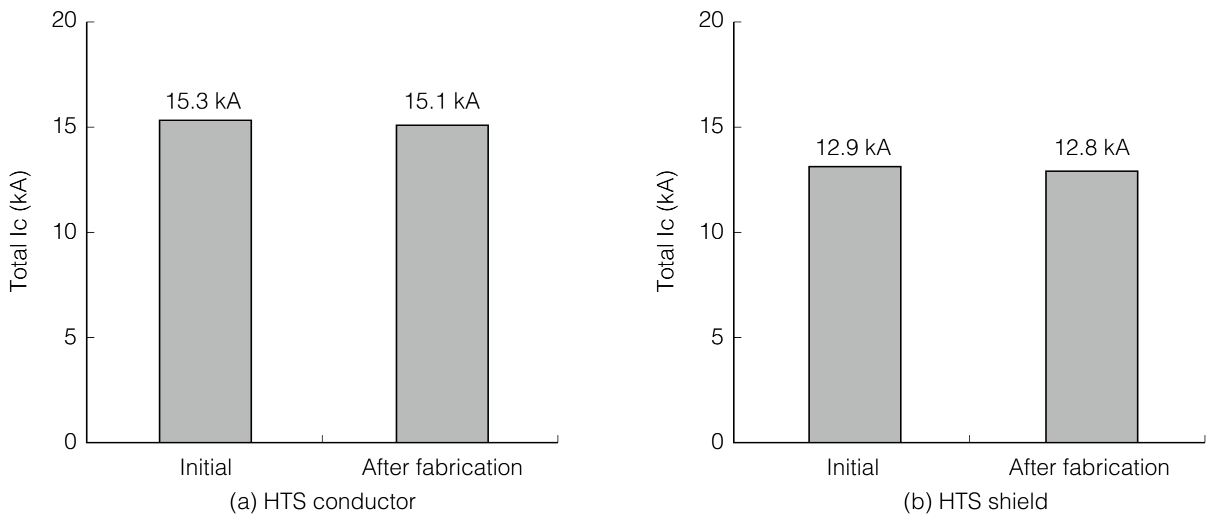

Fig. 6. Measurement results of total I_c of all Y-based wires before and after fabrication of cable core.

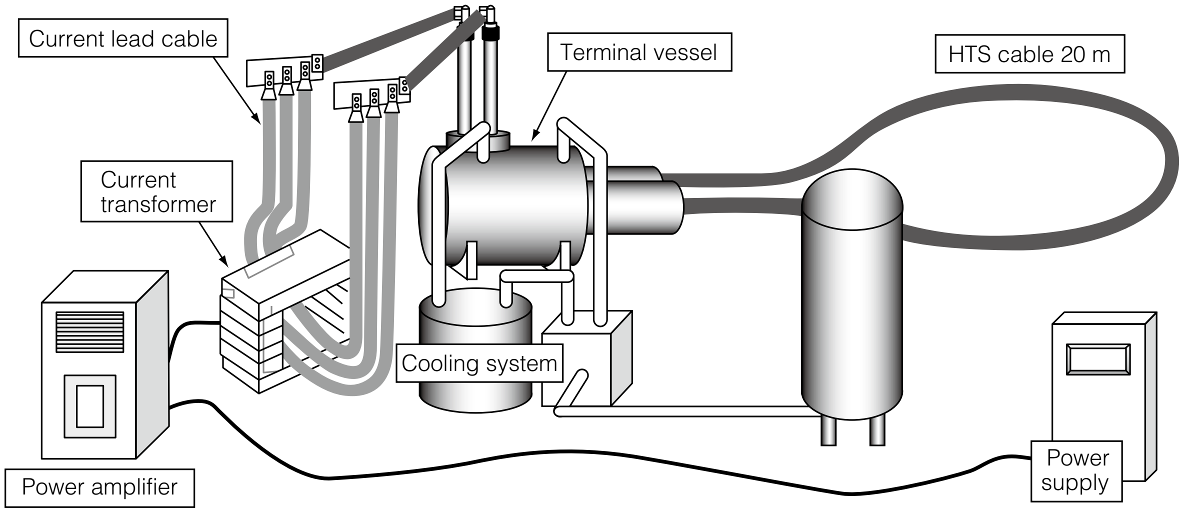

Fig. 7. Layout of current loading test line of the HTS cable.

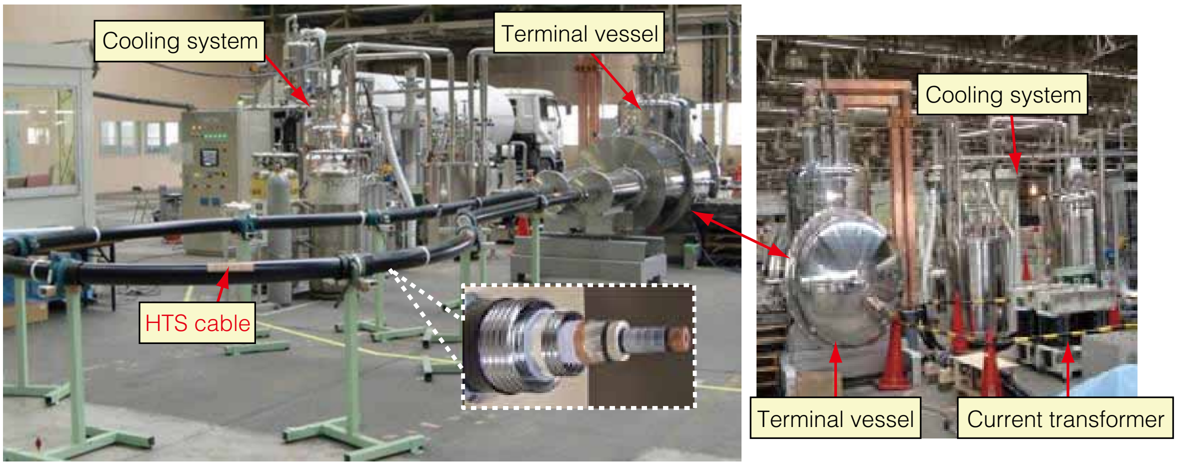

Fig. 8. The whole view of verification system.

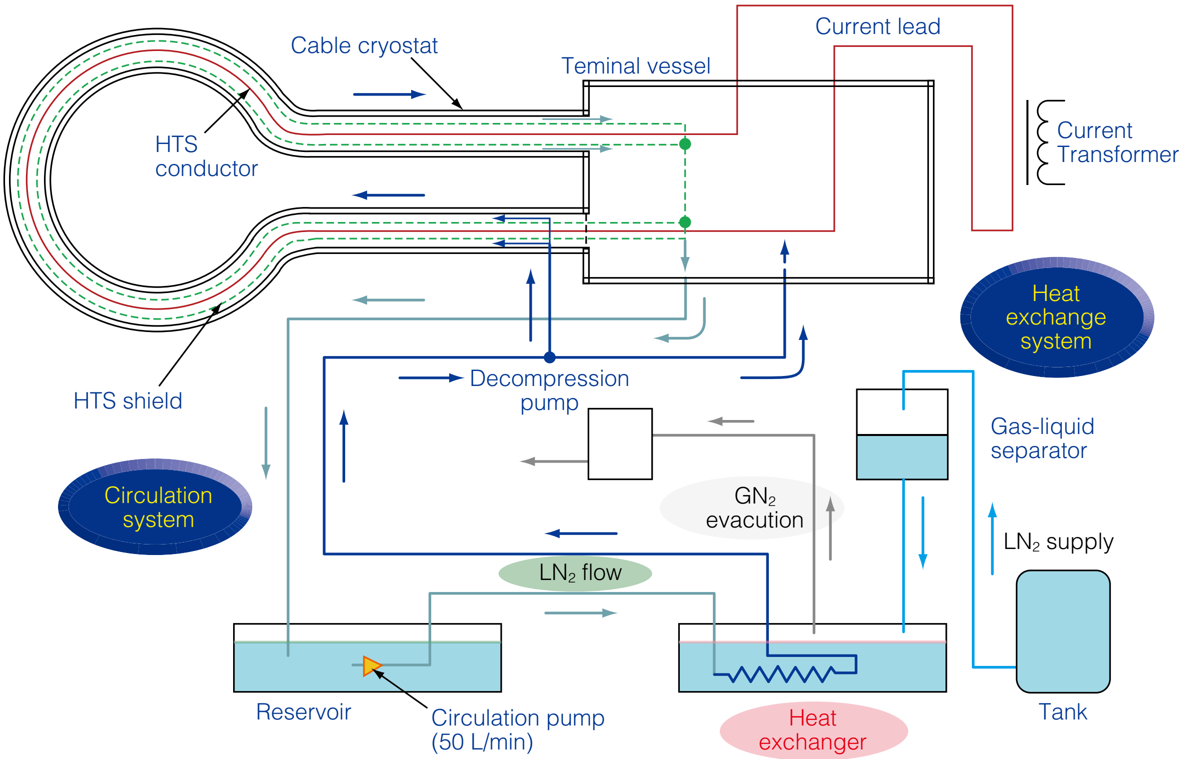

Fig. 9. Schematic of the cooling system.

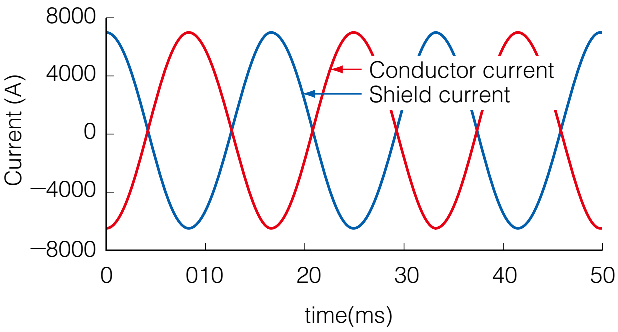

Fig. 10. Measurement results of conductor current and shield induced current at 5 kA rms at 67 K.

ger. Fig. 9 shows the cooling system of the verification system. The cooling system employed a circulation system for cooling the HTS cable and a heat exchange system for cooling the liquid nitrogen by the sub-cooled liquid nitrogen. It was possible to change the operating temperature from 67 K to 77 K by the cooling system. The cooling capacity of the cooling system was 2 kW.

4.2 AC current loading characteristics

Fig. 10 shows the current waveforms when the AC current of 5 kA was applied to the HTS cable. The induction rate of shield current to conductor current was approximately 98 %. In addition, the long-term (20 cycles) test was successfully conducted, where 1 cycle is a set of 8-hour current loading and 16-hour unloading.

AC current was supplied to the HTS cable conductor of the current loading test line and the loss compo-

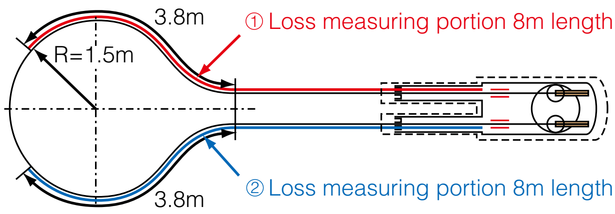

Fig. 11. Measurement portion of AC loss of HTS cable.

nent of the tap voltage was measured using a lock-in amplifier. The frequency of the AC current was 60 Hz in this test. Fig.11 shows the measurement portion of AC loss of the HTS cable, Fig. 12. shows the measurement results of total AC loss of the HTS cable conductor and the shield layer. The AC loss at 67 K was measured in the current loading test line, the AC loss at 77 K was measured by another short sample as mentioned in section 3.2. The measured AC loss was achieved as 1.4 W/m at 77 K and 1.0 W/m at 67 K at 5 kA rms.

5. Conclusion

Fujikura developed a 66kV-5 kA rms HTS power cable using our own Y-based IBAD-PLD wires with the world's highest Ic≧500 A/cm-width(@ 77 K, s.f.) and constructed the test line with the 20 m- long cable for AC current loading test excecution. The technical targets such as large current loading and low AC loss were achieved at practical temperature 77 K of LN_2 for the first time in the world. The result verified that it was possible to reduce AC loss by decreasing the load factor with high Ic HTS wires. In addition, it enabled to set the cooling temperature for designing the cryo-system of actual line. In the next step, we will make cable system compact based on these results, along with progresses towards lower transmission voltage and larger current transmission capacity which are advantages of HTS power cable.

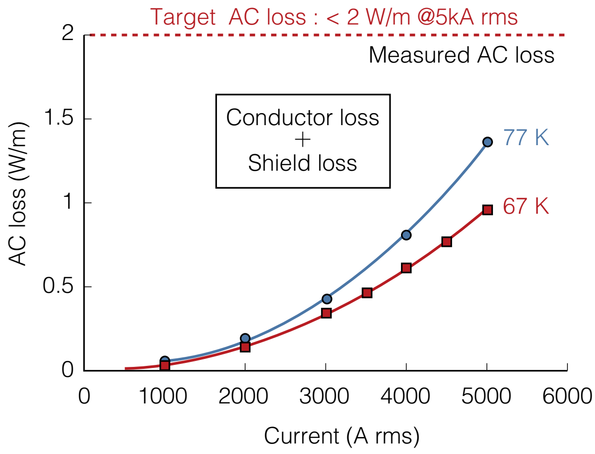

Fig. 12. Measurement result of AC loss of HTS cable.

Acknowledgements

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