The Development of 275 kV-3 kA YBCO High-Tc Superconducting Power Cable

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ABSTRACT In response to the increase in the supply and the demand of the electric power, Furukawa Electric has been developing a 275 kV-3 kA High temperature Superconducting (HTS) Power cable. This test has been commissioned by the New Energy and Industrial Technology Development Organization (NEDO) since 2008. The cable is able to transmit a large capacity of electricity of 1.5 GW which is the equivalent amount of power capacity of a single thermal power plant with low loss, and is expected to be put to practical use an electric power trunk line in the future.

The fundamental technology for the designing the HTS cable has been accumulated based on the result of such tests as the alternative current (AC) loss test, the withstand voltage test, the partial discharge test, and the over-current test. The 30 m HTS cable for a long-term electrical voltage and current load test was designed and manufactured according to the technologies. The insulation thickness was determined on the basis of the designed stress from the tests and the test conditions for the superconducting cables specified in standards such as IEC, JEC. The cable was also designed to withstand the over-current of 63 kA-0.6 sec and to satisfy the requirement to have the total of the dielectric loss and the AC loss under transmission current be less than 0.8 W/m at 275 kV-3 kA. The 30 m HTS cable was made under the above mentioned specifications, and evaluation was made on the attributes of the surplus length. It was confirmed that it satisfied the designed performance.

Furukawa Electric installed the 30 m HTS cable, the end termination and the normal joint at Shenyang Furukawa Cable. The long term electrical voltage and current load test at 200 kV for one month was completed successfully.

1. INTRODUCTION

The superconductive material features two characteristics: a zero electrical resistance and a high current density. The efficient electric instrument is obtainable based on the former characteristic and the powerful magnetic field is an outcome of the latter characteristic. The examples of using the latter characteristic are the magnetic resonance imaging (MRI) of the medical apparatus, the nuclear fusion technology, the accelerator for high energy physics, etc. and the superconductive metal technology in which area Furukawa Electric has a very good reputation. In order to utilize the former property, we need to lower the cooling cost for the superconductivity. The cooling system for the metal superconductor using the liquid helium (-269°C) is not useful from an economic perspective. Since the high-Tc superconductive material is utilized at liquid nitrogen temperature (-196°C), it is expected to be efficient, light weight, compact and energy-saving.

Furukawa Electric Group is not only the first runner in the metallic superconductor technology but making progress in the development of the High-Tc superconductor. Furukawa Electric group has been developing a superconducting cable based on the superconducting technology and an accumulation of the power electric transmission technology. The conventional power electric transmission technology is sought for the utilization of the extra high voltage power line and is progressing to lay the power lines underground, in the tunnel or the conduit in the city. However the tunnel is already fully occupied with the cables and the old cables need to be changed new ones. It would be economic advantageous if the superconduct-

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ing cable which has larger capacity and lower loss than the conventional cable could be installed in the vacant space in a tunnel or a conduit not being used at the moment.

Furukawa Electric has been developing a 275 kV extra high voltage superconducting power cable commissioned by the NEDO since 2008. The cable is targeted to have three times larger capacity and low loss compared to the conventional 275 kV cable. For a superconducting cable of 275 kV rated voltage and 3 kA of the current capacity, the transmission capacity for one line is equivalent to the power capacity of a single thermal plant of 1.5 GW (275 kV $/\sqrt{3} \times 3$ phase $\times$ 3.15 kVA). The cable consisted of a YBCO, which is expected to apply to various types of the electric instruments because of its cost performance, and its lower loss of one quarter to one fifth of the conventional cable even when considering the loss of cooling of the superconducting cable.

Table 1 shows the target of the development and that the targeted cable could perform at a better merit than the conventional cable.

Table 1 Target and merit of 275 kV – 3 kA HTS cable.

Item	Target	Feature
Loss	Total loss of the AC loss and the dielectric loss is less than 0.8 W/m	One quarter to one fifth of the conventional cable even when considering the loss of cooling of the superconducting cable
Electric insulation	The development of a cable, a normal joint and an end terminal	The design is the same as the conventional cable
Over-current	63 kA – 0.6 sec.	No breakdown at the worst case
Outer diameter	150 mm	The same as the diameter of the conventional 275 kV 2500 mm^2
Others	EMI free by the superconducting shield	No leak field on the high current transmission

2. DEVELOPMENT FOR THE REDUCTION OF THE ALTERNATIVE CURRENT (AC) LOSS

The electrical resistance is zero for the superconductor for the direct current (DC), however the alternative AC loss occurs on the AC when superconducting. The variable magnetic field based on the AC transmission is present in the superconductor and, thus, the loss is generated. Since the loss becomes load to the refrigerator used for cooling the superconducting cable, it has to be removed. The magnetic field penetrates from an edge of the tape-like superconductor wire and the characteristic of the edge is very important to solve the magnetic field. The AC loss is ten times larger in the case of limited characteristic of the superconductivity of the edge. The characteristic was improved by cutting the edge with a laser due to its low thermal impact.

Figure 1 shows the laser cutting of the edge of the yttrium series superconductor wire and the whole wire included the cut edge is plated with copper.

Figure 2(a) shows the AC loss normalized with the critical current (*Ic*). 5-C was the assembled superconductor wires with the width of 5 mm having the limited edge performance and 3-C is the assembled superconductor wires with 3 mm width produced by cutting edges with 1 mm each with a laser. The difference of AC loss was more apparent in the low use rate (*It*/*Ic*), the value of 5-C was five to ten times higher than 3-C. The loss value of 3-C obtained was 0.235 W/m at 3 kA. The numbers of the used superconductor wire were increased and the loss per a single superconductor wire was decreased to 0.124 W/m at 3 kA, as shown in Figure 2(b), which is the lowest attained value in worldwide.

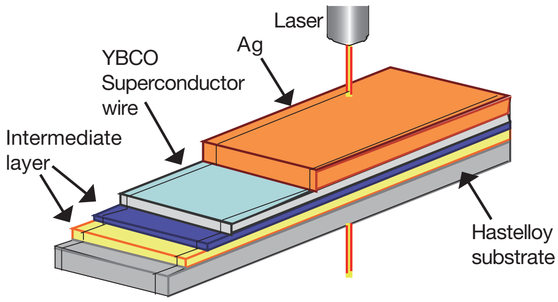


Figure 1 Laser cutting of both edges of YBCO wire.

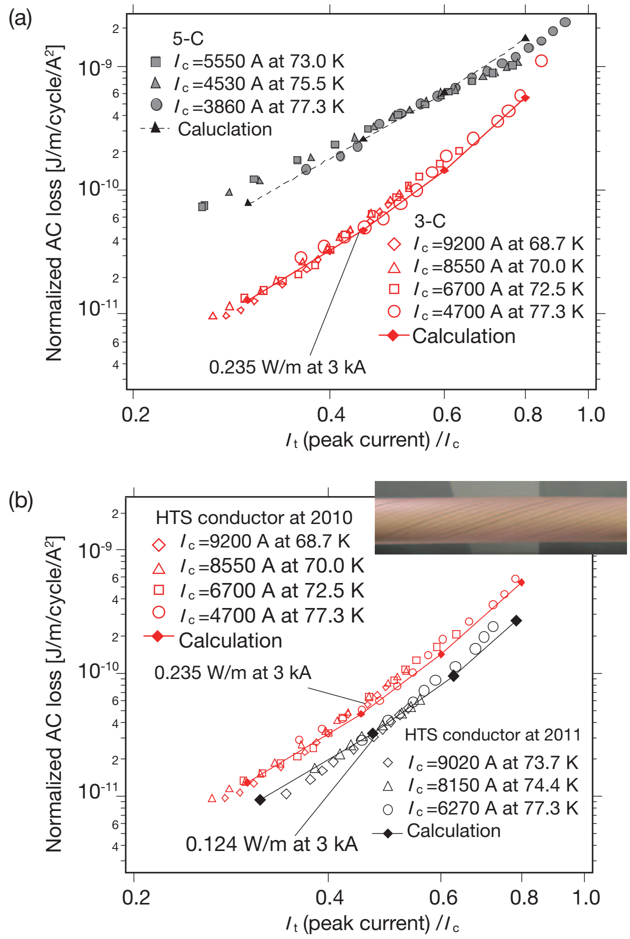


Figure 2 AC loss of HTS conductor.
(a)The comparison of loss between 5-C and 3-C, 3-C using the laser-processed YBCO wires.
(b)Further reduction of loss by adjusting the radius of the conductor.

3. DEVELOPMENT FOR SOLVING THE OVER- CURRENT

Since an over-current of about ten times the rated current flows into the superconducting cable during the short circuit fault, it is necessary for the superconducting cable to withstand the over-current when the cable is used in the power line system. Even though the withstand condition of the over-current for 275 kV system is determined on a specification from the customer, we adopted the value of 63 kA according to JEC 2350 of AC circuit breaker.[1)]

The duration time adopted is 0.6 seconds as the worst case scenario according to the technical report of the Institute of Electrical Engineers of Japan.[2)] The value of 63 kA is 20 times larger than the rated current of 3 kA used in the development of the superconducting cable. As the over-current is shunted for the protection of the conductor, the superconductor wire is protected. The structure of the superconducting cable is shown in Figure 3. The copper stranded former fills the role of the protection conductor for the superconducting conductor side and the braided copper wire fills the role of the protector for the superconducting shield side. The current flows through the superconducting conductor and the superconducting shield at steady condition but the commutation from the superconductor to the copper occurs on the over-current and the superconductor is protected. The cross surface area of the copper for the protection conductor is discussed later. The larger surface area of the protection copper conductor is decreases the temperature rise on the over-current, however the compactness is decreasing. An optimization of the cross surface area for the protection conductor is needed.

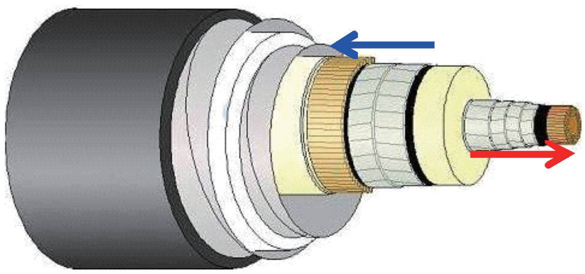


Figure 3 Structure of HTS cable.

In the case of the conductor current in the direction of the red arrow, the conductor shield current flows in the direction of the blue arrow.

The over-current test of the superconducting cable is shown in Figure 4. Two cables were installed in parallel and the superconducting conductor was connected with the generator and the shield circuit was assembled to induce the current in the superconducting shield.

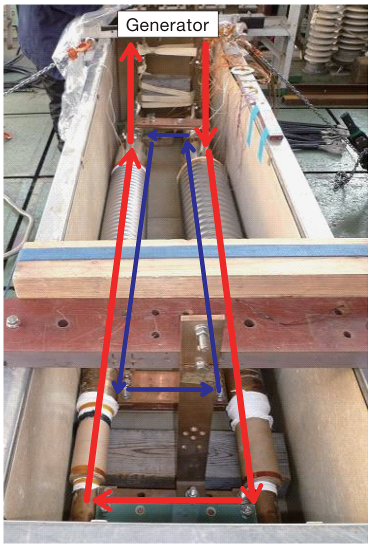


Figure 4 Closed circuit for the over-current test.

The right side cable in Figure 4 had a normal joint and the withstanding performance of the joint was checked. Figure 5 shows the shape of the normal joint. With respect to the conductor side, the reed shaped superconductor wire was installed parallel in the longitudinal direction and jointed. As for the shield side, the joint was carried out on the reinforced insulation layer and the joint method was the same as in the conductor side.

Figure 5 Normal joint of HTS for the over-current test.

Figure 6 shows the waveform for the over-current of 63 kA. A peak of the first wave was set at 158 kA in consideration of the DC component, which was 2.5 times of the over-current. On the other hand, the amplitude of the shield current was 80% of the conductor side. The amplitude of the shield current for the cable without a normal joint was 90% under the same test system. The difference occurred with or without the normal joint because of the magnetic connection at the normal joint.

Since the superconducting shield was installed on the reinforced insulation in the normal joint and the distance between the conductor and the shield of the joint was longer than the cable part, the magnetic connection was weaker. Furthermore the resistance of the terminal was not ignored because the test circuit was short. The amplitude of 80% was relevant according to the above conditions. The real superconducting transmission line will have the normal joint at interval of 100 m and the shield current can be 100% of amplitude of the conductor current.

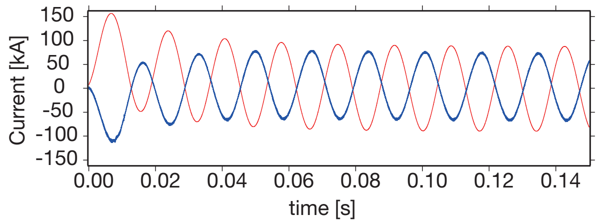


Figure 6 Waveform for the over-current of 63 kA.

An increasing temperature and a recovery time to the initial stage were checked by the duration time of the over-current of 63 kA as a parameter. With respect to increasing of the temperature, it was less than 5 K for 0.05 seconds (3 cycles) and less than 8 K for 0.1 seconds (7 cycles). The recovery to the initial stage was less than 3 seconds for both cases and the result suggested that the cable would be recovering smoothly after the accident. The increasing of the temperature and the recovery time to the initial stage for 0.6 seconds (36 cycles) were less than 20 K and ten minutes respectively and the value of Ic checked after the recovery did not deteriorate. These results showed the cable having enough tolerance for the over current.

4. DEVELOPMENT OF THE 275 KV INSULATION

4-1 Superconducting Cable Insulation for 275 kV

The insulation of the superconducting cable is a composite insulation consisting of the insulating paper and the liquid nitrogen shown in Figure 7. The insulation composition is similar to the oil-filled paper insulated cable (OF cable) consisting of the oil and the insulating paper. The electric design of the insulation is the same as the OF cable. The electric stress is the highest on the conductor and the insulation thickness is designed for the electric stress to be less than the designed stress. The insulating paper shown in Figure 7 is the semi-synthetic paper consisting of the polypropiren film (PP film) sandwiched with the thermal laminated kraft paper. The dielectric loss of the insulating paper is not ignored for the 275 kV system. If the insulating paper used for the 66 kV superconducting cable is applied to the 275 kV system, the loss reaches 0.8 W/m and does not meet the target shown in Figure 1. Therefore a semi-synthetic insulating paper, changing the component ratio of PP film from 40% to 60%, was applied.

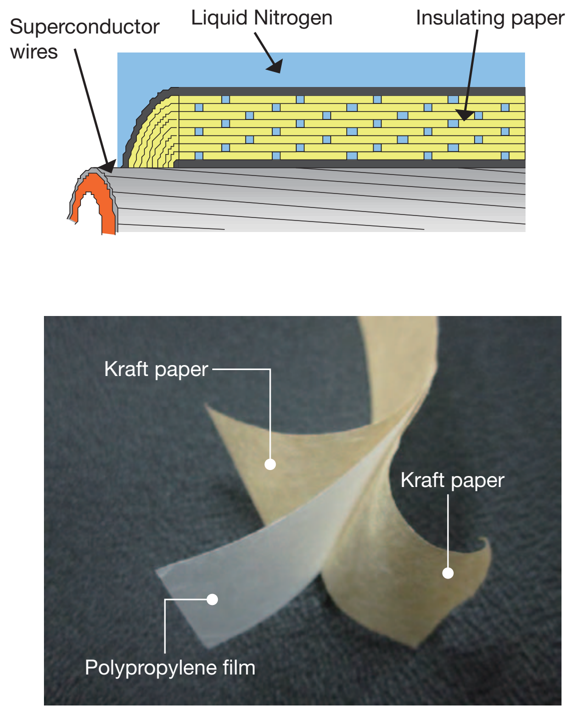


Figure 7 Structure of the electrical insulation for the superconducting cable.

With respect to the electric design, a partial discharge free (no partial discharge) at an abnormal voltage under the operation and withstand against the impulse lightening voltage were considered. The test condition was determined on the basis of IEC62067[3] of the international standard, JEC3408[4] of Japanese electrical standard and the other superconductor test standard. The determination was done at the committee of the NEDO project attended by the professors and the electric power experts.

The partial discharge test voltage was determined to 310 kV taking into consideration the electrical fault voltage, the target and no partial discharge at the test voltage. The value of 310 kV was determined as the 300 kV of the highest line voltage between two conductors times the voltage increased magnification on the load rejection ($1.79/\sqrt{3}$).

The test voltage of lightening impulse was 1155 kV which had a margin of 1.1 times of the withstand impulse voltage of the 275 kV electrical device.

The model semi-synthetic paper insulated cables having the insulation thickness of 1 mm, 10 mm and 20 mm were manufactured and the cables were tested. The designed electrical stress was determined according to the test result.

The result of the partial discharge test is shown in Figure 8. The semi-synthetic paper insulated cable immersed in the liquid nitrogen under absolute pressure of 0.2 MPa was tested for the partial discharge. The electrical stress detected an inception of the partial discharge while increasing in voltage was plotted in Figure 8. The result for the cable with the thickness of 1 mm was closely same as the cable with 10 mm thickness. Furthermore, the cable with the thickness of 20mm had no partial discharge at 300 kV (25.4 kV/mm) nor at 310 kV (26.2 kV/mm). The result suggested that the partial discharge inception voltage was independent from the insulation thickness. The inception voltage was obtained from the result of the thickness of 1 mm. The electric stress at the probability of the inception of 0.1% was 22 kV/mm and the electric stress was used as the design value.

Figure 9 shows the result of the impulse breakdown voltage test. The result of the sample with the insulation thickness of 1 mm was compared with the result of the sample with 10 mm insulation thickness. It suggested that the impulse breakdown voltage was dependent on the insulation thickness. Assuming the variation of the impulse property of 10 mm thickness is the same as 1 mm thickness, the design stress for the impulse breakdown of 83 kV/mm was determined. The outer diameter of the 275 kV cable was designed at 35.4 mm and the thickness of the insulation was 22 mm. The 275 kV cable was confirmed to withstand the target impulse voltage of 1155 kV.

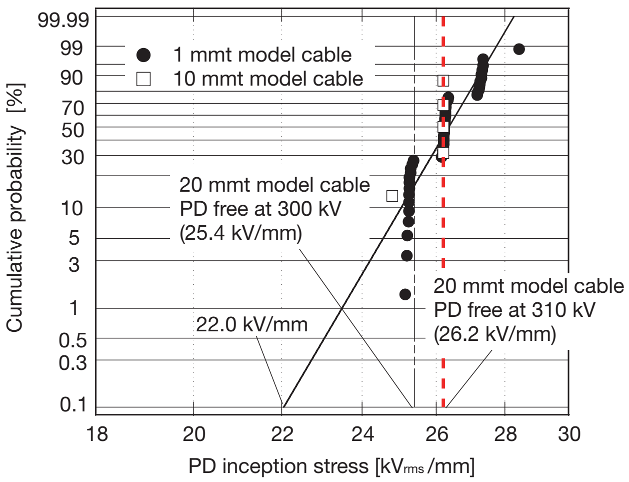


Figure 8 Weibull plot of Partial discharge Inception stress (PDIE) The design stress of PDIE free was 22 kV/ mm.

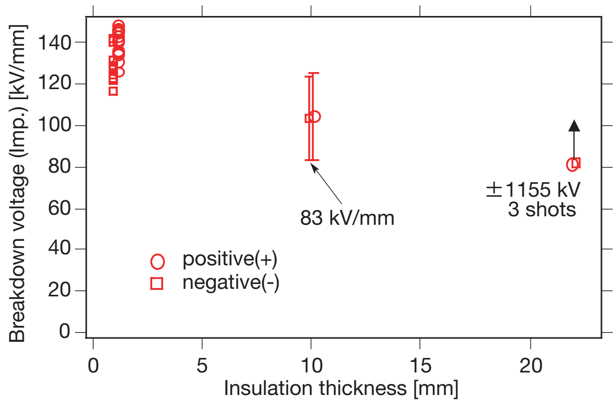


Figure 9 Impulse breakdown voltage of the model cable. Design stress of Impulse free was 83 kV/mm.

4-2 Normal Joint and End Terminal for 275 kV

With regard to the end terminal of the superconducting cable, the stress relief cone for electric field relaxation and the condenser cone to relax the electrical stress for the normal conductivity part from the atmosphere temperature to the liquid nitrogen temperature were designed and developed. The condenser cone was covered with the composite bushing. The composite bushing was consisting of the epoxy based FRP cylinder coated with the silicone rubber and shade, and attached the clasp at the both side of the cylinder. The electric field analysis for the combination of the condenser cone and the composite bushing was carried out, and a relevant design satisfying the target voltage was determined. The composite bushing achieved downsizing to 80% in length and 20% of weight reduction comparing to the porcelain bushing. Furthermore, it was designed so that the superconductor wire would not get damaged on cooling and rising of the temperature, based on the solution for thermal expansion and contraction to prevent the cable from buckling. Figure 10 shows the outdoor end terminal.

With respect to the normal joint for the super conducting cable, the insulation was designed on the basis of the electrical stress in the radial direction and in the longitudinal direction. The electrical stress for the insulation design was obtained from the breakdown test on the insulation model close to the actual cable and taking into consideration the tolerance. The joint of the former and the superconductor wire were carried out as shown in Figure 5 and the joint had low resistance and withstood the over- current.

The end terminal and the insulation part of the normal joint were designed for withstanding an AC voltage of 400 kV and an impulse voltage of 1155 kV, and a current carrying part was designed for withstanding the rated current of 3 kA and the over-current of 63 kA-0.6 sec.

Figure 10 Termination for 275 kV HTS cable.

5. DESIGN AND MANUFACTURING OF 275 KV-3KA SUPERCONDUCTING CABLE

5-1 The Design of the 275 kV-3kA Superconducting Cable

According to the result described in articles 2 to 4, the 275 kV-3 kA superconducting cable was designed and the designed items were summarized in Table 2.

Table 2 275 kV-3 kA HTS cable.

Composition	Specification	Outer diameter
Former	Hollow stranded conductor of 400 mm^2	35.4 mm
Superconducting conductor	Superconducting two layers, Sixty wires with width of 3 mm AC loss of 0.124 W/m at 3 kA	
Insulation	Semi-synthetic paper with thickness of 22 mm Dielectric loss of 0.6 W/m	79.4 mm
Superconducting shield	Superconducting one layer AC loss of 0.076 W/m at 3 kA	81 mm
Copper shield	Copper braided wire of 210 mm^2	90 mm
Protect layer	Semi-synthetic paper	
Double thermal insulated pipe Outer sheath	Double stainless pipe, Vacuum insulation layer, Poly-ethylene sheath	150 mm

The 400 mm^2 hollow copper wire strands was used as the former. The former can withstand the over-current of 63 kA-0.6 sec. and protect the superconductor, and decrease the temperature on the line fault. If it is needed for the temperature to decrease more, the diameter of the former can be larger.

The superconductor wire having the width of 3 mm and a constant *Jc* (critical current density) in the cross sectional direction was used for the superconducting conductor and the AC loss at 3 kA was 0.124 W/m.

The semi-synthetic paper insulation consisted of the kraft paper and the PP film, the composite rate of the PP film being larger than the conventional semi-synthetic paper was used and the insulation thickness was 22 mm. The design of the thickness was determined by the electric stress on the conductor shield wound up on the superconducting conductor to be less than the designed stress. Since the larger conductor makes the insulation thickness thinner, the capacity becomes larger and the dielectric loss is increased. On the other hand, the smaller conductor makes the insulation thickness thicker and the dielectric loss is decreasing. The insulation design shown in Table 2 makes the electric loss of 0.6 W/m.

Even though the superconducting shield layer being one layer, however, since the wound diameter of the shield was larger than the conductor, the numbers of the used superconductor was more than the conductor. An anti-phase current against conductor current in the superconducting shield was induced by the magnetic field of the conductor and the superconducting shield sealed the magnetic field by the anti-phase current. The disturbance of the magnetic field created by the superconducting shield is small because of the distance from the conductor being long and the AC loss of the shield is expected smaller than the conductor, the value is one-third to one-fourth according to our experience. However, the superconductor wire used for the shield has the width of 5 mm with deteriorated *Jc* on the edge, the analyzed result suggested that the AC loss of the shield was 60% of the conductor loss.

According to the above result, the total loss was 0.8 W/m associated with the AC loss at 3 kA of 0.2 W/m with the dielectric loss of 0.6 W/m.

The stainless (SUS) thermal insulated inner pipe and the super insulation (SI) of the vacuum insulation material were wound, and the SUS outer pipe with polyethylene sheath for the cold area, and the target of the total outer diameter was 150 mm.

5-2 The Manufacturing of the 275 kV-3 kA Superconducting Cable

The superconducting cable was manufactured according to the design shown in Table 2. The structure of the manufactured cable is shown in Figure 11.

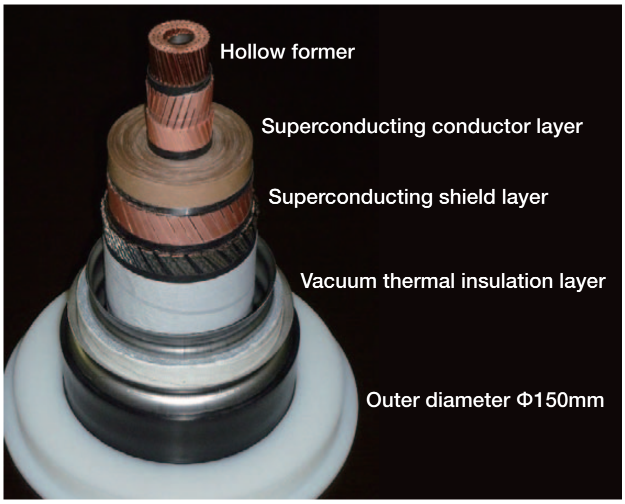
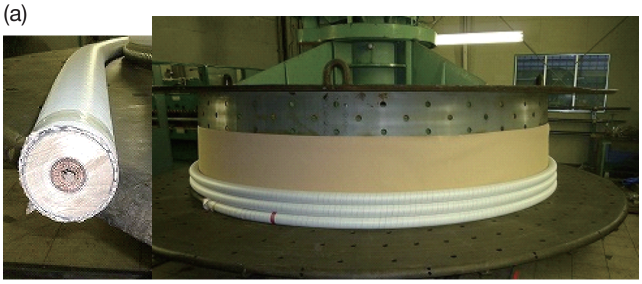


Figure 11 Structure of 275 kV-3 kA HTS cable.

The superconductor wire with a single length of more than 50 m was used. Every superconductor wire was checked *Ic* for the total length. The wire with the width of 3 mm for the conductor with more than 80 A (the average of 97 A) of Ic and the width of 5 mm for the shield with more than 100 A (the average of 117 A) were used. The superconducting cable core with the length of around 50 m was manufactured and the core of around 20 m out of 50 m was applied to the bend test, the structure examination, the withstand voltage test, the over-current test and AC loss test. Figure 12 (a) shows the superconducting cable core with length of 30 m for a demonstration and Figure 12 (b) shows the superconducting core covered with the thermal insulated pipe.

The result of the tests for the core of 20 m was described below. The core had neither break nor ruck on the insulation after the bend test, the structure examination was satisfied with the dimension of Table 2. The result of the withstand voltage test was satisfied with the designed property. The withstand voltage test was done immersed nitrogen under the atmospheric pressure being more severe than the test liquid nitrogen under pressure.

(a)



(b)

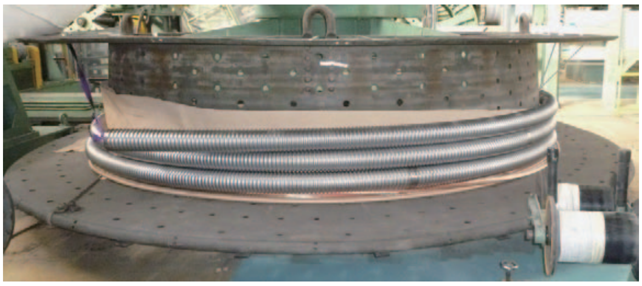


Figure 12 Manufacturing of the HTS cable.
(a) HTS core
(b) HTS core with the thermal insulated pipe

Figure 13 shows the result of *Ic* measurement. It was 6440 A on the conductor side and 5920 A on the shield side immersed nitrogen under the atmospheric pressure. Each result of the *Ic* was larger than the expected value, the average of *Ic* of the superconductor wire times the numbers of used wires, 5820 A and 5031 A respectively. The result shows no deterioration of *Ic* during the manufacturing. With respect to the shield side, the result indicated that the transition from the superconducting to the normal state occurred slowly and the transition suggested the localized deterioration in the superconductor wire in the longitudinal direction. The suggestion was supported by the *Ic* measurement result for the superconductor wire before the cable manufacturing.

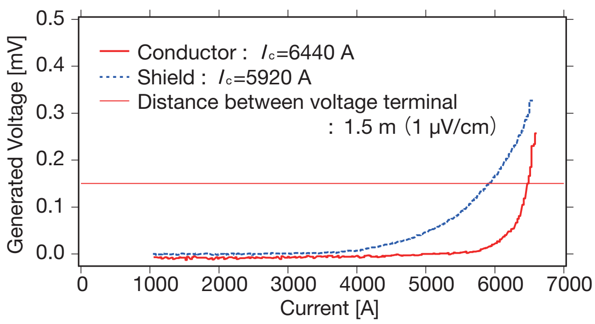


Figure 13 V-I characteristics of the HTS cable sample.

6. A LONG TERM ELECRICAL VOLTAGE AND CURRENT LOAD TEST AT 275 KV – 3KA

6-1 The Installment of the Normal Joint and the Transfer of the Cable

The superconducting cable of 30 m with the normal joint had been manufactured, and then the terminal for the superconducting conductor and superconducting shield and the stress relief cone were fitted to the end terminal, and the cable was laid on the pallet shown in Figure 14 and was transported to Shenyang Furukawa Cable located in Shenyang city, Liaoning, of the test yard. The superconducting technology is very interesting in East Asia where the demand of the energy is increasing tremendously and the test carried out in China would be to broadcast the Japanese technology to the world and to contribute to advance the superconducting technology globally.

With respect to the transportation route, the cable was transported by road from Chiba to Yokohama, from Yokohama to Dalian port by sea and from Dalian to Shenyang by road. The transportation was controlled with an acceleration meter installed on the pallet and the result was less than 3G, and the shape of the cable appeared normal after the transportation.

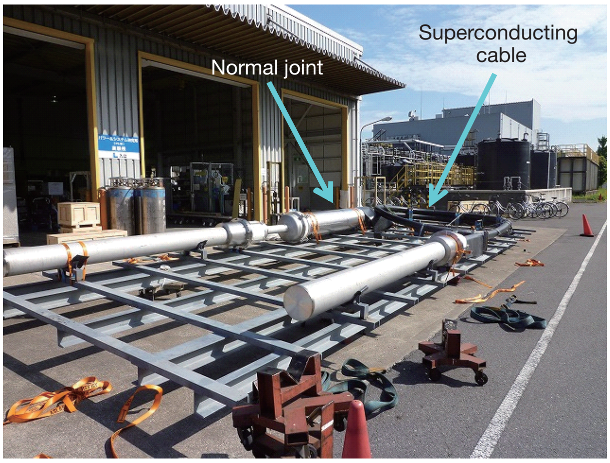


Figure 14 Transportation of the HTS cable with the normal joint.

6-2 The Demonstration System at Shenyang Furukawa Cable Co.

After the test yard was ready, the AC transformer for loading the voltage and the XLPE cable with the conductor area of 2500 mm^2 for carrying current of 3 kA were installed preliminarily. The superconducting end reservoir was installed and the transported superconducting cable was connected to the reservoir.

The cooling system was also installed and flow diagram for the cooling system was shown in Figure 15. The liquid nitrogen for cooling the superconducting cable was on the closed-loop circulation and the nitrogen was cooled through the sub cooler of the heat exchanger having a cooling ability of more than 3 kW. The liquid nitrogen in the sub cooler was cooled based on decreasing the saturation vapor pressure through depressurizing by an air displacement pump. Since the liquid nitrogen in the sub cooler was vacuumed out and consumed, the consumed nitrogen was resupplied from the cold evaporator.

The *Ic* of the conductor and the shield, including the normal joint, was measured after the cooling with the liquid nitrogen immersing. The result was 6800 A on the conductor and 7000 A on the shield and showed no deterioration occurring after the cable transportation and the cable installation for the long term electrical voltage and current load test. Figure 16 shows the layout of installation of the 30 m cable. The superconducting cable was bent in the shape of a U and three XLPE cables were connected with one end terminal. This means that the superconducting cable can transfer three times the current. The loaded voltage and term were determined as 200 kV by converting the line voltage of 300 kV to a voltage to ground, and one month taking into consideration the accelerated deterioration respectively. The long term electrical voltage and current load test started in November, 2012 and was completed in December, 2012. The result of the partial discharge test for the 275 kV superconducting cable after the long term electrical voltage and current load test was zero at 310 kV of the designed voltage. It showed that the cable maintained the initial property after the accelerated deterioration test equivalent to 30 years. Further the long term electrical voltage and current load test is planned to continue for one year.

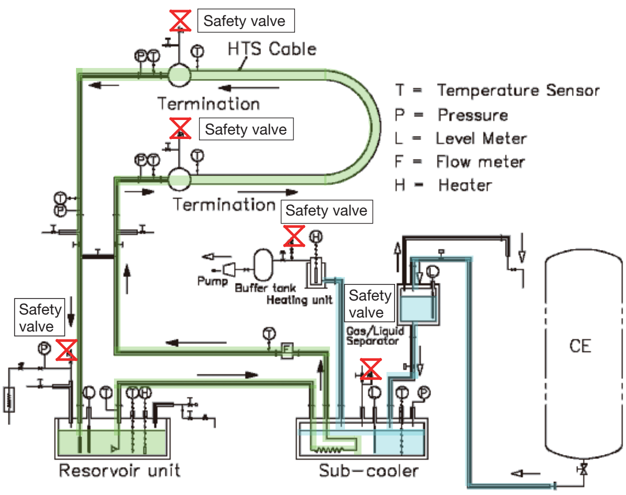


Figure 15 Flow diagram of cooling system.

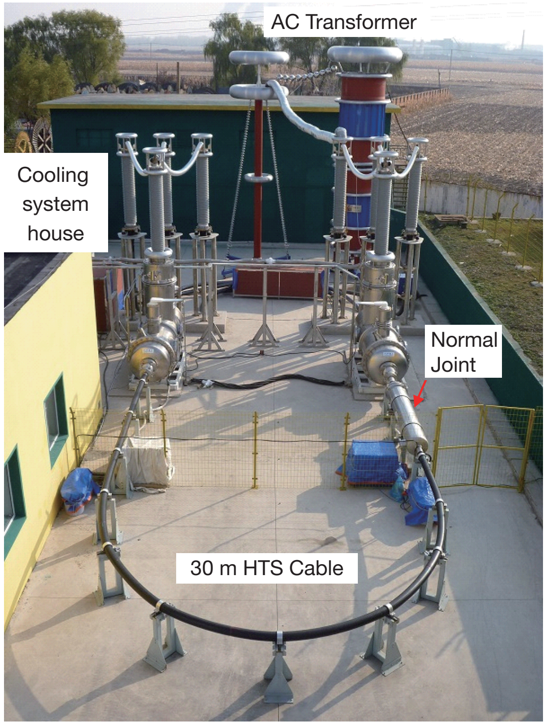


Figure 16 Layout of demonstration of 275 kV-3kA HTS cable.

Acknowledgement

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We thank Mr. Sato, General Manager of Viscas Corporation for cooperating in manufacturing the superconducting cable of high quality. With respect to the test at Shenyang Furukawa, we thank Mr. Uetake, Chief of headquarters for sponsoring the test activities. We also secured a lot of support from Mr. Li, General Manager of the quality assurance department and others for the installation of XLPE cable, the operation of the long term electrical voltage and current load test and the partial discharge measurement, etc. We would like to express our sincere appreciation and gratitude for their support.

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